

## Seismogenic sources responsible for destructive earthquakes in north-eastern Italy

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**ABSTRACT** The paper discusses the seismogenic characteristics of NE Italy related to earthquakes with  $M_w \geq 5.5$ , and the geometry of the related sources re-drawn by following the DISS standard procedure. Therefore, this paper represents an update of a previous work which investigated the Prealpine area between the Lessini Mountains and the Italian-Slovenian border, and defined the seismogenic sources potentially responsible for earthquakes with  $M_w \geq 6$  within the GNDT-2000 project. For inclusion in the DISS, the sources of that previous work have been processed following a 3-step process, which is a routine procedure used each time the parameters of a seismogenic source are taken from published works. The first step was a consistency check of the source dimensions (aspect ratio, from length/width relationships and according to the fault type), of their position and geometry (minimum and maximum depth and dip), and of some seismological parameters of the expected/associated earthquakes (slip,  $M_w$  from both Wells and Coppersmith's and Hanks and Kanamori's relationships, and seismic moment). All these parameters were verified by using the Fault Studio software. The second step involved the inclusion of seismological information, such as the measured stress drop, to infer slip on the fault plane and rupture area and to compare these parameters with the rupture area hypothesised on the basis of the geological information. The third step of the data processing deals with the analysis of the intermediate size historical seismicity ( $5.5 \leq M_w \leq 6.0$ ) and the possible association with faults belonging to the identified active thrust systems of the eastern Southalpine Chain front or to more internal faults (both thrust and strike-slip faults) not included in the data set of the previous work.

### 1. Introduction

Within the framework of the GNDT-2000 project, Galadini *et al.* (2005) investigated the Prealpine area between the Lessini Mountains and the Italian-Slovenian border, in order to define the seismogenic sources potentially responsible for earthquakes with  $M_w \geq 6$ . After the publication of the mentioned paper, further work became necessary to introduce the seismogenic sources and the related kinematic-dynamic information in the Database of Individual Seismogenic Sources [hereby DISS; Valensise and Pantosti (2001), DISS Working Group (2005)], which is a GIS based compilation of possible sources of earthquakes of  $M$  5.5 or higher. Indeed, the DISS processing follows a procedure which is different from that adopted in Galadini *et al.* (2005). Firstly, DISS reports sources potentially responsible for earthquakes with  $M_w \geq 5.5$  [while the threshold adopted

by Galadini *et al.* (2005), was  $M_w \geq 6.0$ ). Moreover, the energetic aspect is derived by considering the potential rupture area of each source, the slip on the fault plane and hence, by calculating the expected seismic moment. Finally, the sources are represented by simplified rectangular planar surfaces, with the fault trace at the surface (or for blind faults, the intersection of the along-width projection of the plane with the surface) given by a linear segment and not by curvilinear traces (better representing the geologic-geomorphologic information) as adopted by Galadini *et al.* (2005).

The reasons why the fault data set studied by Galadini *et al.* (2005) was included in the new edition of the DISS are the following: 1) the recent/present activity of the faults, constrained by stratigraphic and geomorphic criteria; 2) their dimensions, making them possible sources of future large earthquakes in the magnitude range of interest of the database; and 3) the association of some of the faults with historical earthquakes. Besides, the last issue of the DISS [DISS 2.0, Valensise and Pantosti (2001)] was characterised by a lack of information in the Veneto-Friuli area, mainly due to the few active tectonics studies, present in the literature that deal with the identification of individual seismogenic sources.

On this basis, this paper discusses the seismogenic characteristics of NE Italy related to earthquakes with  $M_w \geq 5.5$ , and the geometry of the related sources re-drawn by following the DISS standard procedure. In this way it represents a formal update of the work by Galadini *et al.* (2005). Since the structural-geomorphic content is the same as that reported in the already published paper, no detailed descriptions about this are included here. Therefore, after a section dedicated to the general neotectonic-seismotectonic aspects, the procedure adopted to define the seismogenic sources will be illustrated. Finally, a map with seismogenic sources potentially responsible for earthquakes with  $M_w \geq 5.5$ , will be produced [with sources in the magnitude range  $5.5 \leq M_w \leq 6.0$  for the pre-1976 events, not previously produced by Galadini *et al.* (2005)].

