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Seismogenic sources potentially responsible for earthquakes with $M \geq 6$ in the eastern Southern Alps (Thiene–Udine sector, NE Italy)

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SUMMARY

New geomorphological and structural data permitted to define the active faulting framework of the eastern Southern Alps (NE Italy). All the active faults detected in the investigated area are thrust segments of the complex thrust system, which has been responsible for the latest building of the Eastern Southalpine chain (ESC). Geomorphological investigations were performed to identify the surficial traces of recent fault activity, generally represented by gentle scarps connecting uplifted palaeolandscapes of Quaternary age with the flat and lower areas of the Venetian and Friulian plains. Surficial and subsurficial data (the latter from reflection seismic profiles) available for the investigated faults indicate that the thrusts have been responsible for the displacement of the entire wedge of Quaternary deposits. In the western sector of the investigated area, the six recognized fault segments represent portions of a 100-km-long thrust system, at the boundary between the Alpine relief and the plain areas. In the eastern sector, active tectonics is the result of parallel thrust segments, located both in the Alpine mountainous area and in the Friulian plain. The 3-D geometry of the active thrust segments has been derived from new structural surficial surveys and the interpretation of reflection seismic profiles for a total length of 1700 km. On this basis, we defined the geometry of 10 seismogenic sources whose dimensions are consistent with the occurrence of earthquakes with $M \geq 6$. The comparison between the source geometry and the highest intensity data point distribution of large historical earthquakes has permitted to make hypotheses on the association of past seismic events to specific seismogenic sources. This procedure indicated that no large historical events can be attributed to three sources (Montello-Conegliano, Arba-Ragogna, Medea). This may indicate an elapsed time since the last activation of more than eight centuries, based on the completeness of the historical catalogues. The available data define, therefore, sources (and related areas) for which a high level of seismic hazard may be invoked.

Key words: active fault, eastern southern Alps, NE Italy, seismic hazard, seismogenic source, thrust tectonics.

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1 INTRODUCTION

Historical seismic catalogues indicate that the eastern Southern Alps (NE Italy, Veneto and Friuli regions) were struck by at least eight earthquakes with $M \geq 6.0$ during the second millennium (e.g. Working Group CPTI 1999). Considering (i) the frequency of earthquake occurrence and (ii) that this area has a high population density and the highest density of industrial settlements among the most seismic regions of Italy, a high level of seismic risk can be invoked (e.g. GNDT-ING-SSN 1996). For this reason, the definition of the regional neotectonic and seismotectonic characteristics has been the object of numerous studies (e.g. Carulli *et al.* 1981; Zanferrari *et al.* 1982; Slejko *et al.* 1989; Del Ben *et al.* 1991; Peruzza *et al.* 2002) particularly after the 1976 May 6 earthquake (M 6.5), which caused damage up to I 9.5 of the Mercalli-Cancani-Sieberg (MCS) scale in the Friuli region.

Although modern investigations on the regional seismotectonics started more than 25 yr ago, knowledge on the seismogenic sources of the eastern Southern Alps is still sparse. This is mainly the result of the fact that the recent/present tectonic activity is related to the motion of systems of blind thrusts, whose characteristics (e.g. length of the single segments, slip rates) cannot be defined through traditional geomorphic analyses only. For this reason, most of the data on the seismogenic sources of the eastern Southern Alps derive from the application of algorithms that permit to define the geometry of a source from the intensity distribution data points of historical earthquakes (e.g. Sirovich *et al.* 2000; Valensise & Pantosti 2001). During recent years, however, knowledge on the subsurficial

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structural characteristics of the eastern Southern Alps has strongly improved as a result of the increasing amount of data from reflection seismic surveys (e.g. Nicolich *et al.* 2002). Moreover, recent works have shown that detailed geomorphologic investigations can define the areas affected by the continuous deformation, which typically represents the surficial expression of the blind thrusts (e.g. Ferrarese *et al.* 1998; Benedetti *et al.* 2000).

In this paper, we try to define the geometric and kinematic characteristics of the seismogenic sources that affect the eastern Southern Alps (between the towns of Thiene and Udine), on the basis of the available geomorphologic data related to the surficial expressions of the active faults, of new geological and structural mapping and of the results of reflection seismic surveying. Before presenting our data and hypotheses, a review of the previous studies on neotectonics and seismotectonics will be proposed. The available data (literature and original authors' data) will define the geometry of seismogenic boxes and the characteristics of the expected earthquakes in terms of magnitude M_w (derived from the source dimension) and kinematics of the movement (rake). Once the sources are defined, hypotheses on the association with the historical earthquakes (based on the comparison of the highest intensity data point distribution with the geometry of the sources) will be discussed. This procedure will permit to identify sources to which active deformation is related and for which historical earthquakes are lacking. The identification of such sources, that can be concisely defined as silent, permits to define areas affected by a high level of seismic hazard.

2 TECTONIC FRAMEWORK

The investigated area comprehends the Veneto-Friuli pre-Alpine region between the Lessini Mountains to the west and the Italian–Slovenian border to the east (Fig. 1). This zone corresponds to the (Plio-)Quaternary front of the Eastern Southalpine chain (ESC), an embricate fan of low-angle thrusts, approximately WSW–ENE to WNW–ESE trending (Doglioni & Bosellini 1987; Castellarin *et al.* 1992). The ESC is a SSE verging thrust belt showing fault propagation folding and fault bend folding as typical mechanisms of imbrication and shortening. The chain formation, persistent since the Late Oligocene, strongly involved the crystalline basement that crops out along the inner thrust, known as the Valsugana line (Doglioni 1990). During the Mesozoic, the region was part of the passive margin of the Adria Plate, and normal faults related to the Mesozoic extension were frequently reactivated and inverted during the Neogene contractional events (e.g. Doglioni 1992a). The region east of the Tagliamento river (Fig. 1), is structurally more complicated than the western one. It is characterized not only by N–S and E–W trending Mesozoic inherited structures, but also by the Palaeogene NW–SE faults related to the W propagation of the external Dinarides thrust belt (Fig. 1; e.g. CNR-PFG 1983). In the eastern (i.e. Julian) sector, the front of the ESC extends as far as the lower Friulian plain (Poli *et al.* 2002). As visible in the Udine-Gorizia sector, it corresponds to a set of S verging, WNW–ESE trending low-angle thrusts geometrically influenced by the inherited structures of the NW–SE Dinaric

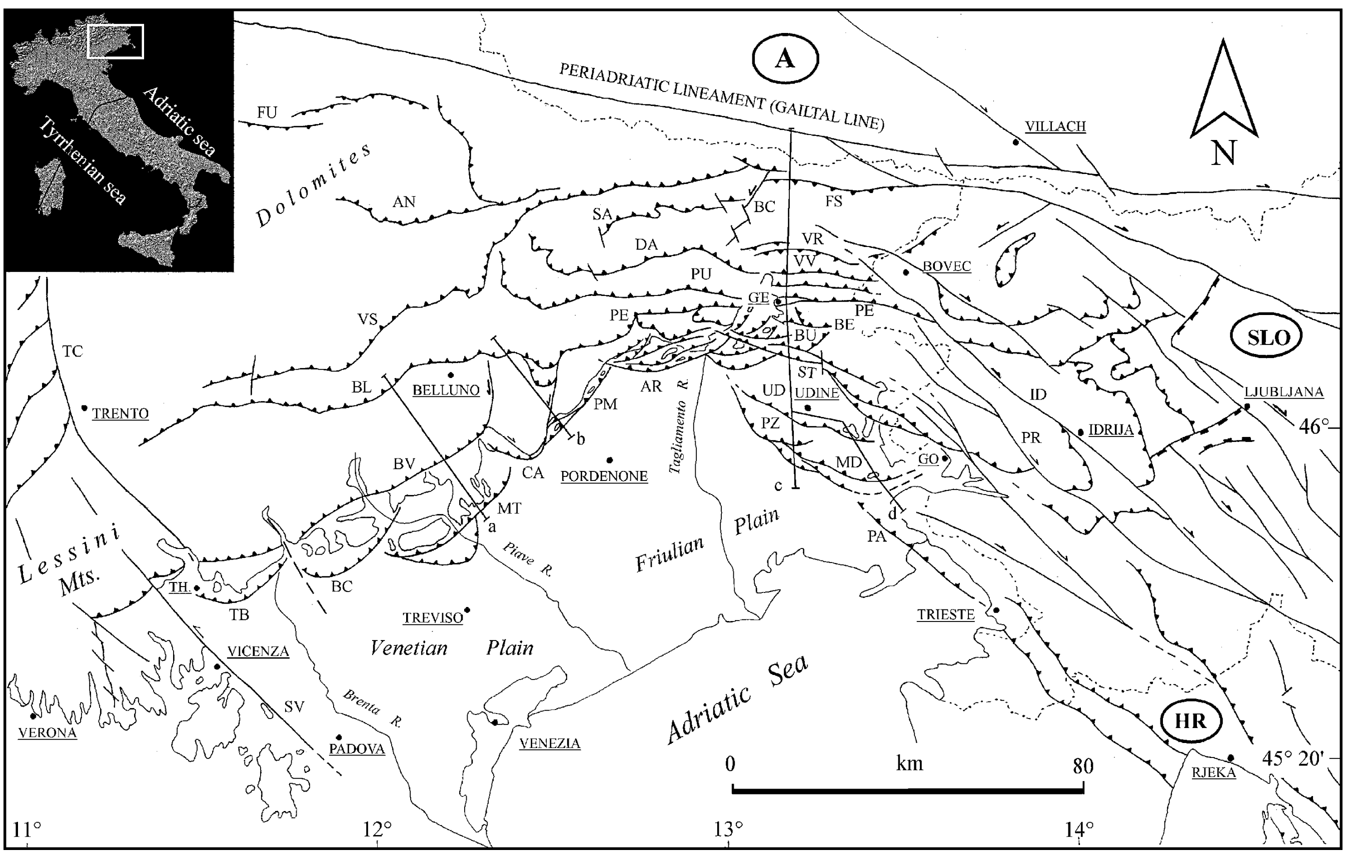

Figure 1. Structural model of NE Italy and W Slovenia. The letters a, b, c and d define the traces of the geological sections reported in Figs 11, 14, 4 and 6, respectively. Legend (towns): TH, Thiene; GE, Gemona; GO, Gorizia. Legend (structures): TC, Trento-Cles fault; SV, Schio-Vicenza fault; TB, Thiene-Bassano fault; BC, Bassano-Cornuda fault; BV, Bassano-Valdobbiadene fault; BL, Belluno fault; VS, Valsugana fault; FU, Funes fault; AN, Antelao fault; MT, Montello fault; CA, Cansiglio fault; PM, Polcenigo-Maniago fault; AR, Arba-Ragogna fault; PE, Periadriatic thrust; PU, Pinedo-Uccea fault; DA, Dof-Auda fault; SA, Sauris fault; BC, But-Chiarsò fault; FS, Fella-Sava fault; VR, Val Resia fault; VV, Val Venzonassa fault; BE, Bernadia fault; BU, Buia fault; ST, Susans-Tricesimo fault; UD, Udine-Buttrio fault; PZ, Pozzuolo fault; MD, Medea fault; PA, Palmanova fault; ID, Idrija fault; PR, Predjama fault.

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Palaeogene front. The latter have sometimes been completely re-utilized during the formation of the ESC.

West of the Tagliamento river, the most recent compressive front affects the base of the Venetian and Carnic Prealps and corresponds to the WSW–ENE striking Polcenigo-Maniago and Arba-Ragogna thrusts (Poli *et al.* 2002).

The Venetian sector is dominated by the SE-verging Bassano-Valdobbiadene thrust (Doglioni 1992a,b), a major structure that produced a morphological relief of approximately 1200 m above the plain (Fig. 1). In the westernmost sector, the thrust is crossed by the NW–SE trending Schio-Vicenza strike-slip fault system. The latter is interpreted as the Late Miocene—Quaternary kinematic junction between the ESC and the central western Southern Alps (Castellarin & Cantelli 2000; Zampieri *et al.* 2003).

In this sector of the Venetian Prealps, the southernmost front of the ESC consists of (Fig. 1):

(i) the Montello thrust, NNW dipping and WSW–ENE striking (e.g. Benedetti *et al.* 2000; Fantoni *et al.* 2001);

(ii) two minor WSW–ENE trending, NNW dipping thrusts, here reported as Bassano-Cornuda and Thiene-Bassano thrusts.

3 SEISMICITY

The eastern Southern Alps have been struck by numerous earthquakes with magnitude up to 7 during historical times, as indicated in the catalogue by Working Group CPTI (1999). The eight earthquakes with magnitude between 6 and 7 damaged areas located in a roughly NE–SW trending narrow belt between the Alpine domain and the Venetian and Friulian plains (Fig. 2a).

The 1695 (Febrary 25) earthquake occurred in the Asolo area (Fig. 2a). A detailed study of this event is reported in Boschi *et al.* (1995) who classified with *I* 10 (MCS) the maximum damage and attributed this damage level to three localities. A high level of damage has been in villages along the border of the Venetian plain, in the area between Bassano del Grappa and the Piave river.

The Mount Cansiglio-Alpago area was affected by two earthquakes in 1873 (June 29) and 1936 (October 18; Fig. 2a). The strongest effects of the 1873 quake have been detected between Belluno to the west and the Alpago area to the east. An intensity *I* 9/10 (MCS) was attributed to seven localities by Boschi *et al.* (1997), while an intensity *I* 10 (MCS) at six localities was reported in Monachesi & Stucchi (1998).

The highest intensity data points related to the 1936 event (*I* 9 and 8/9 MCS, reported in Barbano *et al.* 1986) are located both in the Alpago area and, to the south, at the limit between the Cansiglio relief relief and the Venetian plain.

The 1348 (January 25) earthquake caused significant damage in Friuli, Carinthia (Austria) and western Slovenia (Hammerl 1994). Points with intensity *I* 9.5 (MCS) are reported for three Friulian localities in Monachesi & Stucchi (1998).

The 1511 (March 26) earthquake damaged Friuli and Slovenia. Intensity *I* 9 (MCS) is reported for five localities (including Udine) in Monachesi & Stucchi (1998), while *I* 10 (MCS) was attributed to Idrija (Slovenia) and *I* 9 to three Italian and one Slovenian localities by Boschi *et al.* (1995).

The 1976 May 6 event (M_s 6.5 in Working Group CPTI 1999) was responsible for significant damage (*I* 9.5 MCS) at 16 localities in the Tagliamento river area (Monachesi & Stucchi 1998). The 1976 September 15 (09:21 h GMT) event struck the same region already damaged by the May 6 event, contributing to increase the damage at several localities (intensity up to 8/9–9 MCS at three localities, according to Monachesi & Stucchi 1998). A detailed description of the seismotectonic characteristics of these two earthquakes will be proposed in the first section dedicated to the seismogenic sources east of the Tagliamento river.

The 1117 (January 3) earthquake, which damaged the westernmost sector of the investigated area, is the most problematic event among those discussed above. The historical information about the damage distribution is sparse and only defines significant damage in the Verona and Padova areas (Boschi *et al.* 1995). A possible epicentral area east of Verona has been recently proposed on the basis of integrated geological, archaeoseismological and historical data (Galadini *et al.* 2001a).

Numerous other damaging earthquakes characterized by magnitude between 5 and 6 affected the Alpine southern border in the western sector of the investigated area (Fig. 2b; e.g. Barbano 1993). The strongest events occurred in 1776 (Tramonti earthquake, M_a 5.8), 1794 (Tramonti earthquake, M_a 5.3), 1812 (Sequals earthquake, M_a 5.6) and 1836 (Bassano earthquake, M_a 5.3).

