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Quaternary capable folds and seismic hazard in Lombardia (Northern Italy): the Castenedolo structure near Brescia

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ABSTRACT

We identify evidence of late Quaternary compressive tectonics in the Northern sector of the Central Po Plain through a systematic revision of the literature, new field mapping, and a new study of seismic reflection data obtained by ENI E&P. In particular, the reinterpretation of ca. 18.000 km of seismic profiles clearly shows a belt of segmented, 10 to 20 km long, fault propagation folds, controlled by the Plio-Quaternary growth of several out-of-sequence thrusts. As an example of this active structural style, in this paper we focus on a buried fold located just south of the Castenedolo Hill, a few km SE of Brescia. Although the Castenedolo anticline has long ago been described as a young compressional structure (e.g., Desio, 1965), no detailed structural analysis of this feature has been performed until now. We calculated the uplift rates of this fold through the analysis of its syntectonic sedimentary record as imaged by the extremely high quality ENI E&P subsurface data available in the area. The evolution of this anticline was a discontinuous process characterized by several tectonic uplift pulses (with rates of ca. 0.1 mm/yr) of different duration, separated by periods of variable extent in which no fold growth occurred. The Quaternary growth history of this anticline and the presence of faulted and folded late Pleistocene to Holocene deposits at nearby sites (Ciliverghe and Monte Netto) demonstrate that the significant seismicity of this area (e.g., the December 25, 1222, Io = IX MCS Brescia earthquake, Magri & Molin, 1986; Guidoboni, 1986) must be related to active compressional structures within the Brescia piedmont belt. Our regional investigations show that the structural and paleoseismic setting illustrated near Castenedolo is typical of the whole Lombardia domain of the Southern Alps. This implies that the currently accepted seismotectonic model for this region, and related seismic hazard assessment, should be thoroughly and carefully re-evaluated.

Key words: *Active tectonics, Southern Alps, fault propagation folds, capable faults.*

RIASSUNTO

Pieghe capacità e pericolosità sismica in Lombardia (Italia Settentrionale): la struttura di Castenedolo (Brescia).

Attraverso la revisione dei dati di letteratura, il rilevamento geologico di campagna su alcune strutture di interesse, e grazie allo studio di alcune sezioni sismiche reso possibile dalla collaborazione con ENI E&P, si è giunti ad identificare chiari segni di tettonica compressiva Quaternaria localizzati nel settore settentrionale della Pianura Padana. In particolare la reinterpretazione di circa 18000 chilometri di profili sismici a riflessione ha evidenziato la presenza di una fascia di pieghe per propagazione di faglia, lunghe circa 10-20 Km, che deformano la successione Plio-Pleistocenica padana. I tassi di sollevamento relativi ad una piega posta poco a Sud del Colle di Castenedolo (BS), selezionata come struttura illustrativa dello stile tettonico che domina la deformazione attiva nell'area di studio, calcolati grazie all'architettura della sequenza sedimentaria sindeformativa, hanno evidenziato un processo di crescita episodico, caratterizzato da diverse fasi di sollevamento (con tassi di ca. 0,1 mm/anno) intervallate da fasi di quiescenza. L'analisi dei tassi di sollevamento quaternari di questa struttura e la presenza di depositi tardo-pleistocenici e olocenici piegati e fagliati in siti contermini (Ciliverghe e Monte Netto) dimostrano che la significativa sismicità caratterizzante l'area (illustrata, ad esempio, dal terremoto del 25 dicembre 1222, Io = IX MCS; Magri & Molin, 1986; Guidoboni, 1986) deve essere posta in relazione alle strutture compressive presenti nella fascia pedemontana bresciana. Qualora l'assetto sismotettonico rappresentato dalla struttura di Castenedolo possa essere considerato comune all'intero fronte strutturale Sudalpino Lombardo, come sembrano suggerire sia l'analisi della sismica a riflessione che diverse evidenze di carattere morfostrutturale, il livello di sismicità di quest'area potrebbe risultare in realtà significativamente diverso da quello – assai modesto – che viene generalmente delineato in letteratura.

Termini chiave: *Tettonica attiva, Sudalpino, pieghe per propagazione di faglia, faglie capaci.*

1. INTRODUCTION

Seismic hazard assessment is a challenging process that makes use of an interdisciplinary approach, including data and techniques belonging to diverse research fields. Among these, paleoseismological analyses are of particular value in areas characterized by moderate to low tectonic activity, where the identification of capable faults (*sensu* Azzaro, 1998; IAEA, 2002; i.e., a fault showing potential for displacement and/or deformation at or near the ground surface) and folds (in the following, we use this term to indicate a fold that is capable of triggering tectonic displacement and/or displacement at or near the ground surface) is a key point for the definition of the local seismicity level. In these regions «characteristic» earthquakes may show, in fact, recurrence intervals longer than the time window covered by the seismic catalogue, and therefore historical and instrumental data might prove to be inadequate for evaluating seismicity (e.g., Meghraoui & Crone, 2001; Michetti & Hancock, 1997; Michetti *et alii*, 2005).