## 2. Neotectonic-seismotectonic framework

The investigated area is located at the border between the Southern Alps fold and thrust-belt and the Venetian-Friulian plain, and follows the Pliocene-Quaternary front of the eastern Southalpine Chain (ESC) (Fig. 1). The eastern sector of the Southern Alps is affected by the highest seismicity in the whole Alpine chain. Shortening and crustal thickening are still active and the most intense seismic activity has been recorded along the southern margin of the ESC. The seismic activity is almost exclusively due to the activation of compressional sources, as indicated by the focal mechanisms (e.g. Slejko *et al.*, 1999), linked to the evolution of the S-SE verging thrust fronts, with main compression directed between NNW-SSE and N-S; strike-slip focal mechanisms characterise the western-Slovenian territory (e.g. Fitzko *et al.*, 2005) and the Alto Tagliamento area north of Tolmezzo (Poli *et al.*, 2000; Bressan, 2002).

The ESC has been struck by numerous earthquakes with magnitude between 6 and 7 during historical times, as indicated in the catalogue by Working Group CPTI (2004): 1117 (Verona area), 1348 (Carnia region), 1695 (Asolo area), 1873 (Belluno area), 1936 (Bosco Cansiglio) and 1976 (Friuli).

During the 70s and the 80s, a large amount of data on the Pliocene-Quaternary fault activity of NE Italy was collected. Data were summarised in Zanferrari *et al.* (1982), CNR-PFG (1987),