The distribution of the moderate seismicity in the eastern sector of the investigated area, roughly corresponding to the Friuli region, is different from that of the western sector (e.g. Barbano 1993). Fig. 2(b) shows that earthquakes with magnitude between 5 and 6 struck a zone larger than that affected by similar events in the Veneto region and that many earthquake epicentres are located within the Alpine domain. The strongest events occurred in 1700 (Raveo earthquake, M_a 5.7), 1788 (Tolmezzo earthquake, M_a 5.6), 1928 (Carnia earthquake, M_e 5.7) and 1977 (Trasaghis earthquake, M_a 5.3).

In contrast, the earthquakes that affected the Venetian and Friulian plains were generally characterized by magnitude lower than 5, with exceptions represented by the 778 Treviso, 1268 Trevigiano and 1279 Friuli earthquakes (M_a 5.8, 5.1 and 5.1, respectively; Fig. 2b). In such cases, however, the information about the damage distribution is sparse. The real epicentral location and the magnitude may be significantly different from those reported above. For example, in the case of the AD 778 earthquake, the information only derives from a German source, indicating the destruction of edifices in Treviso and in other (undefined) towns, with casualties.

4 ACTIVE FAULTS IN THE NE ALPS: PREVIOUS WORKS

A large amount of data on the Plio-Quaternary fault activity in NE Italy was collected during the 1970s and 1980s. These data were summarized in the 'Neotectonic Map of Italy' (CNR-PFG 1987). Evidence of the huge amount of fieldwork can be found in numerous publications (Zanferrari *et al.* 1982; Carton & Castaldini 1987; Forcella & Sauro 1988; Slejko *et al.* 1989; Castaldini & Panizza 1991) and reports (e.g. Cavallin *et al.* 1988a,b,c).

Faults characterized by Plio-Quaternary activity have been mapped in Zanferrari *et al.* (1982), CNR-PFG (1987) and Castaldini & Panizza (1991). The first paper reports information on the Plio-Quaternary activity of 66 faults and fault systems located between Lake Garda and the Friuli region. This information was transferred to the 'Neotectonic Map of Italy' (CNR-PFG 1987), where the major south-verging thrust systems bordering the Venetian and Friulian plains and affecting the pre-Alpine domain were mapped as unsegmented structures active during the Pliocene and the Quaternary.

The recent activity of the thrusts bordering the Venetian and Friulian plains was also remarked in the 'Map of active faults between the Po and Piave Rivers and Lake Como' (Castaldini & Panizza 1991), reporting 112 active faults in the area between Lake Garda and the Friuli region. The authors mapped four main ENE–WSW trending compressive structures, i.e. the Bassano-Valdobbiadene,

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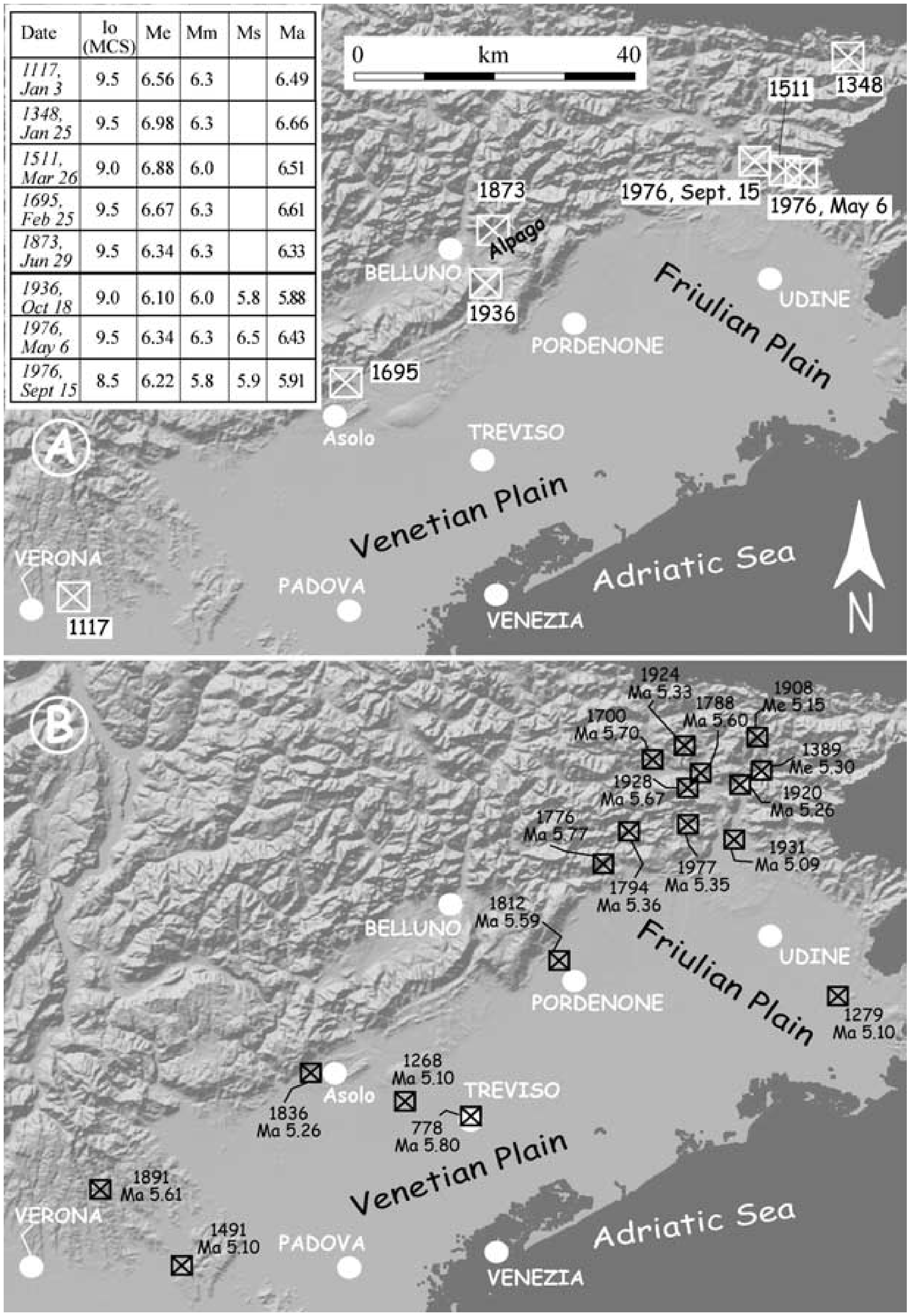

Date	Io (MCS)	Me	Mm	Ms	Ma
1117, Jan 3	9.5	6.56	6.3		6.49
1348, Jan 25	9.5	6.98	6.3		6.66
1511, Mar 26	9.0	6.88	6.0		6.51
1695, Feb 25	9.5	6.67	6.3		6.61
1873, Jun 29	9.5	6.34	6.3		6.33
1936, Oct 18	9.0	6.10	6.0	5.8	5.88
1976, May 6	9.5	6.34	6.3	6.5	6.43
1976, Sept 15	8.5	6.22	5.8	5.9	5.91

Figure 2. (a) Seismicity map of NE Italy, showing the distribution of earthquakes with $M_e > 6$. Epicentral location of the pre-1976 earthquakes has been derived from Monachesi & Stucchi (1998). The epicentres of the 1976 shocks have been derived from Slejko *et al.* (1999). (b) Seismicity map of NE Italy, showing the distribution of earthquakes with M_e or M_a values between 5 and 6. The table included in the (a) reports the different parameters describing the earthquakes (i.e. epicentral intensity and different magnitude values) as derived from the catalogue by Working Group CPTI (1999). Note that the 1936 and 1976 (September 15, 09:21 h GMT) earthquakes are reported with some M values lower than 6 in Working Group CPTI (1999); the presence of at least one M value higher than 6 has been considered, however, as a condition to include the earthquake in the list of the $M > 6$ earthquakes. The M_e defines the equivalent macroseismic magnitude, following the procedure defined by Gasperini & Ferrari (1995, 1997). The M_m is a macroseismic magnitude estimated from the values of I_o, while the M_a is the weighted mean of the other M values whose calculations follow procedures described in Working Group CPTI (1999). The M_s values have been estimated by Margottini *et al.* (1993) fo Italian earthquakes of the 20th century. The used map is a shaded relief image obtained from the processing of digital elevation data by the Istituto Geografico Militare at the 1:250 000 scale.

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Aviano, Sacile and Valsugana South lines, together with a large number of minor faults. Information on the segmentation was not included in this paper. Further recent regional works (e.g. Tellini *et al.* 2001) did not update significantly the described framework.

A summary at the regional scale of the active faults affecting the eastern Southern Alps has been recently proposed by Galadini *et al.* (2001b). In this work, the authors critically reviewed the available literature and reported data from new fieldwork in the western sector of the investigated area. The produced map included the main faults (surficial traces) whose length may be consistent with the occurrence of earthquakes with $M \geq 6.2$ (based on the rupture length/magnitude relationship by Wells & Coppersmith 1994). The mapped faults are characterized by conclusive evidence of activity or by indication of probable activity during the Late Pleistocene—Holocene (after the last glacial maximum, LGM). The result of this operation was an inventory of eight faults (major structures unsegmented) affecting the area between Thiene and the eastern Friulian border. Therefore, the critical review of the published material led Galadini *et al.* (2001b) to drastically reduce the number of active faults affecting the investigated region.

Available geologic data show that recent activity is the result of blind thrusting responsible for differential vertical movements and continuous deformation of Late Quaternary deposits and landforms located over the buried fault tip lines (Benedetti *et al.* 2000; Merlini *et al.* 2002; Peruzza *et al.* 2002). This deformative style prevents the possibility to understand the fault behaviour through the extended use of palaeoseismological investigations.

Moreover, the re-utilization of NW–SE trending Dinaric thrusts by the Neo-Alpine tectonics (e.g. Poli *et al.* 2002) limits the effectiveness of the geomorphological approach to define surficial expressions of active structures in the easternmost sector of the investigated area. The landscape of the eastern Friuli area has, indeed, experienced a strong imprinting from the activity of the presently inactive Dinaric thrusts. The Alpine re-utilization of these structures results in fainter geomorphic features, whose analysis and interpretation may be very difficult.

5 FROM UNSEGMENTED FAULTS TO SEISMOGENIC SOURCES: ADOPTED PROCEDURE

The identification of active fault segments is the first step towards the definition of the seismogenic behaviour of an area (Schwartz & Coppersmith 1984). Active fault segments may represent, indeed, the surficial expression of single seismogenic sources.

Fault activity in the investigated area is defined by the evidence of Late Quaternary deformation, similarly to other world cases of active blind thrust systems (e.g. Berberian 1995; Shaw & Suppe 1996; Burrato *et al.* 2003). Where the tectonic activity is expressed by the motion of blind thrusts (as in the investigated area), the evidence of Holocene displacement events cannot be obtained by means of the palaeoseismological investigations, which are commonly performed in the analysis of the fault activity. The information can only be derived by the geomorphologic study of the interaction between the thrust growth and the landscape (e.g. the evidence of continuous deformation affecting landforms and deposits), and by surficial and subsurficial structural data, which define the fault geometry and the late Quaternary activity. In such cases, linking the surficial evidence of recent activity with the subsurficial structural data defining the deep fault geometry is a common procedure in the seismotectonic investigations (e.g. Burrato *et al.* 2003).

The geomorphologic and structural surficial investigations are used to define the segmentation of the active thrust systems (e.g. de Polo *et al.* 1991; Mirzaei *et al.* 1999). Thrust segments in the investigated area have been defined on the basis of a new structural framework (Fig. 1; Poli *et al.* 2002) and new geomorphological investigations. Following the traditional criteria (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 as a result of the presence of another thrust segment with an *en échelon* relationship. A strong consistency has been observed between structural and geomorphologic data. Typically, the geomorphic evidence of a thrust (a prominent scarp emerging from a plain) decreases in the areas where the structural data permit to locate the fault tips. In some cases, transverse structures conditioned the drainage from the Alpine chain to the plain areas. Therefore, the main rivers flow along valleys superimposed on transverse faults delimiting single segments, as already observed in other cases of thrust tectonics (e.g. Lawton *et al.* 1994). Parallel and very close thrusts affecting an area have been considered as the manifestation of a single main fault splaying at the surface.

Apart from the geomorphologic features at the surface, the evidence of recent blind fault activity is usually derived from reflection seismic profiles across the faults. Geophysical data (constrained by borehole information) define the deep geometry of a fault, thus permitting to link the fault surficial expression to a fault surface at depth. The image of the fault at depth is commonly defined for several kilometres (generally more than 5 km) and this visibility permits to make hypotheses about the 3-D geometry of the seismogenic source. If the geophysical information is not exhaustive, the fault deep geometry has to be defined on the basis of surficial structural constraints. Indeed, the reconstructed thrust geometry at the surface and the geometry of the displaced stratigraphic units usually permit to make structural extrapolations at depth in order to hypothesize the 3-D thrust geometry.

If the fault (i.e. a seismogenic source) was responsible for a large earthquake in recent times (i.e. in the last few decades), constraints on the deep fault geometry can also be derived from the epicentral locations of the main shock and the aftershocks. This information helped in the definition of the seismogenic sources related to the 1976 Friuli earthquakes (see below).

The damage distribution of a historical earthquake also represents a tool to define the geometry of the causative source. Two different procedures to infer the source from the damage have been adopted in previous works (Gasperini *et al.* 1999, adopted in Valensise & Pantosti 2001; Sirovich *et al.* 2000). We consider these procedures of source definition as necessary when geological and geophysical data are lacking. This is not the case for the investigated area. However, the source inferred from the damage distribution of the 1936 earthquake in the Cansiglio area by Valensise & Pantosti (2001) and Sirovich *et al.* (2000) is definitely consistent with the available structural data. For this reason, the geometry of the Cansiglio source has been derived in the present paper by merging the structural geological data with the information reported in the mentioned works.

Because the purpose of this paper is the definition of seismogenic sources potentially responsible for earthquakes with $M \geq 6$ and considering that the energy release depends on the source dimension, we focused our attention on faults characterized by dimensions (fault area and fault length at the surface) large enough to produce earthquakes with such a magnitude.

After having reconstructed the surficial and deep geometry of a fault, we defined seismogenic sources (Fig. 3) following the criteria

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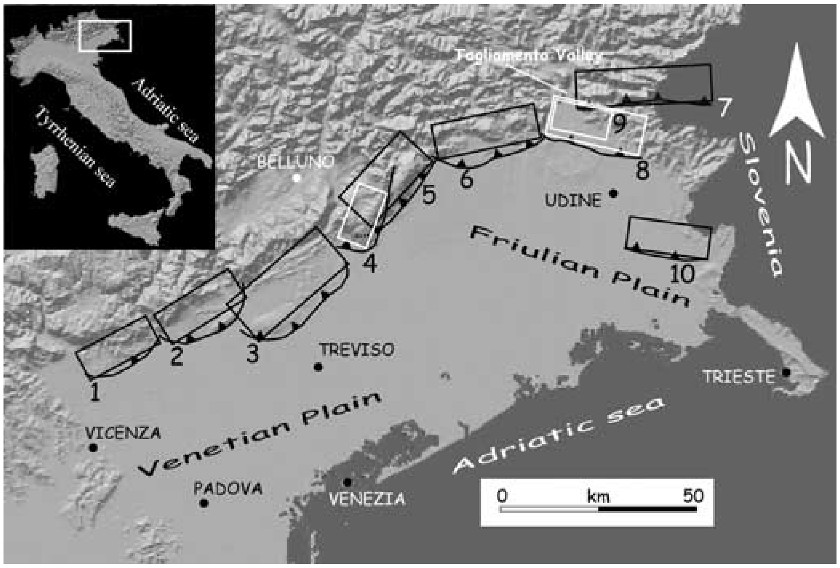

Figure 3. Map of the seismogenic sources in the Thiene–Udine sector of the eastern Southern Alps: (1) Thiene Bassano; (2) Bassano-Cornuda; (3) Montello-Conegliano; (4) Cansiglio; (5) Polcenigo-Maniago; (6) Arba-Ragogna; (7) Gemona-Kobarid; (8) Susans-Tricesimo; (9) Trasaghis; (10) Medea. The sources defined by black rectangles have been mostly defined through geological (both surficial and subsurficial) data; the white sources have been derived from mixed geological–seismological data (see text for further explanations).

already used by Valensise & Pantosti (2001). These authors represented sources from geological and geophysical data as the projection at the surface of the rectangular rupture plane. In our cases, the rupture plane is defined by the ramp portions of the thrusts. Indeed, the high dip of these fault sectors seems to favour the triggering of the large earthquakes more than the low-dip portions, as indicated by historical cases (e.g. Philip *et al.* 1992; Mori *et al.* 1995). The reader has to take into account, however, that the reported source geometries represent simplifications of the actual 3-D shape of the sources, particularly in the cases of the easternmost sector of the investigated area where the active faults re-use pre-existing structures.

Lines are also reported beside each rectangle, defining the source surficial expression as it has been inferred from surficial geological and geomorphological data. Because we are generally dealing with blind thrusts, the lines approximate the limit between areas affected by different vertical movements, i.e. the location of gentle scarps related to continuous deformation. If the line is absent, no evidence of the source at surface can be detected with the traditional geological and geomorphological methods. This usually means that the deformation rate at the surface is significantly lower than the rate of geomorphic modification as a result of exogenic factors.

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 landforms and deposits. For this reason, we conventionally fixed the minimum depth of the source at 1 km. The only exception is represented by the Trasaghis source, which affects the deep subsurface and which has no surficial evidence.

Different colours have been used in Fig. 3 for the sources that have been defined prevalently on the basis of geologically inferred active tectonic data (black line) and for the sources whose definition also takes into account seismological constraints (white line). In the latter case, the same colour (white) has been used both for the sources defined through the contribution of seismological instrumental data (Susans-Tricesimo, Trasaghis) and for the source (Cansiglio) whose definition also took into account the damage distribution data of a historical earthquake (see sections dedicated to the seismogenic sources for further explanations).

6 THE SEISMOGENIC SOURCES ($M \geq 6$) OF THE EASTERN SOUTHERN ALPS: AVAILABLE STRUCTURAL AND GEOMORPHOLOGICAL DATA

Some seismogenic sources in the investigated area have already been defined in the 'Database of potential sources for earthquakes larger than M 5.5 in Italy' (Valensise & Pantosti 2001), by merging regional/local geological and seismological information. In the ESC, the authors reported eight geologically inferred sources and six derived from seismological data (damage distribution, method by Gasperini *et al.* 1999).

Considering that (i) new structural data are available for the investigated sector (e.g. Fantoni *et al.* 2002; Merlini *et al.* 2002), (ii) new surficial data (geological and geomorphological) are currently being collected (projects of the National Geological Survey and of the National Group for the Defense against Earthquakes), and (iii) recent structural and kinematic analyses strongly reduce the role of the inherited Dinaric thrusts with NW–SE trend in the active tectonics affecting NE Italy (see section dedicated to the tectonic framework), we defined a framework of active fault segments and seismogenic sources by merging the information already available from the literature with new geomorphological, geological and geophysical data. The result of this work has been summarized in Fig. 3 and Table 1, while the review of the available data and the description of the new data will be the object of the next subsections.

The slip rate inferred from modern geomorphological investigations is available only for few of the investigated structures (Montello-Conegliano and Arba-Ragogna). For this reason, we generally reported the slip rate as derived from Castaldini & Panizza (1991). Unfortunately, the rate interval is quite large (generally 0.1–1 mm yr^{-1}). Estimates of the minimum vertical slip rate based on

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Table 1. Main geometric–kinematic characteristics of the seismogenic sources affecting NE Italy. Numbering as in Fig. 3.

Seismogenic source	Rupture length (km)	Downdip rupture width (km)	Rupture area (km^2)	Minimum depth (km)	Maximum depth (km)	Rake	Vertical slip rate ($mm\ yr^{-1}$)	Min. vertical slip rate ($mm\ yr^{-1}$)	Magnitude	Associated historical earthquake
Thiene-Bassano (1)	20	9.5	190	≈1	5.75	100°	<1*	—	6.43	1117 (January 3)
Bassano-Cornuda (2)	22	11	242	≈1	6.2	100°	<1*	0.42–0.5	6.49	1695 (February 25)
Montello-Conegliano (3)	30	16	480	≈1	12	100°	1^+	0.32–0.4	6.72	—
Cansiglio (4)	15	10	150	0	7	120°	<1*	0.4–0.47	6.24	1936 (October 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 (January 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	—

*From Castaldini & Panizza (1991).
+From Benedetti *et al.* (2000).
^Based on data by Zanferrari *et al.* (2005b).

the displacement of the base of the Quaternary deposits are also reported in Table 1 (see Discussion for details).

The slip vector has been defined by considering kinematic data derived from works of structural geology and geodesy (e.g. Castellarin *et al.* 1992; Caporali & Martin 2000; Castellarin & Cantelli 2000) or the data on the regional stress field obtained through seismological analyses (Bressan *et al.* 1998; Slejko *et al.* 1999). In the latter case, we hypothesized the present fault kinematics by comparing fault attitude and stress field.

In the following, the seismogenic sources will be described by distinguishing two sectors in the investigated area: sector 1, the region east of the Tagliamento river and, sector 2, the much wider sector between this river and Thiene. Structural-geological reasons conditioned this choice, because sector 1 is much more complicated than sector 2 from the structural viewpoint, for example:

(i) at least three, almost parallel, primary active faults can be defined in sector 1 (while only one fault set has been defined in sector 2);

(ii) geometrically conditioning re-utilization of pre-existing Dinaric thrusts by the Alpine tectonics has been documented in sector 1 (Poli *et al.* 2002); and

(iii) the strike of the active faults in sector 2 is different from that of sector 1.

6.1 The seismogenic sources east of the Tagliamento river

6.1.1 Susans-Tricesimo and Trasaghis (nos 8 and 9 in Fig. 3 and Table 1)

A large amount of data is available for this sector as a result of the numerous seismological, geological and geophysical works made during and after the 1976 earthquake sequence. The main shock occurred on 1976 May 6 (M_s 6.5; Working Group CPTI 1999) was attributed to the compressive structure affecting the Buia-Tricesimo area, characterized by a Dinaric (NW–SE) trend, while the 1976 September 15, 09:21 h GMT shock (M_s 5.9; Working Group CPTI 1999) was related to the activation of the Periadriatic thrust, characterized by an Alpine (E−W) trend (Amato *et al.* 1976; Finetti *et al.* 1976; Wittlinger & Haessler 1978; Carulli *et al.* 1980; Barbano *et al.* 1985; Del Ben *et al.* 1991).

Geological investigations in the days following the main shock permitted to identify surface breaks along the Periadriatic thrust. These features were, however, differently interpreted as the possible evidence of surface faulting (Bosi *et al.* 1976) or the effect of slope instability phenomena (Cavallin *et al.* 1977).

During 1977 and 1978, geodetic investigations were performed throughout the entire region struck by the 1976 sequence. In particular, triangulation data were collected (19 benchmarks) and 88 points related to four levelling routes were analysed. Previous triangulation data were collected in 1949, while the measurements of the levelling routes were previously made in 1952–1953 (three routes) and in 1929 (one route; Arca *et al.* 1985 and references therein). Levelling indicated the uplift of the sector between Udine and Venzone (approximately 6 km north of Gemona, see Fig. 4 for location) with a maximum of approximately 18 cm in this locality (Talamo *et al.* 1978). The triangulation results gave a peak of maximum shear strain between Venzone and Gemona (Bencini *et al.* 1982). Measurement errors may be, however, so flagrant to render the triangulation data unreliable.

The levelling data have been processed by Arca *et al.* (1985) and Briole *et al.* (1986) in order to define the geometry of the sources

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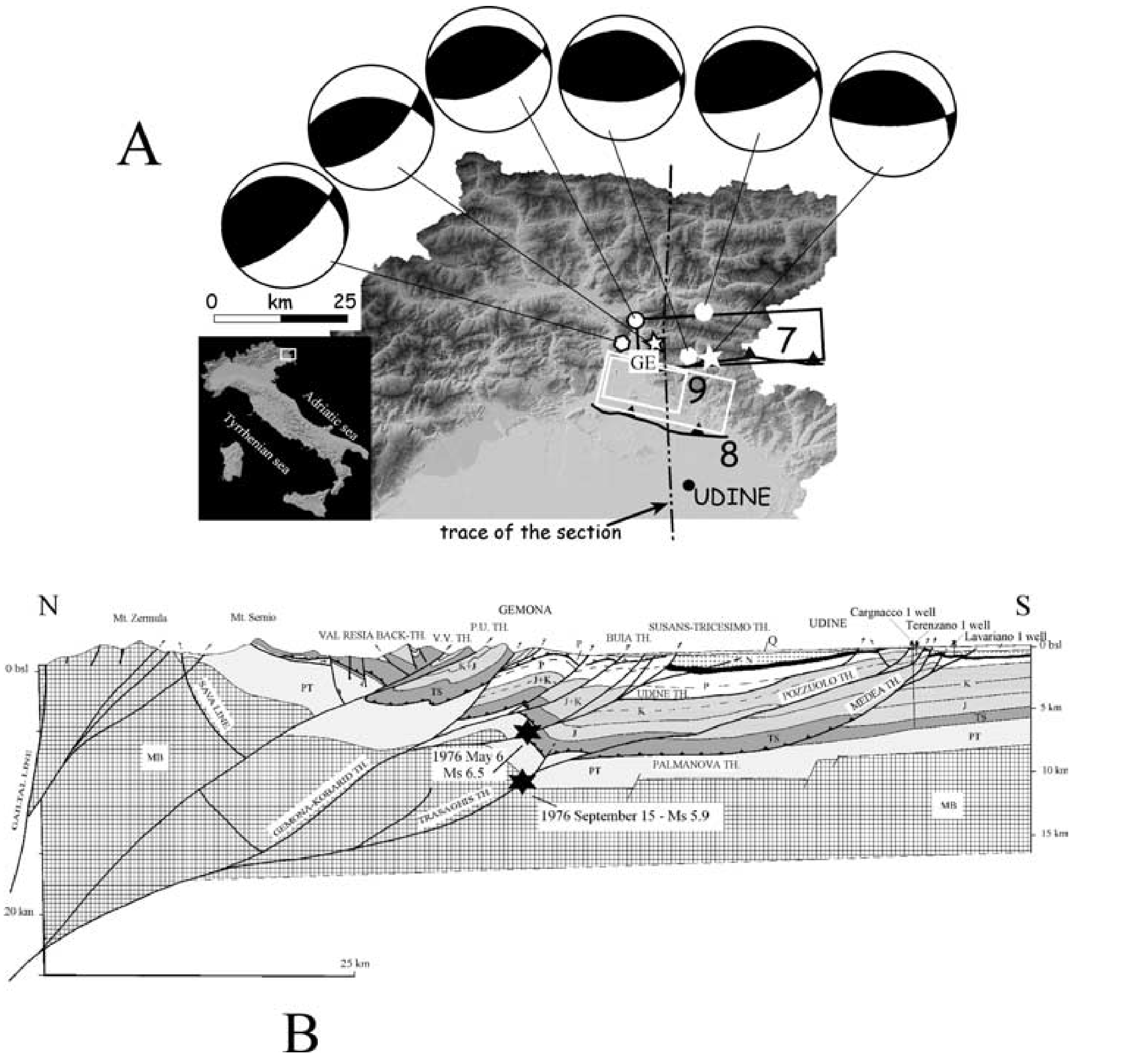

Figure 4. (a) Epicentral locations and focal mechanisms of the 1976 May 6 (white symbols) and 1976 September 15 (09:21 h GMT; black and white symbols) earthquakes according to the most recent works: the stars define the solutions proposed by Slejko *et al.* (1999; also adopted by Peruzza *et al.* 2002; Poli *et al.* 2002), the polygons define the solutions proposed by Aoudia *et al.* (2000), the circles define the solutions by Pondrelli *et al.* (2001); the sources are numbered as in Fig. 3 and Table 1 (7, Gemona-Kobarid; 8, Susans-Tricesimo; 9, Trasaghis); the hypothesis by Pondrelli *et al.* (2001) on the May 6 epicentre location is consistent with the activation of the Gemona-Kobarid thrust, while those proposed by Slejko *et al.* (1999) and Aoudia *et al.* (2000) are consistent with the activation of the Susans-Tricesimo thrust; the shaded relief image has been obtained from altimetric data available on the map of the Istituto Geografico Militare at the 1:25 000 scale. (b) Geological section across the eastern Southern Alps in the Friuli region (c of Fig. 1, trace also reported in the inset a). The hypocentral locations of the 1976 earthquakes (projected on the section) have been reported, according to the hypotheses by Peruzza *et al.* (2002) and Poli *et al.* (2002). Legend: PU TH, Pinedo-Uccea thrust; VV TH, Val Venzonassa thrust; Q, Quaternary; N, Neogene; P, Palaeogene; K, Cretaceous; J, Jurassic; TS, Upper Trias; PT, Permo-Trias; MB, Magnetic basement. The traces of the Palaeogene W-verging Dinaric thrusts are indicated by black triangles.

responsible for the 1976 sequence. The authors used a linear inversion technique constraining the initial geometry of the sources on the basis of the available seismological data. Based on this analysis, the observed deformation can be modelled by means of three different sources (that responsible for the shock of May 6 and those responsible for the strongest events of September 15, one occurring at 03:15 h GMT and the other at 09:21 h GMT). The largest source (associated with the May 6 event) is defined by a rectangle having ENE–WSW trending projection at the surface located approximately 5 km south of of Gemona.

The seismological data related to the 1976 sequence have been processed again in more recent works (Aoudia *et al.* 2000; Pondrelli *et al.* 2001; Peruzza *et al.* 2002). These authors attributed both earthquakes to Alpine structures. In particular, Aoudia *et al.* (2000) relocated 34 earthquakes of the Friuli sequence that occurred in 1976 and 1977. The main shock epicentre was located approximately 9 km east of the Gemona village (Fig. 4). According to the authors, the area covered by the relocated aftershocks (a surface 25 km long, 15 km wide) is consistent with that of the source responsible for the 1976 main shock. The focal mechanism of the May 6 shock permits to hypothesize the activation of a N-dipping thrust plane (Fig. 4). Aoudia *et al.* (2000) also constrained the source geometry by means of geological data. The authors identified some possible surficial expressions of the seismogenic source along ridges (defined as Susans,

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Buia and La Bernadia mountains segments) resulting from the deformation caused by the blind thrust activity. The source surficial expression is located approximately 10 km south of the proposed earthquake epicentre, close to the projection at surface of the source hypothesized by Arca *et al.* (1985). As for the shock of September 15 (09:21 h GMT), Aoudia *et al.* (2000) proposed a focal mechanism consistent with the activation of a NE–SW thrust with a minor strike-slip component (Fig. 4).

In contrast, Pondrelli *et al.* (2001) defined an epicentral location of the two largest shocks of the sequence (May 6 and September 15, 09:21 h GMT) approximately 8 km north of that proposed by Aoudia *et al.* (2000; Fig. 4). This epicentral location and the proposed focal mechanisms (N-dipping thrust planes) are consistent with the activation of the Periadriatic thrust (north of the structures mapped by Aoudia *et al.* 2000, i.e. the source no. 7 in Fig. 3, defined as Gemona-Kobarid in this paper; Pondrelli *et al.* 2001). These authors also remarked the consistency of the proposed epicentral location with the surface breaks reported in Bosi *et al.* (1976) and the geodetic data from levelling (Talamo *et al.* 1978). The proposed epicentral location appears, however, less consistent with the damage distribution. In the case of Periadriatic thrust activation the most severe damage should, indeed, be centred some kilometres north of the thrust surficial expression. This is not the case of the 1976 sequence (e.g. Monachesi & Stucchi 1998).