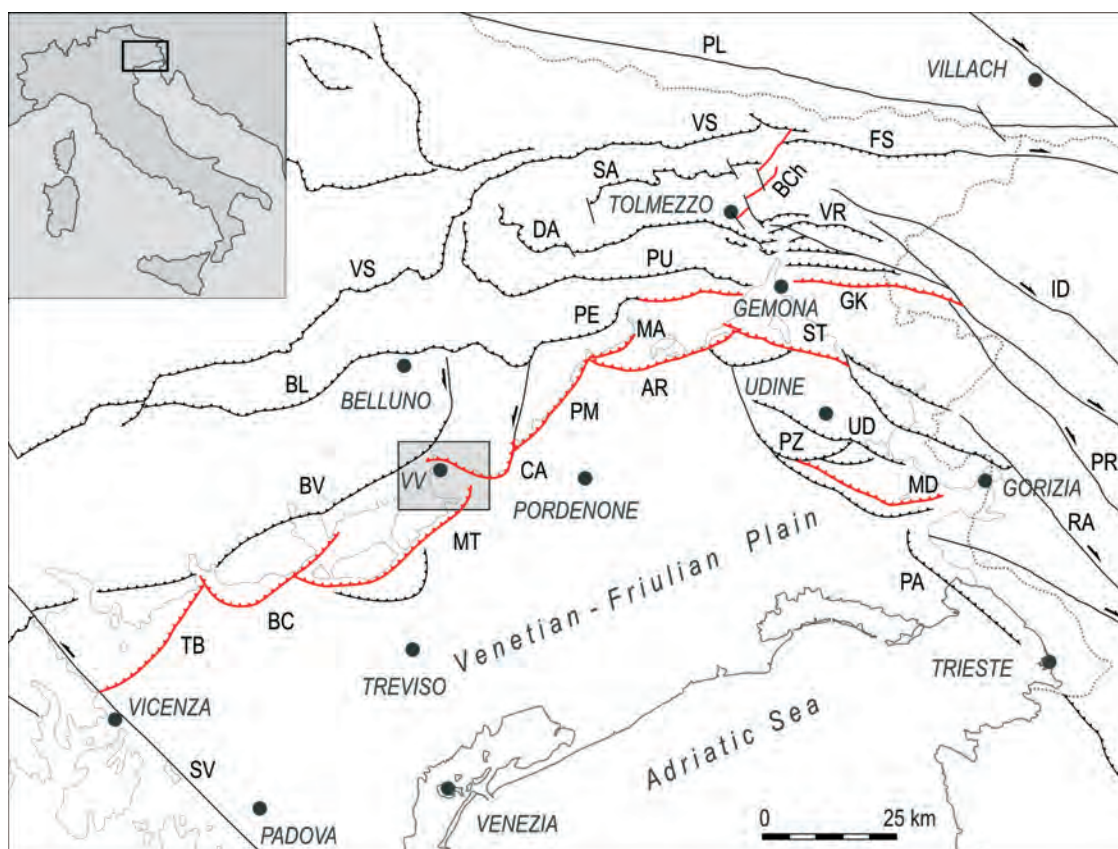


Fig. 1 – Structural sketch-map of NE Italy and western Slovenia. Red lines show active faults described in the text. Legend: AR, Arba-Ragogna thrust; BC, Bassano-Cornuda thrust; BCh, But-Chiarsò fault; BL, Belluno thrust; BV, Bassano-Valdobbiadene thrust; CA, Cansiglio thrust.; DA, Dof-Auda thrust; FS, Fella-Sava line; GK, Gemona-Kobarid thrust; ID, Idrija fault; MA, Maniago thrust; MD, Medea thrust; MT, Montello thrust; PA, Palmanova line; PE, Periadriatic thrust; PL, Periadriatic line; PM, Polcenigo-Maniago thrust; PR, Predjama fault; PU, Pinedo-Uccea thrust; PZ, Pozzuolo thrust; RA, Rasa line; SA, Sauris thrust; ST, Susans-Tricesimo thrust; SV, Schio-Vicenza line; TB, Thiene-Bassano thrust; UD, Udine-Buttrio thrust; VR, Val Resia thrust; VS, Valsugana thrust. Grey rectangle indicates Vittorio Veneto (VV) study area.

Slejko *et al.* (1989) and Castaldini and Panizza (1991). Until the 90s, the seismotectonic interpretation was conditioned by a strong cylindricism and numerous parallel thrusts were considered as active (e.g. the Sacile, Aviano, Bassano-Valdobbiadene and Periadriatic thrusts and the so-called Belluno line). Moreover, no hypotheses on the fault segmentation were available.

New geological data and a critical review of the literature permitted Galadini *et al.* (2001) to draw a summary of the active faults affecting the eastern Southern Alps at a regional scale. In this product, the number of active faults was drastically reduced with respect to previous works. Moreover, at a local scale, new geological and geophysical data on the Pliocene-Quaternary activity of the thrust fronts have been published since the end of the 90s (Ferrarese *et al.*, 1998; Aoudia *et al.*, 2000; Benedetti *et al.*, 2000; Sauro and Zampieri, 2001; Avigliano *et al.*, 2002; Merlini *et al.*, 2002; Peruzza *et al.*, 2002; Poli *et al.*, 2002; Caputo *et al.*, 2003; Zanferrari *et al.*,

2003; Fitzko *et al.*, 2005). These data were fundamental for the definition of the seismogenic sources reported in Galadini *et al.* (2005).

### 3. Active fault segments: the procedure for the identification

Thrust segments in the investigated area have been defined on the basis of a new structural framework and new geomorphological investigations. The identification of active fault segments, probably representing the surficial expression of single seismogenic sources, is the first step towards the definition of the seismogenic behaviour of an area (Schwartz and Coppersmith, 1984). Segmentation has been based on traditional procedures (e.g. de Polo *et al.*, 1991; Mirzaei *et al.*, 1999). The termination of a single segment is located where the fault is crossed by a transverse structure (e.g. a transfer fault) or where the deformation decreases for the presence of another thrust segment with an *en-échelon* relationship.

Since the tectonic activity of the ESC is expressed by the motion of blind thrusts, the conclusive evidence of Upper Pleistocene-Holocene deformation can rarely be obtained by means of surficial investigations. In contrast, the geomorphological evidence of general Late Quaternary activity can be detected. Moreover, geomorphological data on the recent fault activity are sometimes debatable. For example, the lack of evidence of recent displacements in the mountainous region may have been conditioned by the erosional-depositional geological evolution of the Alps since the Last Glacial Maximum (LGM). Intense erosion by the glacial tongues and subsequent rapid deposition of thick successions of alluvial deposits may have hidden the evidence of recent fault activity.

Anyway, geomorphological investigations were performed to identify the surficial traces of the recently active faults. The geomorphological evidence of Upper Quaternary deformation is due to the response of the landscape to the buried thrust growth. This deformation is generally continuous over wide areas, across the projection at surface of a buried thrust and represented by gentle scarps connecting uplifted paleolandscapes of Quaternary Age with the flat and lower areas of the Venetian and Friulian Plains.

Apart from the geomorphologic features at the surface, evidence of recent, blind fault activity was derived from the analysis of industrial reflection seismic profiles. Therefore, the geophysical data (constrained by borehole data) defined the deep geometry of the faults. The study of the reflection, seismic lines between Conegliano and Cividale allowed us to define the buried geometry of the ESC front in the Venetian-Friulian plain, the relationships between the Paleogene and the Neogene compressive structures in the easternmost sector (Friuli region) as well as the Late Miocene-Quaternary structural evolution of the area.