More recently, Peruzza *et al.* (2002) and Poli *et al.* (2002) integrated structural and seismological data and plotted hypocentres of the 1976 sequence over structural sections reporting the main thrust systems of the region. These sections resulted from new geological and geomorphological data collected during the Italian Geological Cartography Project, Friuli Venezia Giulia Region (CARG-FVG Project; Zanferrari *et al.* 2005a, b) and a detailed review of seismic reflection profiles surveyed by Emi/Agip. Based on the available data, the authors concluded that:

(i) the Susans-Tricesimo thrust (Fig. 4; Table 1) may be considered as the the May 6 event;

(ii) the deeper (12 km) September 15 (09:21 h GMT) event may have been caused by a blind thrust (Trasaghis thrust in Fig. 4 and Table 1); and

(iii) some secondary high-angle back-thrust structures (i.e. S-dipping thrust planes) may have played a major role in triggering some of the aftershocks.

The surficial expressions of the thrust planes (Buia and Susans-Tricesimo) proposed by Aoudia *et al.* (2000), Peruzza *et al.* (2002) and Poli *et al.* (2002) as the causative source of the May 6 event are separated by few kilometres (Fig. 4b). However, the use of an updated structural framework makes the hypothesis by Peruzza *et al.* and Poli *et al.* (Fig. 4b) preferable.

The conclusions of the mentioned authors are quite different from those by Pondrelli *et al.* (2001) because the Susans-Tricesimo thrust surficial expression is located more than 10 km south of the Periadriatic thrust. Moreover, the source proposed by Peruzza *et al.* and Poli *et al.* appears to be consistent with the 1976 damage distribution.

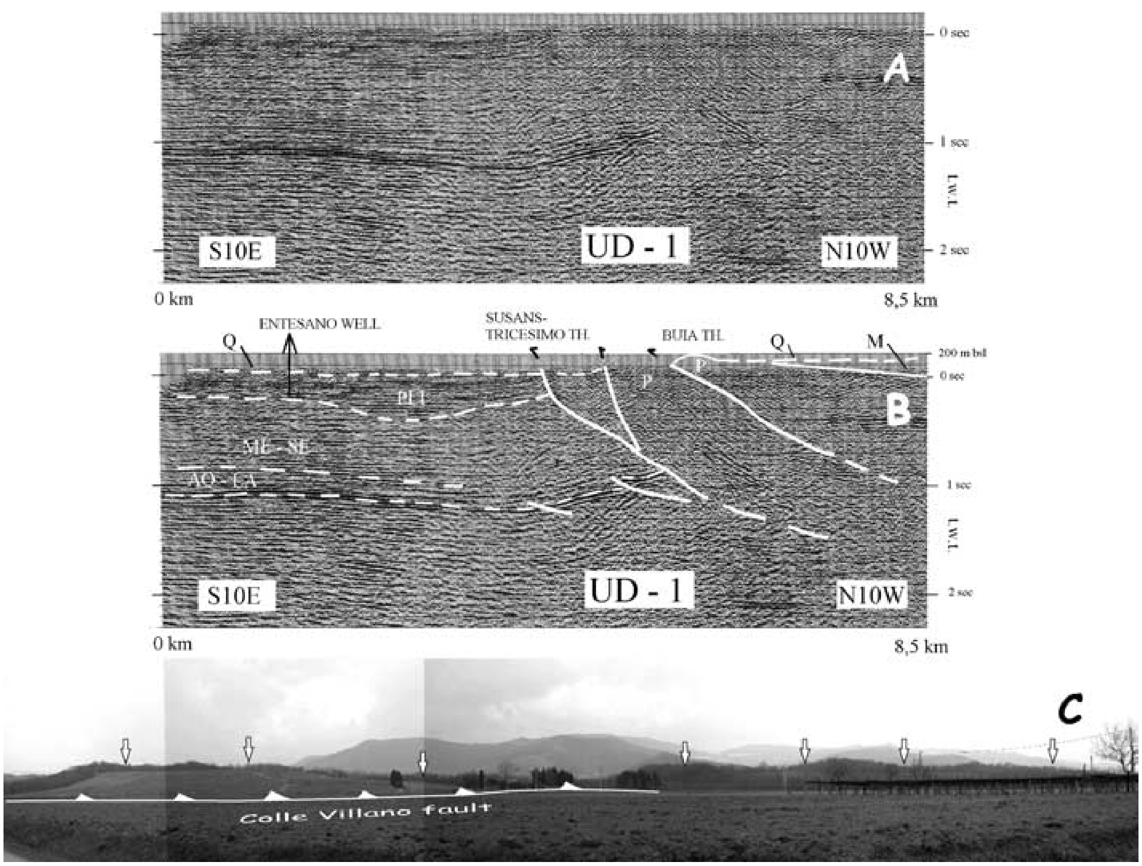

Figure 5. Reflection seismic section (a) across some of the south-verging thrusts of the Friuli region and (b) related interpretation. (c) Surficial expression of the Susans-Tricesimo source (view from Bellazoia towards the north): the formation of the hills resulted from the activity of the Colle Villano thrust, i.e. the northernmost splay of the Susans-Tricesimo thrust system; note the suspended flat topography on the left. Legend: Q, Quaternary; PLI, Pliocene; M, Miocene; ME-SE, Messinian-Serravallian; AQ-LA, Aquitanian-Langhian; P, Palaeogene.

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Both hypotheses (Susans-Tricesimo and Periadriatic thrusts) are not consistent with the geodetic solution, because Arca *et al.* (1985) and Briole *et al.* (1986) defined a source whose surficial expression is located halfway between the two mentioned thrusts. In this case, however, some large aftershocks may have contributed so significantly to the continuous surficial deformation to condition the geodetic source solution. In conclusion, the available data seems to be more consistent with the activation of the Susans-Tricesimo thrust during the May 6 event than with the activation of other reverse faults of the investigated region.

The geometry of the source (Fig. 3) was obtained by means of the available reflection seismic profiles (Fig. 5). The seismic profile of Fig. 5 shows the deformation of the Quaternary deposits in the hangingwall of the fault. Secondary faults related to the Susans-Tricesimo thrust have been responsible for the discontinuous cropping out of Eocene turbiditic sequences in the Friulian plain and for the formation of scarps with a WNW–ESE trend (Fig. 5c). As a result of the fault activity, terraces of probable Pleistocene age are suspended over the Friulian plain (Fig. 5c).

As for the September 15 (09:21 h GMT) event, the hypocentre location proposed by Poli *et al.* (2002) and Peruzza *et al.* (2002) after the revision of the entire seismic sequence and the more recent focal mechanisms (e.g. Aoudia *et al.* 2000; Pondrelli *et al.* 2001) are consistent with the activation of a blind thrust (Fig. 4). This thrust defines the Trasaghis source in Fig. 3 and Table 1. The source geometry has been obtained by merging the structural data represented in the geological section of Fig. 4 and the knowledge about the regional trend of the Alpine structures with the seismological information (energy release, constraining the source geometry) related to the above mentioned event.

Because the 1976 earthquakes are the only instrumentally well-constrained strong events in the investigated area, the Susans-Tricesimo and Trasaghis sources are the only cases of earthquake–structure association that can be based on the comparison of geological and instrumental data.

6.1.2 *Medea (no. 10 in Fig. 3 and Table 1)*

South of the Susans-Tricesimo thrust system, the following structures with evidence of Late Quaternary activity can be identified: the Udine-Buttrio, Pozzuolo and Medea thrusts (Figs 1, 4 and 6). The available reflection seismic profiles by Emi/Agip (e.g. Venturini 1987; Merlini *et al.* 2002; Peruzza *et al.* 2002) and the borehole data (Venturini 2002) show that the Pleistocene deposits are involved in the deformation.

Surficial evidence of recent activity along the three mentioned thrusts derives from the slight tilting of the surface, which formed at the top of alluvial deposits related to the LGM (approximately 19 000 BP) south of Udine (Zanferrari *et al.* 2005a). Prominent scarps affect the Friulian plain over the tip line of the buried thrusts (Fig. 7). For example, in the area Buttrio-Dolegna del Collio (eastern sector of the Udine-Buttrio thrust), the significant uplift is demonstrated by the presence of Pleistocene erosional palaeolandsurfaces (of pedimentary origin) topographically suspended over the present plain (Fig. 7c; Carobene 1984). Moreover, in the same sector, the activity of the Udine-Buttrio thrust was responsible for the tilting of Pleistocene conglomerates cropping out in the northern sector of the Buttrio hill (Feruglio 1929; Zanferrari *et al.* 2005a). The geological section obtained from the reflection seismic data (Figs 4 and 6) shows, however, that the western segment of the Udine-Buttrio thrust develops at the boundary between the Friulian carbonate platform and the Palaeogene turbiditic sequences. The displacement occurred along the original contact between the two mentioned stratigraphic units, as a result of the activity of the Udine-Buttrio thrust, which ramps in the Udine area, forming the scarp of Fig. 7(b). However, the scarce depth of the fault ramp (an almost horizontal attitude is supposed at a maximum of 4 km below the surface; see Fig. 4) suggests that the fault is not the source of large magnitude earthquakes. For these reasons, although the Udine-Buttrio thrust has clear evidence of Late Quaternary activity, we do not consider it as an independent seismogenic source responsible for earthquakes with $M \geq 6$.

Similar geomorphic and structural characteristics can be related to the Pozzuolo thrust (Figs 1 and 4). It is, indeed, characterized by a prominent scarp with a trend similar to that of the Udine-Buttrio fault. The fault activity was responsible for the uplift of the Pozzuolo, Variano and Orgnano hills (Comel 1946; Desio 1952; Zanferrari *et al.* 2005a), but the fault plane displays a low dip at a depth of few kilometres (Fig. 4). For this reason, also this thrust cannot be presently considered as the surficial expression of a significant seismogenic source.

In the case of the Udine-Buttrio and Pozzuolo thrusts, however, the presence of prominent scarps affecting Late Pleistocene landforms (Fig. 7) suggests caution in excluding a seismogenic role related to earthquakes with $M \geq 6$. We cannot exclude, for example, a very recent phase of activation of the thrusts, responsible

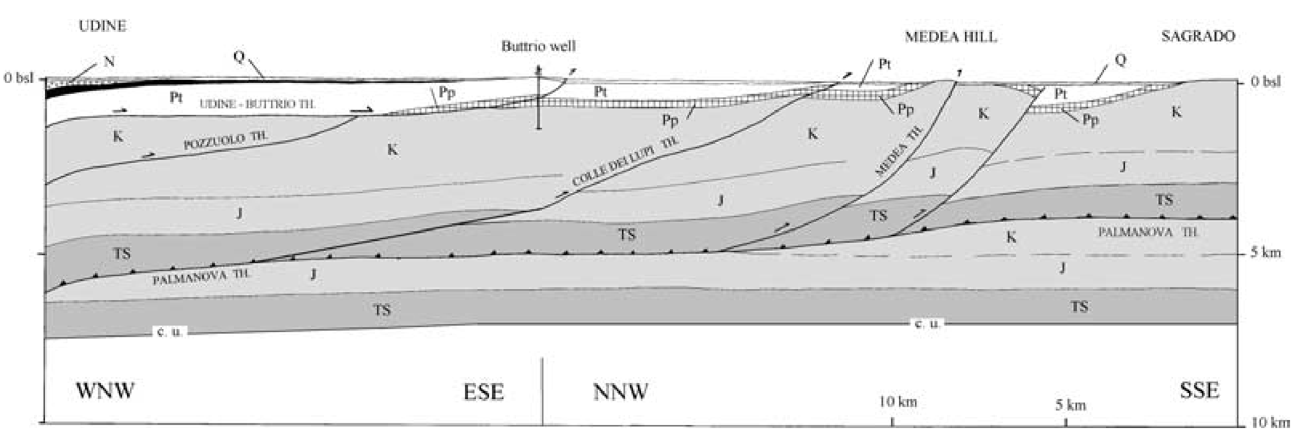

Figure 6. Geological section across the eastern Southern Alps in the Friuli region (d of Fig. 1). Legend: Q, Quaternary; N, Neogene; Pt, Palaeogene turbidites; Pp, Palaeocene carbonate platform; K, Cretaceous; J, Jurassic; TS, Upper Trias; CU, Carnic unconformity. The traces of the Palaeogene W-verging Dinaric thrusts are indicated by black triangles.

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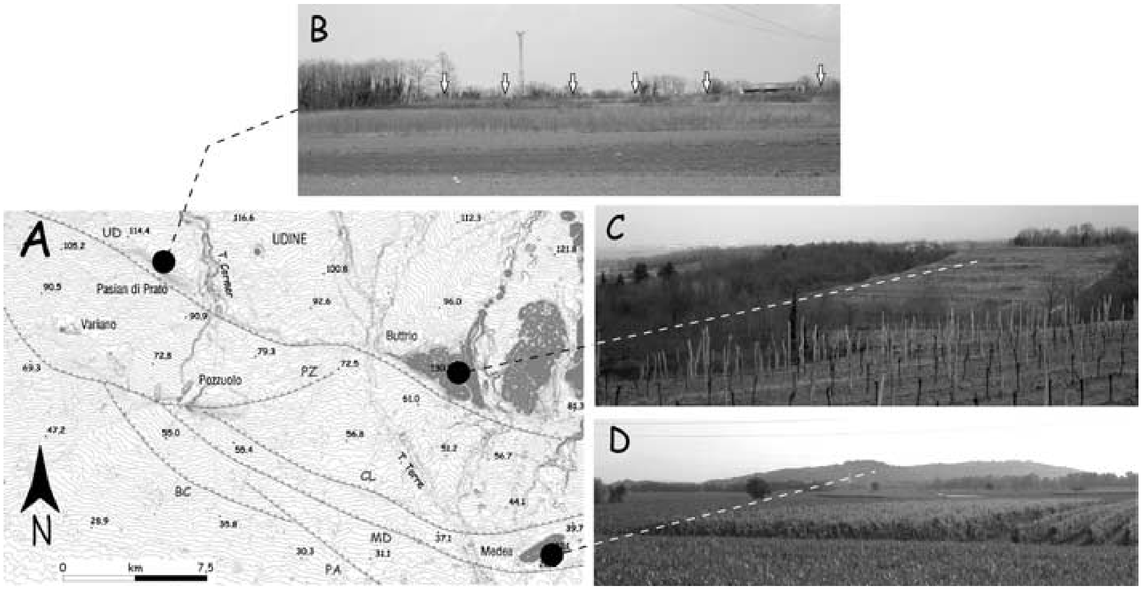

Figure 7. (a) Structural model and digital elevation model (DEM) of the Udine area; the elevation model has been obtained from data of the Friuli-Venezia Giulia Region (Regional Technical Numerical Map) at the 1:5000 scale (with precision comparable to the 1:2000 scale and uncertainty of ±40 cm in the flat areas); the average density of points for which the elevation is available is 2 per square of 100 × 100 m; the DEM has been calculated with steps of 50 m; lines define elevation differences of 1 m; numbers define elevation in metres above sea level; (b) panoramic view (from south) of the Pasian di Prato scarp related to the Udine-Buttrio fault; (c) view from the uplifted terraces of the Buttrio area; (d) panoramic view (from south) of the Medea hill, uplifted by the activity of the Medea thrust.

for scarce cumulated vertical offsets at depth, undefined through the traditional reflection seismic data. In this case, therefore, further subsurface investigations are necessary to fully understand the seismogenic behaviour of these faults.

ESE of the Pozzuolo fault, the Medea thrust has been mapped in Figs 1 and 3. The fault trace at the surface is approximately 23 km long. The activity of the fault was responsible for the uplift and the deformation of the Medea hill (Fig. 7d; Poli 1996). The fault plane displays a high dip up to a depth ranging between 5 and 8 km (Figs 4 and 6), i.e. the frontal ramp is deeper than those of the previously described faults. For this reason, the fault is considered as the surficial expression of a seismogenic source, which may originate earthquakes with $M \geq 6$. The geometry of the Medea source (Fig. 3; Table 1) has been inferred from the available structural data set (Figs 1, 4 and 6) derived from surficial geological and Emi/Agip reflection seismic data.

6.1.3 Gemona-Kobarid (no. 7 in Fig. 3 and Table 1)

The Gemona-Kobarid segment of the Periadriatic thrust is limited, towards the west, by the Tagliamento valley. The valley is an important structural boundary, because west of it the structural framework of the Southern Alps is different from that of the eastern portion (e.g. Venturini 1990). The eastern boundary of the Periadriatic thrust is represented by the Idrija fault, a major NW–SE strike-slip structure located in W Slovenia (e.g. Bernardis *et al.* 2000; Bajc *et al.* 2001). The Gemona-Kobarid thrust is an outstanding structural feature whose high-angle ramp bounds to the north the entire Friulian thrust edifice to which recent activity can be related (Figs 1 and 4). The location of some shocks of the 1976 sequence along this thrust (Poli *et al.* 2002) suggests that its activation was triggered by the Susans-Tricesimo source (from which originated the main shock of 1976 May 6), located to the south. Because the

Figure 8. Surficial expression of the Gemona-Kobarid source. (a) View from Villanova delle Grotte towards the north: the base of the slope is affected by the Gemona-Kobarid thrust; the arrow indicates the abrupt dip change of the slope, suggesting a recent (probably Late Quaternary) period of significant fault activity, following a phase of reduced activity and/or prevalence of the exogenic geomorphic agents over the tectonic ones. (b) View from Monteaperta towards the east; also in this case the arrows mark the abrupt dip change of the slope, having the same significance as photograph (a).

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Gemona-Kobarid thrust affects a mountainous environment presently experiencing strong erosion, the surficial evidence of recent activity cannot be comparable to that of the thrusts affecting the Friulian plain. Actually, only some geomorphic indication of recent activity is available. Most of the carbonate slope forming the emergent thrust hangingwall displays triangular facets and suspended landscapes, which suggest hangingwall uplift (Fig. 8a). Moreover, the slope shows a general convex-upwards profile, with a prominent scarp in the piedmont area (Fig. 8b), whose formation may be the result of the interaction between linear differential erosion along the thrust surficial expression and hangingwall uplift. Surface breaks have been detected after the 1976 May 6 shock along a secondary thrust (Mount Cuarnan). However, as previously reported, these coseismic ruptures have been differently interpreted both as tectonic (Bosi *et al.* 1976) and as gravitational (Cavallin *et al.* 1977). Finally, the displacement of speleothems observed in some caves of the Tagliamento river area (Mocchiutti & D'Andrea 2002) may represent the effect of movements along secondary faults related to the Gemona-Kobarid thrust. The mentioned authors reported the tilt of stalactite axes and the displacement of active karstic conduits. The displacements range between a few millimetres and some centimetres.

The Gemona-Kobarid source has been defined on the basis of the deep fault geometry reported in Fig. 4, reconstructed by means of structural surficial data and the knowledge on the regional structural style at depth.

On the whole, the structural framework of Fig. 3 for the area east of the Tagliamento river is quite different from that summarized in CNR-PFG (1987). Recent NW–SE (Dinaric) trending thrusts are reported in the latter throughout most of the region. These faults are completely substituted, in Fig. 3, by Alpine thrusts and related seismogenic sources. This option is consistent with the already mentioned Neogene–Quaternary strong structural influence of the inherited Palaeogene NW–SE thrusts (Peruzza *et al.* 2002).

6.2 The seismogenic sources of the Tagliamento river—Thiene sector

Although the previous inventories (e.g. Castaldini & Panizza 1991) presented numerous active faults affecting also the Alpine area, our structural and geomorphologic investigations indicate that conclusive evidence for active faulting can only be related to the so called Aviano line (Castaldini & Panizza 1991), i.e. the approximately 100-km-long thrust fault system bordering the E Venetian and W Friulian plain (made of the Thiene-Bassano fault, TB, Bassano-Cornuda fault, BC, Montello fault, MT, Cansiglio fault, CA, Polcenigo-Maniago fault, PM, and Arba-Ragogna fault, AR, thrusts of Fig. 1). Observed geomorphic features testify to significant vertical movements along this structure, as indicated by uplifted terraces, abandoned river valleys, subsiding sectors close to thrust surficial expressions and gentle scarps affecting recent depositional surfaces. For this reason, we focused our attention on this structure and tried to define fault segments and related sources.

The Aviano line has been segmented by mapping the different fault branches on the basis of their geomorphic expressions and subsurficial structural data. The segments of this compressive structure usually mark the borders of mature landscapes carved on Neogene–Quaternary sediments, suspended over the present plain.

6.2.1 Montello-Conegliano (no. 3 in Fig. 3 and Table 1)

The Montello plateau is probably the most evident case of uplifted landscape (Fig. 9). It is carved on conglomerates and sands of Late Pliocene—Early Pleistocene age, according to Fantoni *et al.* (2002) and data from works in progress by authors of the present paper. The plateau is affected by intense karstic erosion indicated by the abundance of dolines and it is suspended up to 150 m above the present Venetian plain; an abandoned valley (palaeo-Piave river) affects its SW termination, while the present Piave river flows to the N of the Montello hill (Ferrarese *et al.* 1998; Benedetti *et al.* 2000). According to the two mentioned works, the terrace formation is the consequence of the Montello uplift resulting from the activity of the underlying blind thrust. Each terrace marks a phase of river deepening as a result of the increase of the relief. The surficial karst morphology clearly indicates the diachroneity of the landforms being much more mature in the older than in the younger terraces (Ferrarese *et al.* 1998). Moreover, NW–SE topographic profiles indicate that the different terraces are characterized by a convex morphology, resulting from the tectonic warping. The convexity is more evident in the older than in the younger terraces, thus indicating a continuity of the tectonic activity during time. According to Benedetti *et al.* (2000), the terrace formation occurred in a time interval covering the last 0.35 Myr, while the abandonment of the palaeo-Piave valley occurred between 14 000 and 8000 BP.

The SW end of the Montello structure is defined by a clear periclinal attitude of the anticline. The NE prolongation of the structure is represented by the SE border of the Conegliano palaeolandscape (Fig. 9), a dissected and incised terrace with probable remnants of the

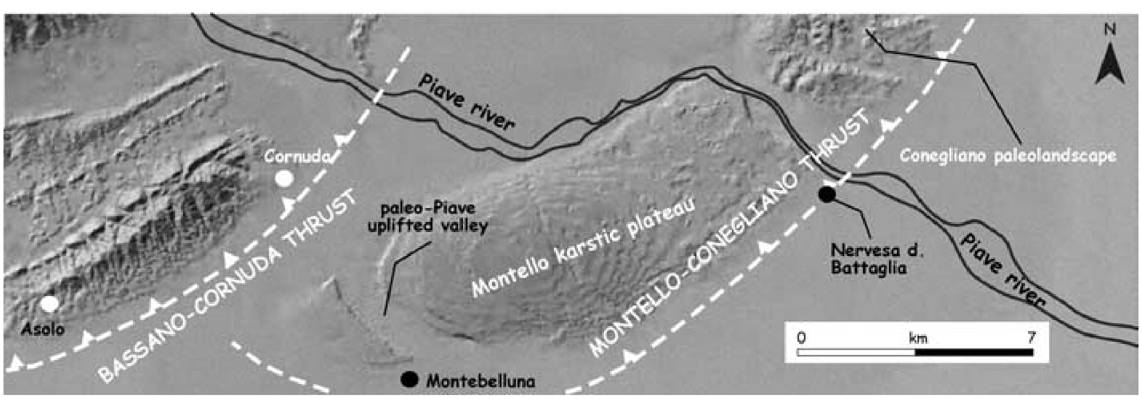

Figure 9. Geomorphologic scheme of the Asolo-Conegliano area (shaded relief image from altimetric data available on the map of the Istituto Geografico Militare at the 1:25 000 scale). Uplifted palaeolandscapes can be observed NW of the Bassano-Cornuda and Montello-Conegliano thrusts. The uplift of the Montello relief conditioned the drainage of the Piave river (see text for further details).

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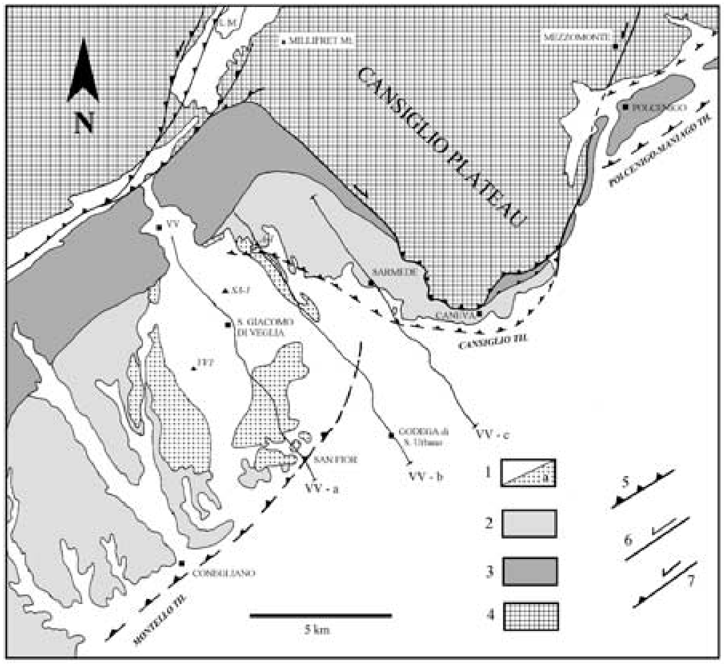

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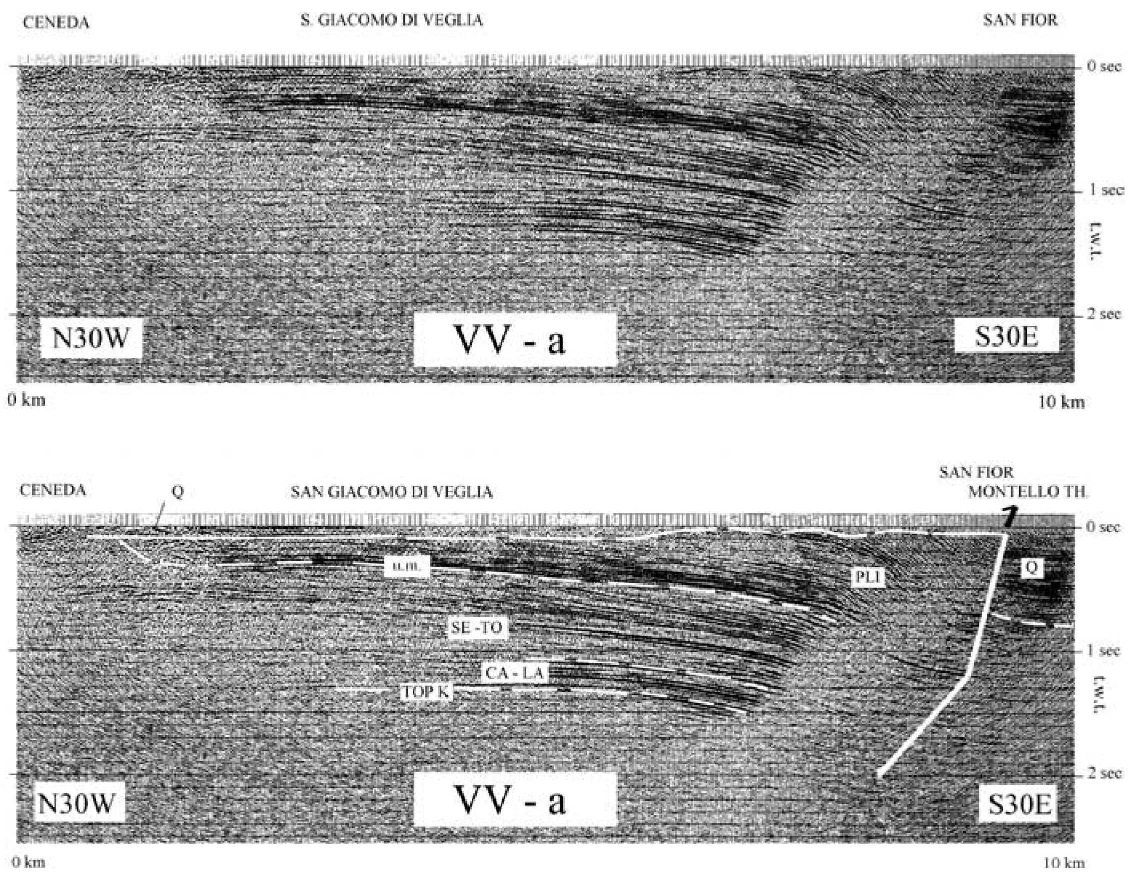

Figure 10. (a) Geological framework of the area between Conegliano and Polcenigo (Montello-Conegliano, Cansiglio and Polcenigo-Maniago thrusts). Legend: 1, Quaternary deposits; 1a, moraine of the Vittorio Veneto LGM glacial tongue; 2, Conegliano succession (clays, sands, conglomerates; Pliocene–?Pleistocene, pp); 3, terrigenous-carbonate succession (Oligocene–Miocene); 4, carbonate successions (Jurassic–Cretaceous), Scaglia Rossa Formation (lower Eocene—upper Cretaceous), marly–arenaceous flysch (Eocene); 5, thrust; 6, strike-slip fault; 7, transpressional fault. (b, c, d) reflection seismic sections (see inset a for location) across the Montello-Conegliano and Cansiglio thrusts and related interpretations. Legend: Q, Quaternary; PLI, Pliocene; SE-TO, Serravallian-Tortonian; CA-LA, Chattian-Langhian; TOP K, top of the Cretaceous carbonate platform; um, Messinian unconformity.