## 4. The seismogenic sources

### 4.1. The procedure adopted by Galadini *et al.* (2005)

The first attempt to summarise the available knowledge on the seismogenic sources responsible for destructive earthquakes is represented by an earlier version of DISS [DISS 2.0, by Valensise and Pantosti (2001)]. In this area the DISS reported the sources of historical earthquakes with geometries constrained mainly by the distribution of the highest intensity

datapoints [method by Gasperini *et al.* (1999)] and, secondarily, by the sparse available geological data. In contrast, the most recent product about seismogenic sources (Galadini *et al.*, 2005) has benefited from previously unavailable reflection seismic data and new surveys, partly made for the new Geological Mapping of Italy in the Friuli Venezia Giulia Region (CARG-FVG Project: Udine, Maniago, Gemona del Friuli and San Vito al Tagliamento Geological Sheets). Basically, geophysical, geodetic, seismological and macroseismic data were merged with the geological-geomorphological and structural information in order to identify the fault segments and the structures having seismogenic potential.

The reconstruction of the 3D-fault geometry was obtained, therefore, by linking the surficial fault expression with the sub-surficial structural data. In this way, Galadini *et al.* (2005) obtained the rupture length, the downdip rupture width and the rupture area. The drawing of the seismogenic sources was based on this 3D geometry characterisation. In this way, and by adopting the equations by Wells and Coppersmith (1994) linking  $M_w$  with the rupture dimensions, the mentioned authors defined seismogenic sources potentially responsible for earthquakes with  $M_w \geq 6.0$ .

Following the criteria already used by Valensise and Pantosti (2001), the geologically-geophysically defined sources were represented by Galadini *et al.* (2005) as the projection at the surface of the rupture plane assumed to be characterised by a rectangular shape. In the investigated area, the rupture plane (i.e. the seismogenic source) is defined by the ramp portions of the thrusts. Lines were also reported beside each rectangle, defining the source surficial expression as it was inferred from surficial geological and geomorphological data. Since the ESC front is generally made of blind thrusts, the lines approximated the limit between areas affected by different vertical movements, i.e. the location of the gentle scarps formed by the differential vertical movement. The absence of the line in the work by Galadini *et al.* (2005) indicated that no evidence of the source at surface could be detected with the traditional geological and geomorphological methods. Available reflection seismic data indicate, however, that almost all the reported sources are characterized by a tip line close to the surface and are responsible for the deformation of (Upper) Quaternary deposits. For this reason, the minimum depth of the source was conventionally fixed at 1 km. The only exception was represented by the Trasaghis source (n. 9 in Table 1, and ID 9 in Table 2), located in the deep sub-surface and having no surficial evidence.

Constraints on the deep fault geometry were also derived from the epicentral locations of the main shock and the aftershocks of the 1976 earthquake. Moreover, the damage distribution of historical earthquakes also represented a tool to define the geometry of the causative sources, based on qualitative procedures such as those already adopted by Galadini *et al.* (1999), simply based on the fact that most of the damage is generally contained in the fault hangingwall.

Structural surficial (e.g. kinematic indicators) and sub-surficial (e.g. the geometry of the deformation) data gave direct information on the kinematics of the fault planes. This structural information and the 3D fault geometries were compared with the kinematic data derived from regional works on structural geology and geodesy (Castellarin *et al.*, 1992; Castellarin and Cantelli, 2000; Caporali and Martin, 2000; D'Agostino *et al.*, 2005) and with information on the regional stress field obtained through the inversion of seismometric data (Bressan *et al.*, 1998; Slejko *et al.*, 1999). This comparison permitted us to define the slip vector for each reported



Table 1 - Geometric-kinematic characteristics of the seismogenic sources affecting NE Italy, from Galadini *et al.* (2005). The ID numbers are the same in the following tables and in Fig. 2.

\* - from Castaldini and Panizza (1991)

+ - from Benedetti *et al.* (2000)^ - based on data by Zanferrari *et al.* (in prep.)