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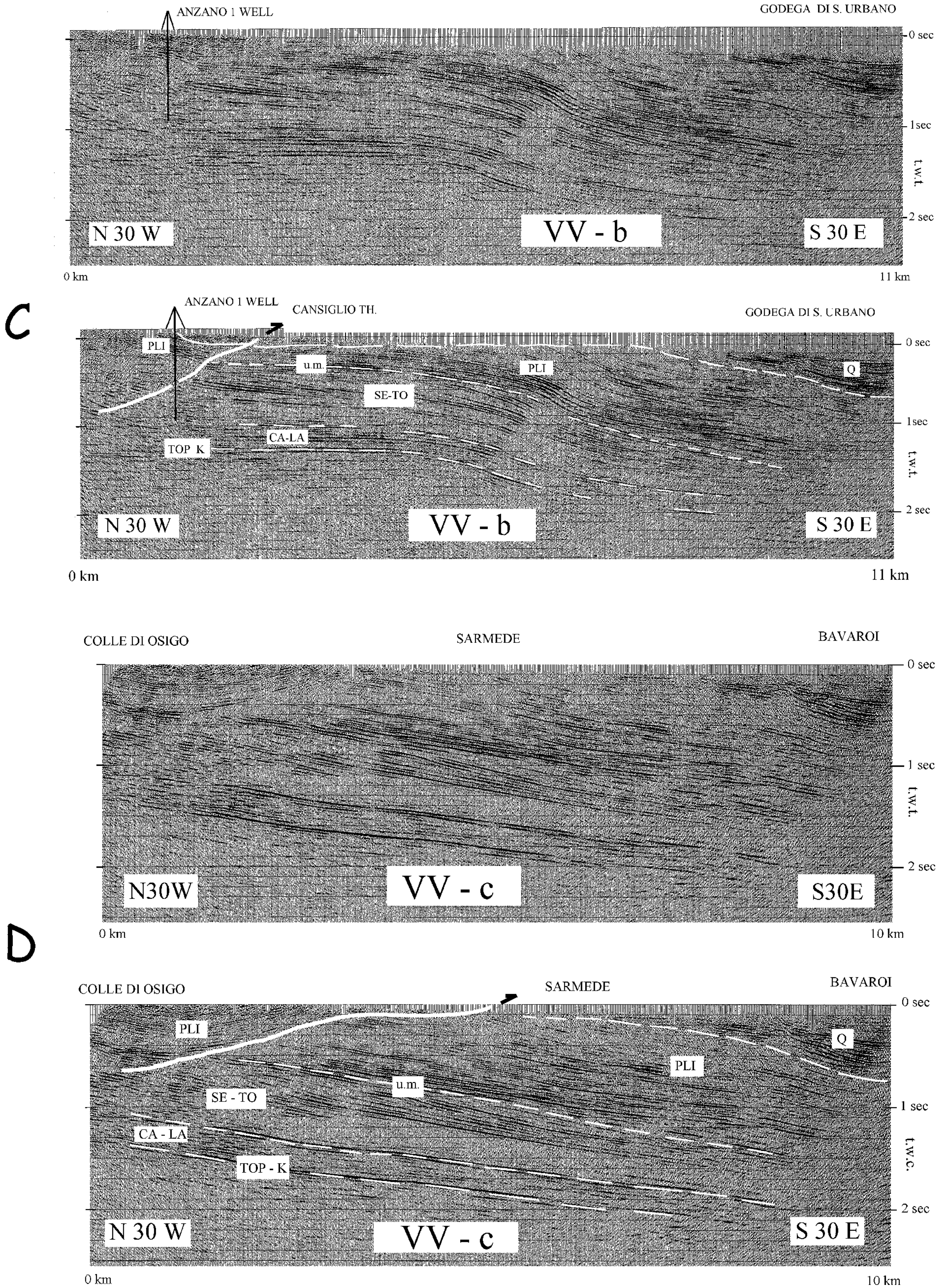

Figure 10. (*Continued*)

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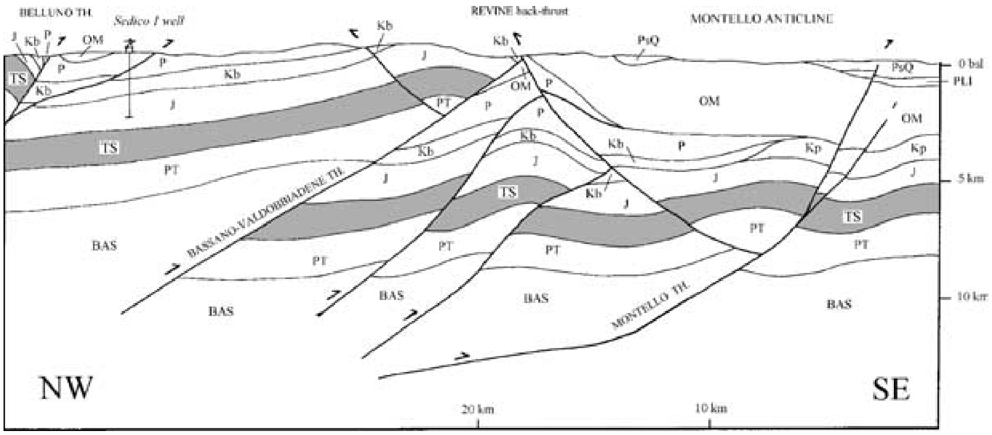

Figure 11. Geological section across the southern margin of the eastern Southern Alps in the Montello area as derived from the data published by Fantoni *et al.* (2001) and structural surficial data (see Fig. 1 for location). Legend: PsQ, Upper Pliocene-Quaternary; PLI, Oligo-Miocene; P, Palaeogene; Kb, Cretaceous (basin); Kp, Cretaceous (platform); J, Jurassic; TS, Upper Trias; PT, Permo-Trias; BAS, magnetic basement.

depositional top surface, carved on a pelitic–conglomeratic complex of Late Pliocene—Early (Middle?) Pleistocene age (Fantoni *et al.* 2002, for the age).

Reflection seismic profiles show the deformation of the Quaternary deposits (Fig. 10; see also Fantoni *et al.* 2001). The eastern along-strike geometry of the thrust has been defined through several seismic profiles of British Gas and CPL Concordia showing the thrust termination east of Conegliano under the Cansiglio thrust (Fig. 10). No evidence of separation between the Conegliano and Montello sectors has been observed from the geomorphic and subsurficial structural points of view, and therefore they define a single thrust segment and represent the surficial expression of a single seismogenic source (Montello-Conegliano). The source geometry at depth has been defined through the structural–geological section (Fig. 11) across the Montello thrust, derived from the reflection seismic data published by Fantoni *et al.* (2001) (Fig. 3; Table 1).

6.2.2 Bassano-Cornuda (no. 2 in Fig. 3 and Table 1)

West of the Montello-Conegliano source, the Bassano-Cornuda segment has been reported (Figs 3 and 9). It shows an *en échelon* relationship with the former and it is also marked by the border of a palaeolandscape carved in Neogene deposits and suspended over the present plain bottom (Parinetto 1987; Fig. 9). According to this author, the uplift of the palaeolandscape in the hangingwall of the Bassano-Cornuda thrust has persisted since the Middle Pleistocene and it is indicated by the presence of three orders of erosional palaeolandsurfaces located at 70–20, 80–40 and 140–70 m above the adjacent Holocene plain.

Pliocene clayey deposits of marine facies crop out in the hangingwall of the thrust (Favero & Grandesso 1982). Similar deposits have been found in boreholes below 1000-m-thick Quaternary deposits in the footwall (Favero & Grandesso 1982). This defines a large vertical offset as a result of the Quaternary fault activity.

At a more local scale, evidence of recent faulting and deformation has been reported in previous studies. In the area of Crespano del Grappa (Col Canil hill, approximately 10 km NE of Bassano) a reverse fault places Lower Miocene sandstones in contact with Quaternary alluvial deposits (Parinetto 1987). According to this author, the fault plane strikes 65°N and dips 60° towards the SE; it represents, therefore, a minor back-thrust related to the N-dipping main fault. In the Valle delle Molle area (close to Bassano), the anomalous attitude of the Late Pleistocene alluvial deposits has been attributed to tectonic deformation (Parinetto 1987). Other secondary faults involving Pleistocene deposits have been described for areas east of Bassano del Grappa (Parinetto 1987). In the same sector (close to the Steggio village), displacements have been observed along NE–SW trending secondary faults, which affect Early Pleistocene lacustrine deposits known as Steggio clays (Paronuzzi & Tonon 1992). The faults have been observed in trenches excavated for stratigraphic purposes and the displacements have been related to left-lateral strike-slip kinematics (Paronuzzi & Tonon 1992) consistent with the general compressive regime of this Alpine sector. According to the mentioned authors, Holocene deposits seal the faults.

The Brenta river valley represents the western termination of this segment, as indicated by the arc-shaped structure in plan view (Fig. 3). In this case, the termination of the segment is marked by the presence of a fault with a trend (NNW–SSE) transverse to the main one (not reported in Fig. 1), affecting the mentioned valley. The geometry of this fault has been defined on the basis of data derived from geo-electrical surveying (De Florentiis & Zambrano 1981). The mentioned authors made 86 geo-electrical logs over the Brenta river alluvial fan and defined the morphology of the substratum. The NNW–SSE trending fault is clearly indicated by a buried bedrock scarp.

6.2.3 Thiene-Bassano (no. 1 in Fig. 3 and Table 1)

West of the Brenta river, we mapped the Thiene-Bassano segment (Fig. 3), marked by a steep scarp bounding the Venetian plain, similar to the previously discussed cases. Subsurface data about the plain, collected in the oil research by means of reflection seismic and borehole surveying were reported in the unpublished study by Aquater (1978). These data have been used to produce a scheme showing the thickness of the Plio-Quaternary deposits by Antonelli *et al.* (1990). According to this scheme, the thickness of the Plio-Quaternary deposits in the footwall of the Thiene-Bassano thrust varies between several hundred and approximately 1000 m. This indicates a significant tectonic subsidence of the areas located south of the fault surficial expression.

The area between Bassano del Grappa and Thiene is reported as having persistently uplifted since the Pliocene by Zanferrari *et al.* (1982), similarly to the other areas already described in the previous sections and characterized by the gentle landscape suspended over the Venetian plain typical of the pre-Alpine area.

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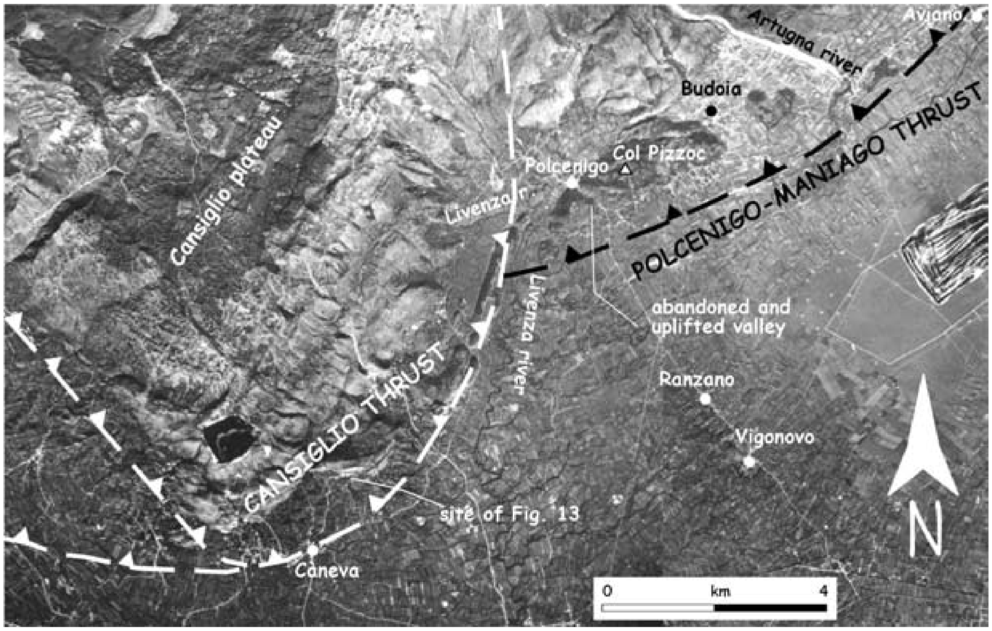

Figure 12. Photomosaic of aerial photographs (survey 1954, Istituto Geografico Militare) of the Cansiglio-Aviano area. The traces (projected at surface) of the Cansiglio and Polcenigo-Maniago thrusts have been reported, together with the main geomorphic features related to the thrust activity.

The vertical movements in the area east of Thiene are also evident in the continuous erosion of the pre-Quaternary basement along sectors of the Astico river valley (approximately 4 km north and east of Thiene) south of the Alpine front (Bartolomei 1976). Based on borehole data, the pre-LGM valley was even deeper than the present one. Indeed, a 56-m-thick alluvial succession has been found in the area close to the scarp representing the surficial expression of the thrust (Bartolomei 1976). Moreover, also the anomalous Astico river course may have been conditioned by the uplift of this sector. The Astico valley was probably characterized by a palaeodrainage towards the south, i.e. towards Thiene, until the Middle Pleistocene (Bartolomei 1976). In contrast, it is presently characterized by a river course having an E–W direction in the pre-Alpine sector and only after a 4-km-long anomalous course direction it displays a NNW–SSE drainage. According to Bartolomei (1976), the present valley results from the shift of the palaeo-Astico course as a result of a Middle Pleistocene glacial tongue, and from the capture by a former minor river having a direction approximately N–S and experiencing regressive erosion. River regressive erosion is the typical effect of the areal uplift.

The western termination of the Thiene-Bassano segment is represented by a NW–SE transverse fault in CNR-PFG (1987). Hydrogeological data reported by Antonelli *et al.* (1990) are consistent with the presence of this fault. Piezometric isolines are, indeed, trending NW–SE in this sector and very close to one another, thus showing a very steep gradient of the aquifer piezometric surface.

6.2.4 Cansiglio (no. 4 in Fig. 3 and Table 1)

In the portion of the Venetian-Friulian plain south of the Cansiglio massif (Figs 3 and 12), the base of the Quaternary deposits has been identified at approximately 900 m below the sea level on the basis of unpublished reflection seismic surveys by Eni/Agip. This thick wedge of Quaternary deposits defines a continuous recent subsidence of the plain area at the front of the Cansiglio thrust and represents the most striking evidence of the recent fault activity.

Late Quaternary activity of the Cansiglio thrust is also demonstrated by the displacement of post-LGM stratified slope deposits along the fault surficial expression (Fig. 13). A colluviated palaeosol underlying these deposits has been radiocarbon dated at 26 640 ± 240 BP. This indicates that the deposition of the slope deposits has probably to be related to the LGM. This hypothesis is also corroborated by the facies of the sediments, which is similar to that of other deposits found along the Alpine slopes and generally attributed to Late Pleistocene periglacial deposition (e.g. Bartolomei 1974; Castiglioni *et al.* 1979; Galadini *et al.* 2001c). Segmentation and the source geometry have been inferred from the surficial structural and reflection seismic data (Figs 3 and 14; Table 1).

Finally, the Cansiglio segment is generally considered as the source of the 1936 earthquake (Sirovich *et al.* 2000; Valensise & Pantosti 2001), on the basis of the processing of the intensity data point distribution (methods by Gasperini *et al.* 1999; Pettenati *et al.* 1999). According to Sirovich *et al.* (2000), the source strikes 232° (52°NE) if the intensity distribution reported in Monachesi & Stucchi (1998) is used and 212° (32°NE) if the used intensity distribution is that by Boschi *et al.* (1995). The strike proposed in Valensise & Pantosti (2001)) is 230° (50°NE), quite similar to the solutions proposed by Sirovich *et al.* (2000).

NNE–SSW trending surface breaks formed some hours before the earthquake, transverse to the road between the villages of Fiaschetti and Sarone in the SE frontal sector of the Cansiglio massif (Andreotti 1937). Although the strike of these breaks is consistent with that of the thrust, their origin is unclear.

6.2.5 Polcenigo-Maniago (no. 5 in Fig. 3 and Table 1)

The terrace levels suspended over the Friulian plain and parallel to the Polcenigo-Maniago thrust segment represent the most direct effect of the recent hangingwall uplift along the mentioned fault (Fig. 12). Gentle scarps on the top of depositional surfaces of alluvial fans can be detected along the entire segment together with evident drainage anomalies. For example, the uplift of the Col Pizzoc hill in the Polcenigo area has caused the abandonment of a fluvial

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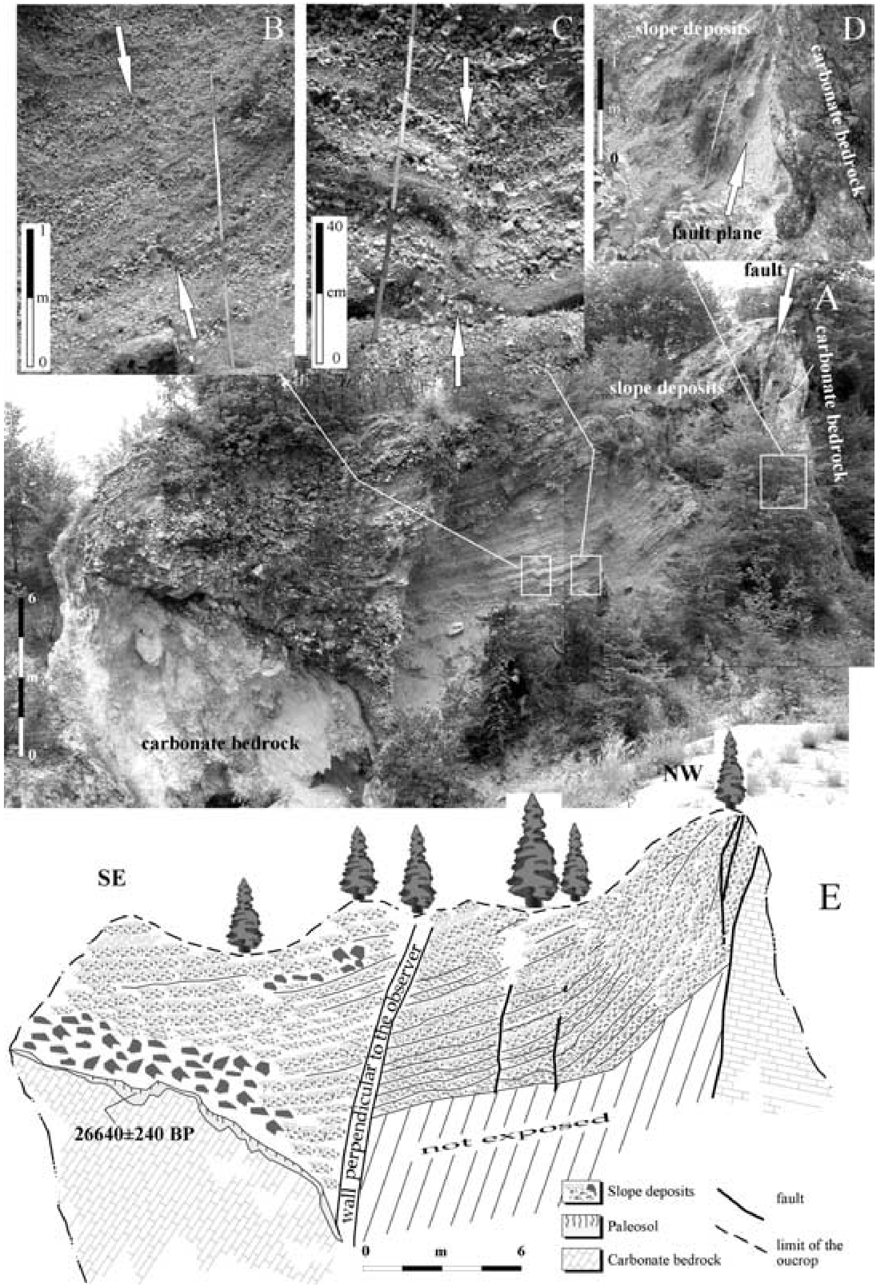

Figure 13. Displaced slope deposits in the Caneva area, at the front of the Cansiglio thrust (see Fig. 12 for location): (a) panoramic view; (b, c, d) details of the displacement; (e) schematic log of the outcrop. Based on the radiocarbon dating of the colluviated palaeosol (26 640 ± 240 BP), the displacement is not older than the uppermost Late Pleistocene, as slope deposits more recent than the reported date are displaced and dragged along the main fault plane (on the right of the photograph, placing the carbonate bedrock in contact with the slope deposits) and displaced along secondary shear planes in the central part of the outcrop.

incision cutting through the hill (Fig. 12). The river that formed this valley flowed towards the south, but the uplift of Col Pizzoc triggered the capture by the Livenza river (flowing around the uplifting area) and the abandonment of the valley crossing the hill, with a process similar to that observed in the Montello area. The eastern portion of the Polcenigo-Maniago thrust probably affects the alluvial fan fed by the Artugna river, between Budoia and Castello d'Aviano. The dip of the top depositional surface of the fan evidently increases in the area where the maximum surficial deformation as a result of the thrust activity is expected (Fig. 12). Terracing resulting from uplift affects the eastern sector, between Castello d'Aviano and Montereale Valcellina, east of the area of Fig. 12 (Avigliano *et al.* 2002a). According to these authors, remnants of Pleistocene alluvial sediments (and the related mature soils) deposited by the Cellina river are suspended by 10–30 m over the surface of the Late Pleistocene alluvial fan, as a result of the uplift of this sector. The soils that developed over these alluvial remnants are definitely more evolved than those that developed over the recent fan (Avigliano *et al.* 2002a).

The huge vertical displacement related to the Polcenigo-Maniago thrust is indicated by the depth of the base of the Quaternary deposits (in front of Aviano: at approximately 450 m below sea level), derived

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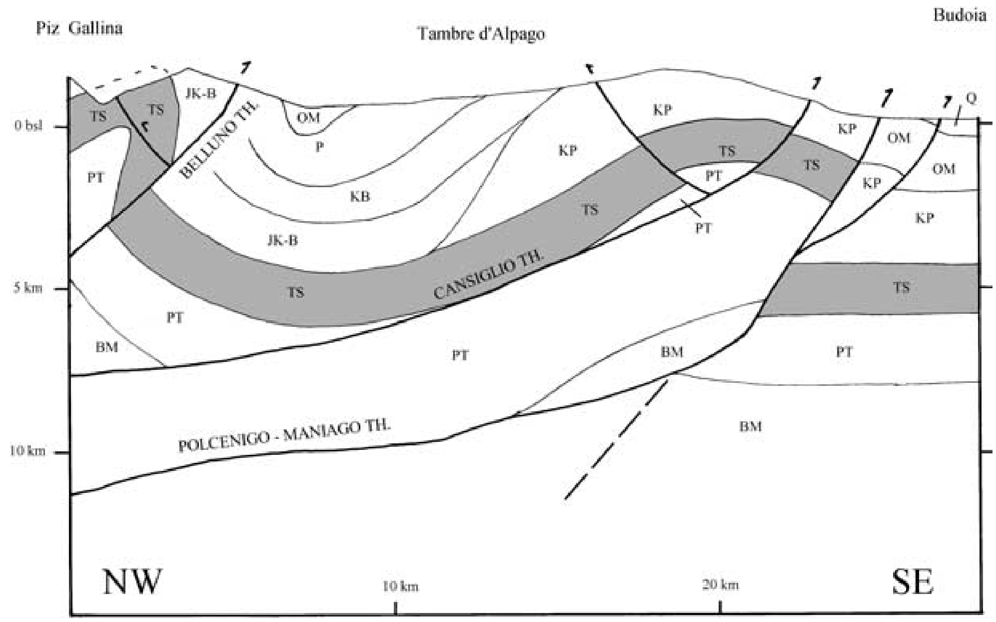

Figure 14. Geological section across the southern margin of the eastern Southern Alps in the Cansiglio area as derived from surficial geological and structural data and subsurficial information (see text for further explanation and Fig. 1 for location). Legend: Q, Quaternary; OM, Oligo-Miocene; KP, Cretaceous (platform); TS, Upper Trias; PT, Permo-Trias; BM, magnetic basement; KB, Cretaceous (basin); JK-B, Jurassic–Cretaceous (basin).

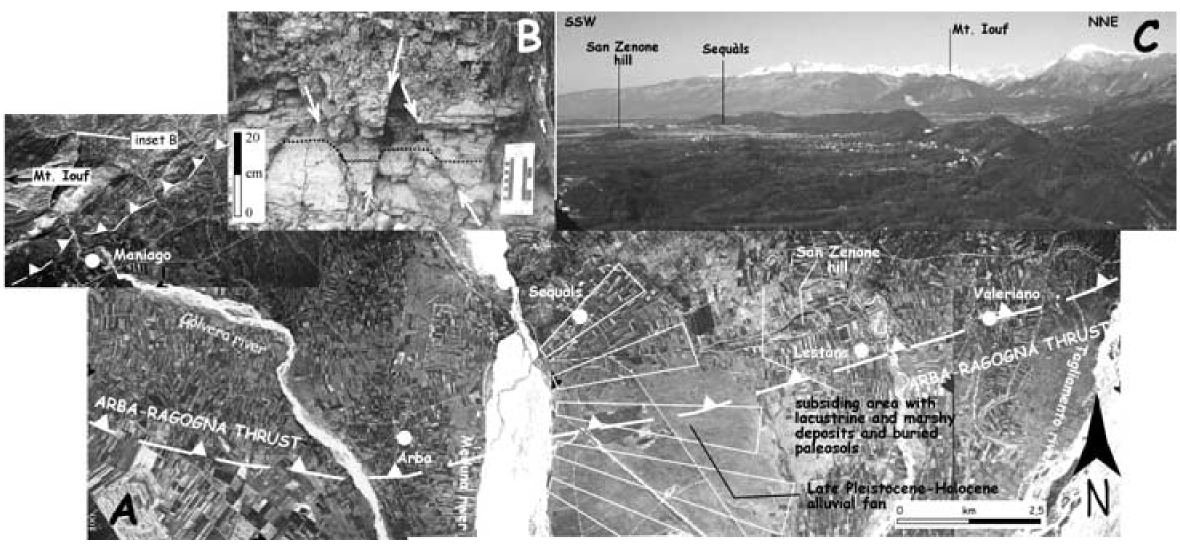

Figure 15. (a) Photomosaic of aerial photographs (survey 1954, Istituto Geografico Militare) of the Maniago-Valeriano area. The trace (projected at surface) of the Arba-Ragogna thrust has been reported, together with the main geomorphic features related to the thrust activity. (b) Displaced lacustrine deposits in the Mount Iouf area (see b for location); the displacement is probably a result of the activity of a secondary thrust related to the Arba-Ragogna source. (c) Panoramic view of the Sequàls area from east: the low hills representing the surficial expression of the thrusts are visible.

from unpublished Eni/Agip reflection seismic surveys. Segmentation and the source geometry (Fig. 3; Table 1) have been inferred from the surficial structural data and the related extrapolation at depth (Fig. 14).

6.2.6 Arba-Ragogna (no. 6 in Fig. 3 and Table 1)

Recent geomorphologic investigations showed that, similarly to the previously discussed cases, also in the case of the Arba-Ragogna thrust the evidence of recent activity mainly consists of subsiding areas and uplifted terraces along the fault surficial expression and displacement of Late Quaternary deposits (Fig. 15).

In the area of Mount Iouf, approximately 3 km north of Maniago, lacustrine deposits dated at 10 360–10 190 BP (1 sigma radiocarbon cal. age) have been mapped in the 'Maniago' sheet (1:50 000) of the new geological map of Italy (Zanferrari *et al.* 2005b). The deposits are displaced by small-scale faults (Fig. 15b) tilted and gently folded by the thrust activity. Close to Sequals, an actively subsiding area has conditioned the deposition of alluvial fan deposits at least since the LGM and the formation of a Holocene marshy area (Avigliano *et al.* 2002b; Fig. 15a). Towards the east, Late Quaternary alluvial deposits in the area of Pinzano (close to the eastern segment termination) are tilted by the thrust activity. As a consequence of the deformation, the deposits are dipping towards the SE instead of

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the SW (representing the primary attitude related to the local alluvial fan deposition; Zanferrari *et al.* 2005b). The NE termination of the Arba-Ragogna thrust is represented by the Ragogna anticline. Recent investigations showed that the top surface of fluvioglacial deposits related to the LGM (dated at 23 040–22 240 BP, 1 sigma radiocarbon cal. age) is displaced by approximately 4 m in the area of the Ponte creek (southern limb of the Ragogna anticline; Zanferrari *et al.* 2005b). The creek is superimposed on the fault, which displaces the surface, as fluvial and fluvioglacial deposits cannot be correlated across the two banks.

7 DISCUSSION

7.1 The identification of the Alpine active faults

In the previous sections, we tried to define the seismogenic sources potentially responsible for earthquakes with $M \geq 6$ in the eastern Southern Alps. It is evident from Fig. 3 that these sources affect the area between the Alpine relief, and the Venetian and Friulian plains. No other significant evidence of recent fault activity has been observed north and south of the sector affected by the reported thrusts. It needs to be mentioned, however, that the lack of evidence of recent activity in the mountainous region may have been conditioned by the erosional–depositional geological evolution of the Alps since the 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. On this basis, the presence of significant seismogenic sources within the Alpine domain, though improbable, cannot be completely excluded. Moreover, the lack of surficial evidence (both geomorphic and structural) of the Trasaghis thrust suggests the possibility that other unknown sources, presently undetectable but potentially responsible for $M \geq 6$ earthquakes, may affect the investigated territory, particularly in the structurally more complicated Friulian sector.

7.2 Kinematic aspects

Both the surficial structural and geodetic investigations (e.g. Castellarin *et al.* 1992; Caporali & Martin 2000) and the directions of the regional stresses obtained through inversion of seismological data (Bressan *et al.* 1998; Slejko *et al.* 1999) contributed to define slip vectors on the reported thrust planes (Table 1). Structural surficial data gave direct information on the kinematics of the fault planes, generally in the hangingwall sectors, where deformed rocks are exposed. Moreover, all the available geological and geophysical data indicate that the investigated region is experiencing deformation conditioned by a subhorizontal NNW–SSE (western sector) to N–S (central-eastern sector) trending σ_1. The comparison between the 3-D thrust geometry with the σ_1 directions and the surficial data have permitted to infer the slip vectors reported in Table 1.

Another fundamental kinematic aspect, i.e. the slip rate, is still poorly defined. The data reported in Table 1 indicate slip rates ≤ 1 mm yr^{-1}, but in almost all the described cases the evaluations are from geomorphologic investigations of more than one decade ago (Castaldini & Panizza 1991). Minimum slip rates could be obtained, for some thrusts, from the depth of the base of the Quaternary deposits in the footwall of the faults. This evaluation needs, however, the definition of the original depositional altitude of the Early Quaternary sediments. The Quaternary deposition in the Venetian and Friulian plains has been conditioned by the different standings of the sea level. In fact, during low-standing periods, the Adriatic sea shoreline was many kilometres south of the present shoreline. This may have conditioned the formation of troughs in the pre-Alpine area subsequently filled by Quaternary deposits during the marine ingressions and the high-standing phases (Castiglioni *et al.* 2001). Therefore, the present depth of Quaternary deposits below the plains in the pre-Alpine areas may not be solely a result of the thrust vertical movements.

Assuming that the sea level during low-standing periods reached negative elevations comparable with that of the LGM (see Haq *et al.* 1987 on this point), i.e. 100–150 m below the present sea level (e.g. Bosi *et al.* 1996), we can obtain information about the minimum vertical offset related to some thrusts reported in Fig. 3. Indeed, the minimum offset can be evaluated by considering the present depth of the base of the Quaternary deposits as a direct result of the footwall lowering. Or, alternatively, we can correctly estimate the minimum offset from this depth once the possibility that the sediments originally deposited at an elevation lower than the present sea level (i.e. during a low-standing period or during an ingression phase) is considered. In this case, taking into account the magnitude of the negative oscillations of the sea level, we have to subtract 100–150 m from the present depth of the deposits to obtain the minimum vertical offset.

In both cases [i.e. (i), considering the present depth as a direct result of the vertical offset or, (ii), considering the depth as the effect of the vertical slip once 100–150 m has been subtracted], we are dealing with minimum offsets, because no deposits that can be clearly attributed to the Quaternary in the hangingwall of the thrusts have been found so far (note that the attribution of some deposits of the Montello hill to the Early Quaternary by Fantoni *et al.* 2002 must still be considered as preliminary).

Taking into account these problems, we hypothesize a Quaternary minimum vertical slip rate of 0.42–0.5 mm yr^{-1} for the Bassano-Cornuda thrust, based on the present depth of the deepest Quaternary deposits at approximately 1000 m below the surface in the footwall of the thrust (see the section dedicated to the seismogenic sources). This value has been obtained by dividing the two extreme minimum offsets (i.e. 1000 and 850 m, the latter considering an original deposition at an elevation 150 m below the present sea level) by the time span of the entire Quaternary period.

Following the same procedure, a similar value (0.4–0.47 mm yr^{-1}) can be estimated for the Cansiglio thrust, considering the base of the Quaternary deposits located at approximately 950 m below the surface.

A Quaternary minimum vertical slip rate of 0.17–0.25 mm yr^{-1} can be estimated for the Polcenigo-Maniago thrust, because the base of the Quaternary deposits is located at approximately 500 m below the surface (see the section dedicated to the seismogenic sources).