Seismogenic source	Rupture length (km)	Downdip rupture width (km)	Rupture area (km <sup>2</sup> )	Minimum depth (km)	Maximum depth (km)	Rake	Vertical slip rate (mm/yr)	Min. vertical slip rate (mm/yr)	Magnitude	Associated historical earthquake
Thiene-Bassano (1)	20	9.5	190	≈1	5.75	100°	<1*	-	6.43	1117 (Jan. 3) (?)
Bassano-Cornuda (2)	22	11	242	≈1	6.2	100°	<1*	0.42-0.5	6.49	1695 (Feb. 25)
Montello-Conegliano (3)	30	15	480	≈1	12	100°	1+	0.32-0.4	6.69	-
Cansiglio (4)	15	10	150	0	7	120°	<1*	0.4-0.47	6.24	1936 (Oct. 18)
Polcenigo-Maniago (5)	21	14	294	≈1	9	100°	<1*	0.17-0.25	6.55	1873 (June 29)
Arba-Ragogna (6)	27	11	297	≈1	6.2	90°	0.17^	-	6.62	-
Gemona - Kobarid (7)	35	15	525	≈1	9	95°	-	-	6.77	1348 (Jan. 25)
Susans-Tricesimo (8)	25	13	325	≈1	6	75°	-	-	6.57	1976 (May 6)
Trasaghis (9)	14	9	126	8.5	14	70°	-	-	6.20	1976 (September 15)
Medea (10)	21	10	210	≈1	5-8	60°	-	0.15-0.22	6.45	-

source.

The data necessary to define the slip rates are generally sparse in the investigated area. Only for a few investigated structures (e.g. Montello-Conegliano and Arba-Ragogna) has it been possible to calculate the slip rates by means of geomorphological procedures (e.g. minimum slip rates based on the displacement of the base of Pleistocene deposits). For this reason, most of the slip rates reported in Galadini *et al.* (2005) were derived from Castaldini and Panizza (1991). In this work, however, the rates are expressed as large intervals of values (always in the order of 0.1-1 mm/yr).

Following the procedure described above, Galadini *et al.* (2005) defined 1) the geometry of ten seismogenic sources potentially responsible for earthquakes with  $M_w \geq 6.0$  (Fig. 1); 2) the maximum expected magnitude per source [by adopting the empirical relationships by Wells and Coppersmith (1994)]; 3) the source kinematics (Table 1).

Finally, the source geometry was compared with the highest intensity datapoint distribution of large historical earthquakes with  $M_w \geq 6$ , in order to make hypotheses on the association of these past seismic events with specific seismogenic sources. Three sources (Montello-Conegliano, Arba-Ragogna and Medea) could not be related to historical earthquakes. Based on the completeness of the historical catalogue for large magnitude earthquakes (e.g. Stucchi and Albinì, 2000), this defines a minimum elapsed time since the last source activation in the order of eight centuries. Evidently, areas characterized by a higher level of seismic hazard may be associated to