The seismic section VV–a reported in Fig. 10b, permits to hypothesize the minimum vertical offset of the Montello-Conegliano thrust in the area of San Fior (Fig. 10a). The base of the Quaternary deposits is defined at approximately 0.8 s two travel time. The inversion of (velocity 2 000 m s^{-1}) defines a depth of approximately 800 m. This permits to evaluate a minimum vertical slip rate of 0.32–0.4 mm yr^{-1}. Benedetti *et al.* (2000) suggested an uplift rate of 1 mm yr^{-1} in the last 121 Kyr (Table 1), on the basis of geomorphological investigations along deformed river terraces.

As for the Arba-Ragogna thrust, the total vertical offset (4 m) affecting fluvioglacial deposits dated at 23 040–22 240 BP (see the section dedicated to the seismogenic sources) permits to evaluate a vertical slip rate of 0.17 mm yr^{-1}. We consider it as a minimum slip rate, because it has been derived from the offset estimated in an area

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close to the eastern fault termination (i.e. in the sector of the thrust oblique ramp).

In the area close to the Pozzuolo and Medea thrusts (footwall sector), the base of the Quaternary deposits has been found at approximately 450 m below the surface on the basis of unpublished reflection surveys by Emi/Agip. Following the same procedure adopted in the previous cases, this value permits to estimate a minimum vertical slip rate of 0.15–0.22 mm yr^{-1}.

As for the Thiene-Bassano and Susans-Tricesimo thrusts, data on the base depth of the Quaternary deposits are too sparse to define vertical offsets. For example, in the case of the Thiene-Bassano thrust, only the base depth of undefined Plio-Quaternary deposits can be recognized. As for the Gemona-Kobarid thrust, a Quaternary slip rate cannot be hypothesized because of the lack of Quaternary deposits or dated Quaternary landforms displaced by the fault.

7.3 Historical earthquakes and sources: hypotheses and implications

Based on the rupture length, downdip rupture width and rupture area, the sources reported in Fig. 3 and Table 1 may be responsible for earthquakes with $M \geq 6$.

Three of these sources have been defined by taking into account also the available seismological data related to the 1936, 1976 (May 6), 1976 (September 15) events (see the sections dedicated to the description of the seismogenic sources). For this reason, these earthquakes have been associated with the Cansiglio, Susans-Tricesimo and Trasaghis sources, respectively.

West of the Cansiglio source, hypotheses about the correlation between the Montello source and some historical earthquakes (778, 1268 and 1859) have been made by Benedetti *et al.* (2000). This correlation is, however, based on faint evidence because historical knowledge about the 778 and 1268 events is sparse (see the section dedicated to the seismicity). As for the 1859 earthquake, it is in fact a small earthquake, reported with M_m 4 in Working Group CPTI (1999). Earthquakes like that of 1859 are quite frequent in the investigated area but, as a result of the small size of the rupture at depth, the correlation with a larger source cannot be reliable without instrumental data.

The available catalogues (e.g. Working Group CPTI 1999) do not report significant earthquakes that may be reliably linked to the Montello-Conegliano thrust (Fig. 2). Considering that historical data probably give comprehensive information about the occurrence of strong earthquakes (no large magnitude earthquakes are missing in the catalogue) in this Italian sector since AD 1200 (Stucchi & Albini 2000), it is probable that the Montello-Conegliano source has been silent at least during the last eight centuries. Our conclusions are consistent with those by Valensise & Pantosti (2001) who defined a source not affected by historical earthquakes in the Montello area.

A similar conclusion, i.e. a silent condition for the last eight centuries, may be drawn for the Arba-Ragogna and Medea sources. Available historical information, indeed, does not permit to identify $M \geq 6$ earthquakes occurred in the sector affected by these sources (Working Group CPTI 1999) (Fig. 2).

The definition of possible historical activity is definitely more complicated for the Thiene-Bassano thrust. Also, in this case, no earthquakes are reported in the catalogues that may be related to this source. Catalogues report the 1117 earthquake in the Verona area (e.g. Working Group CPTI 1999), but recent investigations into this earthquake indicated that it may have originated east of Verona (Galadini *et al.* 2001a). If this is true, the Thiene-Bassano source may be the cause of this event. In this case too, this is a source that has been silent for the last eight centuries.

Seven other earthquakes with $M \geq 6$ occurred in the areas affected by the sources defined in the previous sections. We tried, therefore, to associate the earthquakes with the sources reported in Fig. 3. This has been made by following already published procedures (Galadini *et al.* 1999; Meletti *et al.* 2000): a comparison is drawn between the damage distribution of the earthquake and a geologically inferred source geometry. The highest intensity data points should be mainly located in the thrust hangingwall (with a more limited distribution around the source) and no other source that may be consistent with a certain damage distribution should affect the earthquake area. Following this procedure, it can be seen that most of the 1695 earthquake damage distribution occurred in the hangingwall of the Bassano-Cornuda thrust (Fig. 16). Moreover, the earthquake magnitude (M_e 6.67 according to Working Group CPTI 1999) is consistent with the dimensions of the source (e.g. Wells & Coppersmith 1994). On this basis, we hypothesize that the 1695 earthquake was caused by the activation of the Bassano-Cornuda source.

The definition of the 1348, 1511 and 1873 earthquake sources is more difficult. The former event affected a very large area, as it was responsible for damage in the Gail Valley (Austria), in Slovenia and in the Gemona area (Hammerl 1994). We tentatively hypothesize that the earthquake originated from the activation of the Gemona-Kobarid portion of the Periadriatic thrust, because it seems to be the only active fault segment that may justify the damage distribution related to this earthquake (Fig. 16). Indeed, the sparse information on the damage distribution permits to define (MCS scale) data points (e.g. Monachesi & Stucchi 1998) north of of the Gemona-Kobarid fault (consistently with the thrust kinematics) and in the Friulian sector around the thrust surficial expression (Gemona area).

As for the 1511 earthquake, the fundamental work by Ribaric (1979) defines the occurrence of two main shocks, one in Slovenia and the other in the Friuli area, based on historical data. This may justify the wide damage area affecting both regions. More recently, Boschi *et al.* (1995) concluded that the available historical data do not permit to define the occurrence of two different shocks.

Considering the 1511 earthquake damage as the effect of a single event, different hypotheses are presently available for its origin. Benedetti (1999) hypothesized that this event is related to the activation of the NW–SE dextral Cividale fault (at the easternmost boundary of the investigated area). However, we did not recognize the evidence of recent activity (mainly the dextral offset affecting river valleys transverse to the Cividale fault) reported by this author. Moreover, alluvial terraces related to the LGM and post-LGM deposition are undeformed across the fault. For these reasons, a present activity of the Cividale fault and its role as the causative source of the 1511 earthquake do not seem to be convincing.

The 1998 Bovec (Slovenia) earthquake (M_s 5.7) has focused the attention of the researchers on the Slovenian NW–SE dextral faults. Several authors indicate that the earthquake was originated by the čez Potoče fault segment (Bernardis *et al.* 2000; Bovec-Krn segment in Bajc *et al.* 2001), belonging to the Idrija fault system. A wider study of the entire fault system has permitted to hypothesize that the 1511 earthquake originated from the activation of a 40/50-km-long fault, comprising the čez Potoče segment (Bajc *et al.* 2001; Fitzko 2002). Presently, we believe that this solution is more reliable than that proposed by Benedetti (1999), as a result of the geomorphologic evidence of recent fault activity (e.g. Vrabec 1994; Bajc *et al.* 2001) and the main role played by the Idrija fault within the present kinematic framework (e.g. Poljak *et al.* 2000).

On this basis, we assume that the 1511 earthquake was caused by the activation of the Idrija fault and its source is not among those

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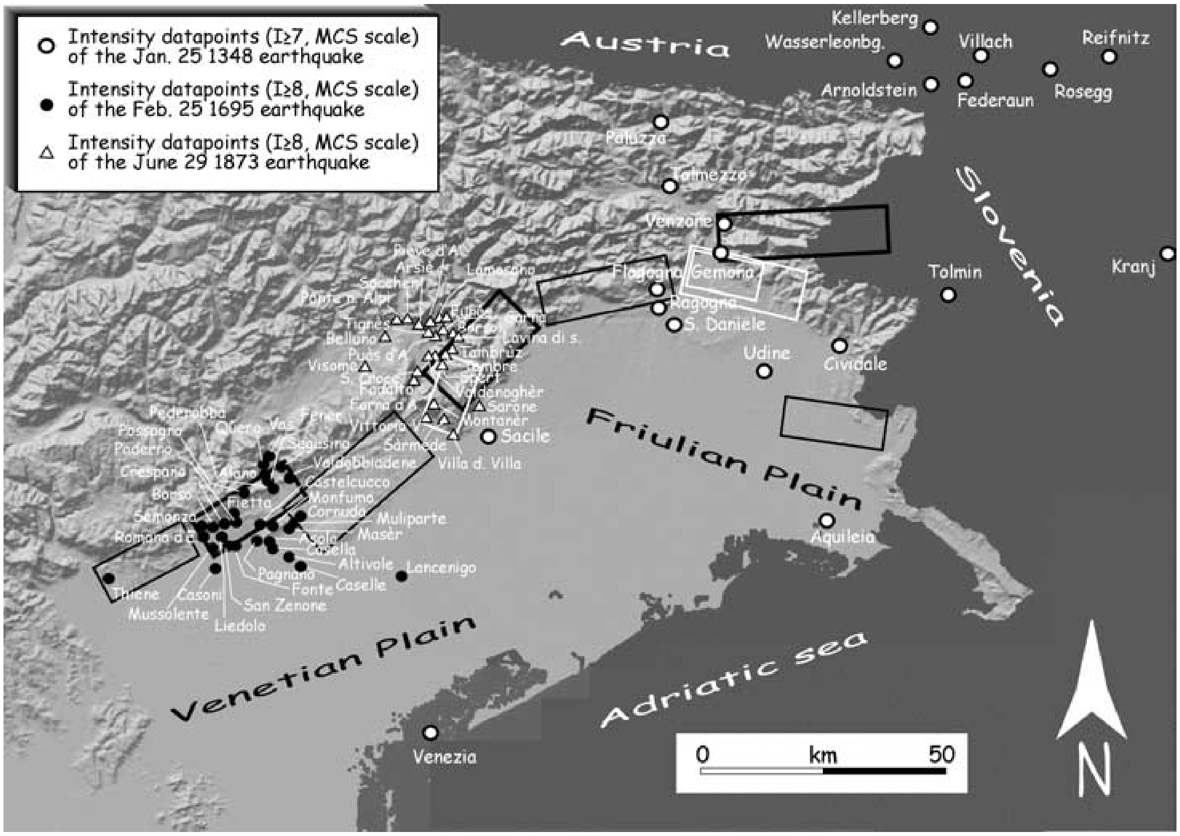

Figure 16. Intensity data point distribution of the 1348, 1695 and 1873 earthquakes (as derived from Monachesi & Stucchi 1998) and seismogenic sources of NE Italy. Thicker lines define the sources that may have been responsible for the mentioned earthquakes, i.e. Bassano-Cornuda (1695 earthquake), Polcenigo-Maniago (1873 earthquake), Gemona-Kobarid (1348 earthquake). The used map is a shaded relief image obtained from the processing of digital elevation data by the Istituto Geografico Militare at the 1:250 000 scale.

defined in the Friuli region. The 1873 event mostly damaged the intermontane area north of the Cansiglio massif (Alpago area). Valensise & Pantosti (2001) named Fadalto a source derived from geological data (e.g. Doglioni 1990), which may be consistent with the occurrence of the 1873 event. This structure represents the eastern termination of the Bassano-Valdobbiadene line of Castaldini & Panizza (1991), i.e. the lateral ramp of a 80-km-long thrust. The lack of evidence of recent activity along the entire Bassano-Valdobbiadene thrust does not seem consistent, however, with the hypothesis of the Fadalto source as the cause of the 1873 earthquake. The geometric–kinematic characteristics of the 1873 source have also been derived from macroseismic data modelling (strike 314°, dip 35°, rake 98°; strike 125°, dip 49°, rake 83°; Pettenati & Sirovich, private communication, 2004). The proposed hypothesis does not seem consistent, however, with the present state of stress affecting the investigated region (e.g. Bressan *et al.* 1998; Slejko *et al.* 1999).

Alternatively, we propose that this earthquake was caused by the Polcenigo-Maniago source. The geometry of the source and the distribution of the highest intensity data points could be consistent (Fig. 16), admitting that the damage distribution has been strongly conditioned by orographic factors (i.e. the lack of intensity data points above the source, as a result of the presence of the uninhabited Cansiglio massif).

In conclusion, the Thiene-Bassano, Montello-Conegliano, Arba-Ragogna and Medea sources may have been silent during the last eight centuries. These sources may define seismic gaps in NE Italy. The seismic hazard in the areas where these sources are located is obviously higher than that related to the areas affected by the sources that have been responsible for historical earthquakes.

7.4 Recurrence intervals

In the previous subsection, we showed that not more than one strong historical earthquake can be attributed to each defined source. Taking into account that the catalogues can be considered as complete for large magnitude earthquakes in the last eight centuries, this means that the seismogenic sources are characterized by long recurrence intervals, i.e. many centuries or, possibly, 1000 yr.

Slip rates lower than 1 mm yr^{-1} seem to confirm this conclusion about the recurrence intervals per source. Indeed, surficial displacements per event related to thrust earthquakes with magnitude between 6.0 and 6.7 (those expected from the investigated thrusts) are generally of several tens of centimetres (0.1–0.7 m in Wells & Coppersmith 1994). Considering, as an example, the Montello-Conegliano thrust (to which a magnitude M_w 6.7 and a slip rate of 1 mm yr^{-1} can be associated), the estimated offset per event (0.7 m; Wells & Coppersmith 1994) permits to evaluate a recurrence interval of 700 yr. This time length obviously increases if the 1 mm yr^{-1} rate incorporated a part of aseismic slip or slip related to low-magnitude events. Indeed, the existence of a significant aseismic component of motion is highly probable for the investigated faults. For example, the geodetic network in the area of the Cansiglio thrust defined evident movements of the fault in recent times that cannot be related to large magnitude earthquakes (Beinat *et al.* 1988; Achilli *et al.* 1989).

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8 CONCLUSIONS

The merge of new geomorphological and structural (both surficial and subsurficial) data with those available from the critically reviewed literature has permitted to define the major active thrust segments that affect the eastern Southern Alps (NE Italy). The defined segments ranges between 14 and 30 km. Subsurficial structural data, derived from more than 1700 km of reflection seismic profiles, have defined the deep geometry of the fault segments. Fault slip vectors have been derived from surficial structural data and the present knowledge on the direction of the stresses affecting the investigated region. Long-term slip rates have been derived from the displacement of Quaternary deposits.

The definition of the 3-D fault geometry has permitted to draw seismogenic sources, which (based on the equations linking fault dimensions with M_w) may be responsible for earthquakes with $M \geq 6$. Nine seismogenic sources have been defined through this procedure. A further source (Trasaghis) has been derived from the comparison of seismological data related to the 1976 September 15 earthquake with the available structural sections, because this source has no surficial evidence. A comparison of the source geometry with the highest intensity distribution data points of historical earthquakes with $M \geq 6$ permitted to make hypotheses on the association of these earthquakes with specific seismogenic sources. Three sources (Montello-Conegliano, Arba-Ragogna and Medea) cannot be related to historical earthquakes. This defines a minimum elapsed time since the last source activation in the order of eight centuries (based on considerations about the completeness of the historical catalogues). A long elapsed time can also be attributed to the Thiene-Bassano source, because only the 1117 earthquake has been tentatively related to this structure.The identification of these silent sources permits to define areas characterized by a high level of seismic hazard, to which more urgent preventive interventions for the defense against earthquakes should be addressed.

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