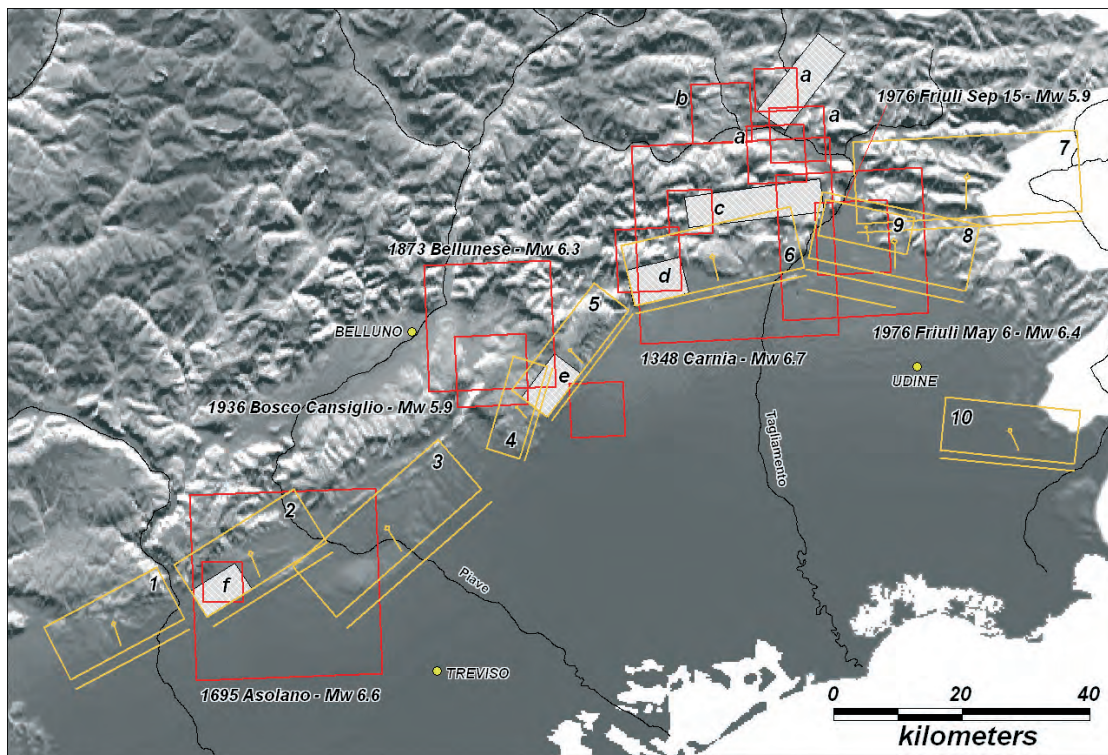


Fig. 2 - Map of the Veneto-Friuli area showing seismogenic sources (identified by the same numbers as in the text and tables), historical seismicity with  $M_w \geq 5.5$  [squares scaled with  $M_w$ , from Working Group CPTI (2004)], and suggested source areas of smaller magnitude earthquakes (in grey, lettered the same as in the text and Table 4). The parameters of the seismogenic sources are listed in Table 2.

these “silent” sources.

#### 4.2. Refinement and update of the seismogenic information for the introduction in DISS

The seismogenic sources of DISS are represented as planar rectangular faults, and are associated with geometrical (location, length, width, minimum depth, maximum depth, dip and strike) and kinematic (rake, slip per event, slip rate, recurrence interval and magnitude) parametrical attributes, as well as to information about the associated earthquakes. Not all these parameters are always available for each seismogenic source in the literature data, and when missing they are derived by using empirical and analytical relationships linking the different dimensions (Hanks and Kanamori 1979; Wells and Coppersmith, 1994).

In order to be included in the DISS, the sources by Galadini *et al.* (2005) have been processed in 3-steps, that is a routine procedure used each time the parameters of a seismogenic source are taken from published works.

STEP 1: The first step was a check of the consistency of the source dimensions (aspect ratio, from length/width relationships and according to the fault type), of their position and geometry (minimum and maximum depth and dip), and of some seismological parameters of the expected/associated earthquakes [slip,  $M_w$  from both Wells and Coppersmith's (1994) and Hanks

Table 2 - Comparison of the geometrical parameters of the seismogenic sources identified by Galadini *et al.* (2005) before and after (in bold-italic) Step 1 of the data processing. The new width were calculated holding the length proposed by the authors fixed. The  $M_w$  are calculated using Wells and Coppersmith (1994) empirical relationships (WC). The seismogenic sources mapped in Fig. 2 have geometrical dimensions according to the length and width columns of this table.

\* from Sirovich and Pettenati (2004)

\*\* from Poli *et al.* (2002)

\*\*\* from Galadini *et al.* (2005)

ID	Name	Length (km)	Width (km)	Min depth (km)	Max depth (km)	Dip	Mw (WC)	Rupture area (km <sup>2</sup> )
1	Thiene-Bassano	20	9.5/ <b>10.5</b>	1	5.75/ <b>6.3</b>	30	6.43/ <b>6.4</b>	190/ <b>210</b>
2	Bassano-Cornuda	22	11/ <b>11.2</b>	1	6.2/ <b>6.6</b>	30	6.49/ <b>6.5</b>	242/ <b>246</b>
3	Montello-Conegliano	30	15/ <b>13.9</b>	1/ <b>2.0</b>	12.0/ <b>10.9</b>	40	6.72/ <b>6.7</b>	480/ <b>417</b>
4	Cansiglio	15	10/ <b>8.5</b>	0	7/ <b>7.5</b>	50*	6.24/ <b>6.2</b>	150/ <b>128</b>
5	Polcenigo-Maniago	21	14/ <b>10.8</b>	1	9/ <b>9.3</b>	50	6.55/ <b>6.5</b>	294/ <b>227</b>
6	Arba-Ragogna	27	11/ <b>12.6</b>	1	6.2/ <b>9.1</b>	40	6.62/ <b>6.6</b>	297/ <b>340</b>
7	Gemona-Kobarid	35	15/ <b>15.5</b>	1	9/ <b>9</b>	35	6.77/ <b>6.8</b>	525/ <b>543</b>
8	Susans-Tricesimo	25	13/ <b>12.2</b>	1	6/ <b>7.1</b>	30**	6.57/ <b>6.6</b>	325/ <b>305</b>
9	Trasaghis	14	9/ <b>8.1</b>	8.5	14/ <b>14.2</b>	29***	6.20/ <b>6.2</b>	126/ <b>113</b>
10	Medea	21	10/ <b>10.8</b>	1	5-8/ <b>7.9</b>	40	6.45/ <b>6.4</b>	210/ <b>227</b>

and Kanamori's (1979) relationships, and seismic moment]. All these parameters were verified by using the Fault Studio [v. 1.1, Basili (2003)] software, that is a MapBasic application (which uses a geographical interface) developed to calculate geometrical and kinematic parameters of seismogenic sources to be introduced in the DISS database. The results are presented in Table 2, reporting the comparison between old and new parameters.

To adjust the geometry of a source to a correct aspect ratio, we held the length and minimum depth, since these are the parameters that can be easily addressed via geological/geomorphological investigations; all the other parameters were derived consequently. For instance, in the case of the Thiene-Bassano source, a length of 20 km [as proposed by Galadini *et al.* (2005)] required a width of 10.5 km (instead of 9.5 km), while a minimum depth of 1 km and a dip of 30° implied a maximum depth of 6.3 km (instead of 5.75 km). Or, if also the maximum depth was kept firm, a dip of 27°.

STEP 2: The second step involved the inclusion of seismological information, such as the measured stress drop, to infer slip on the fault plane and rupture area, and to compare these parameters with the rupture area hypothesised on the basis of the geological information. This information was available only for the sources associated with the shocks of the 1976 Friuli sequence (Cocco and Rovelli, 1989). We used the average stress drop of the 1976 Friuli sequence for all the sources, and derived slip,  $M_w$  and seismic moment of the "characteristic" earthquake



Table 3 - Seismological parameters of the seismogenic sources, derived from the average stress drop of the 1976 Friuli sequence [70 bars, Cocco and Rovelli (1989)] and using analytical relationships.  $M_w$  (WC), derived from the relationships by Wells and Coppersmith (1994) using the scaled (aspect ratio) rupture area;  $M_w$  (HK), derived from the equations by Hans and Kanamori (1979) considering scaled source area and slip;  $M_o$ , seismic moment using scaled rupture area and slip; Seismological  $M_o$ , only for the sources associated with instrumental earthquakes.

\* from Cocco and Rovelli (1989)

\*\* from Sirovich and Pettenati (2004)

\*\*\* from Working Group CPTI (2004)

° from Pondrelli *et al.* (2001)

^ area scaled using relationships among magnitude of associated earthquakes, stress drop, slip and rupture area.

ID	Name	Scaled rupture area (km <sup>2</sup> )	Seismological rupture area <sup>^</sup> (km <sup>2</sup> )	Slip (m)	$M_w$ (WC)	$M_w$ (HK)	$M_o$ (Nm)	Seismological $M_o$ (Nm)	Earthquake (yr)	Earthquake $M_w$ ***
1	Thiene-Bassano	210	—	1.75	6.4	6.7	1.2e+019	—	—	—
2	Bassano-Cornuda	246	—	1.87	6.5	6.7	1.5e+019	—	1695	6.6
3	Montello-Conegliano	417	—	2.68	6.7	7.0	3.6e+019	—	—	—
4	Cansiglio	128	54	0.60	6.2	6.2	2.5e+018	3.3e+018**	1936	5.9
5	Polcenigo-Maniago	227	—	1.82	6.5	6.7	1.4e+019	—	1873	6.3
6	Arba-Ragogna	340	—	2.38	6.6	6.9	2.7e+019	—	—	—
7	Gemona-Kobarid	543	—	3.18	6.8	7.1	5.7e+019	—	1348	6.7
8	Susans-Tricesimo	305	137	1.32	6.6	6.7	1.3e+019	2.9e+018*	1976 (6 May)	6.4°
9	Trasaghis	113	56	0.75	6.2	6.2	2.8e+018	1.0e+018*	1976 (15 Sep 09:21)	6.0°
10	Medea	227	—	1.82	6.5	6.7	1.4e+019	—	—	—

generated by each source by considering the geological rupture area. These parameters were compared to those of the associated historical earthquakes, and in general to understand if the characteristic earthquake of the source has a reasonable dimension.

The results indicate that the seismogenic sources identified via geological/geomorphological approach, are larger than the ones scaled using the seismological relationships (Table 3). For instance, the three sources associated with instrumental earthquakes (4 Cansiglio; 8 Susans-Tricesimo and 9 Trasaghis), have areas determined via geology/geomorphology that are two/three times larger than expected when scaling with the  $M_w$  and the stress drop. The other sources, for which we entered the relationships with the area, have the expected “characteristic” earthquakes with scaled  $M_w$  slightly larger than the associated historical event. This indicates that the geological-geomorphological method may lead to an overestimation of the coseismic rupture dimensions.

STEP 3: Galadini *et al.* (2005) have only considered historical earthquakes with  $M_w \geq 6.0$ , and then have hypothesised that the reported sources could generate earthquakes of this or larger size.

The third step of our data processing deals with the analysis of the intermediate size historical

Table 4 - Earthquakes with  $5.5 \leq M_w \leq 6.0$  from Working Group CPTI (2004), and associated sources.

ID	Date	Locality	Lat	Lon	Intensity	Maw	Source tentatively associated
b	1700-28-07	Raveo	46.43	12.87	9.0	5.8	source north of the Periadriatic thrust
d	1776- 10-07	Tramonti	46.22	12.71	8.5	5.8	fault of the Arba-Ragogna thrust system
a	1788-20-10	Tolmezzo	46.40	13.02	8.5	5.7	fault of the But-Chiarsò system
c	1794-07-06	Tramonti	46.30	12.79	7.5	5.6	Campone segment of the Periadriatic thrust (Meduna valley)
e	1812-25-10	Sequals	46.03	12.59	7.5	5.7	deep source? – two shocks? – fault of the Polcenigo-Maniago thrust system?
f	1836-12-06	Bassano	45.81	11.82	8.0	5.5	fault of the Bassano-Cornuda thrust system
a	1924-12-12	Carnia	46.46	12.98	7.0	5.5	fault of the But-Chiarsò system
a	1928-27-03	Carnia	46.37	12.98	9.0	5.8	fault of the But-Chiarsò system

seismicity ( $5.5 \leq M_w \leq 6.0$ ) and the possible association with faults belonging to the identified active thrust systems of the ESC front or to more internal faults (thrust and strike-slip faults) not included in the previous data set (Galadini *et al.*, 2005). The lack of these sources in the mentioned work was due to the lower energy threshold considered here and the consequent absence of clear surficial active fault expressions. The earthquakes that could enter in this class are listed in Table 4, and their parameters are taken from the Working Group CPTI (2004). Further studies on each individual earthquake are necessary to better constrain the suggested seismogenic sources.

From east to west the studied earthquakes and their tentatively associated sources are the following (Fig. 2 and Table 4).

- a) A cluster of earthquakes located in the Tolmezzo area (Tolmezzo, 1788; Carnia, 1924 and 1928). The 1928 Carnia earthquake shows a strike-slip focal mechanism with plane a: strike  $124^\circ$ , dip  $74^\circ$  to SW; and plane b: strike  $220^\circ$ , dip  $70^\circ$  to NW (Poli *et al.*, 2000). Moreover, other similar strike-slip focal mechanisms were obtained from minor earthquakes [1956  $M_s = 4.8$ , Paluzza event and 1959,  $M_s = 4.9$  Carnia event, in Poli *et al.* (2000, 2002)]. Such solutions indicate activation of WNW-ESE or NNE-SSW strike-slip faults. As a working hypothesis, we consider a NNE-SSW fault, belonging to the But-Chiarsò system, as the seismogenic source of the Carnia-Tolmezzo earthquakes.
- b) The 1700 Raveo earthquake, for which no tectonic structure was identified.
- c) The 1794 Tramonti earthquake, whose location may indicate the activation of the Campone segment of the Periadriatic thrust.
- d) The 1776 Tramonti earthquake that is tentatively associated with a fault of the Arba-Ragogna thrust system (i.e. the Maniago fault in Fig. 1).
- e) The 1812 Sequals earthquake, that is characterised by two distinct macroseismic epicentral areas 30 km away, and as such could be alternatively interpreted as: 1) a deep earthquake, 2) multiple event (two shocks), or 3) associated with a fault of the Polcenigo-Maniago fault system.
- f) The 1836 Bassano earthquake, which is a very localised event and could be associated to a fault of the Bassano-Cornuda thrust system.

## 5. Conclusions

A significant amount of geological data have been collected in the last five years in NE Italy, aimed at better understanding seismogenic behaviour. The available data have been produced during the GNDDT-2000 Project, but also during new geological mapping performed within the CARG FVG Project and a PRIN-2000 (R.U. of Udine University). A strong effort was made in 2003-2004 to transform the geological data in reliable seismogenic information expressed in parametric form and suitable for different engineering purposes. The present paper testifies the last act of the procedure, represented by the preparation of the data for the introduction in the DISS. This final step of the 5-year-long research was necessary, to express the seismogenic information in a form similar to that used for the rest of the Italian territory. This uniformity will permit one to use the seismogenic information on NE Italy also in the course of hazard elaborations applied to the entire national territory.

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