The Southern Alps margin of Lombardia, where crustal strain rates are moderate and strong seismic events infrequent, is a clear example in this line (figs. 1 and 2). Instrumental and historical seismicity of this region has been studied in depth, and earthquake catalogues can be regarded as complete in the last ca. 1000 yr. However,

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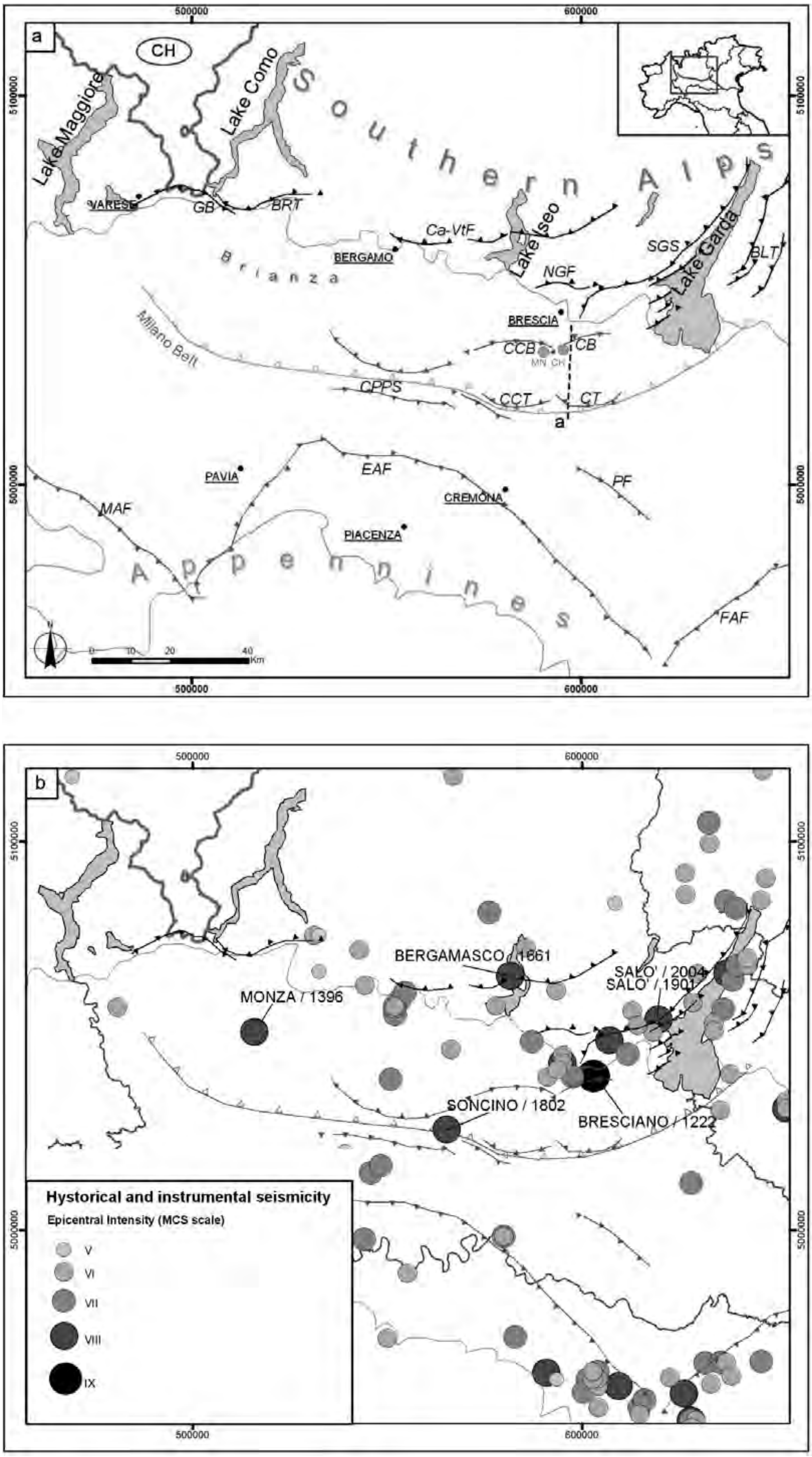

Fig 1 - a) Structural sketch of the main capable faults characterizing the piedmont front and the Po Plain. The letter «a» defines the trace of the seismic profile in fig. 4. LEGEND: BLT, Monte Baldo thrust; Ca-VtF, Corno Alto-Val Trompia Front; BRT, Monte Barro thrust; CB, Castenedolo backthrust; CCT, Capriano thrust; CCB, Capriano backthrust; CH, Castenedolo and Ciliverghe Hills; CPPS, Central Po Plain structures; CT, Castenedolo thrust; EAF, Emilian Arc front; FAF, Ferrarese Arc front; GB, Gonfolite backthrust; MAF, Monferrato Arc front; MN, Monte Netto; PF, Piadena fault; NGF, Nave-Gussago fault; SGS, South Giudicarie system. The lack of capable faults in the Brianza sector might be an artefact due to the poor resolution of local seismic reflection data. We also show the leading edge of the late Miocene South-verging thrusts, i.e. the so called Milano Belt (modified from FANTONI *et alii*, 2004), in order to mark the boundary between the Southern Alps and the Apennines; *b*) Seismicity map of the study area (modified from GUIDOBONI *et alii*, 2007). Labels indicate the most significant earthquakes that struck the study area. The epicentral location of the November 26, 1396 (Io = VIII MCS) Monza earthquake is poorly constrained. – a) *Carta schematica strutturale del fronte pedemontano e del settore settentrionale della Pianura Padana. La lettera «a» indica la traccia del profilo sismico riportato in fig. 4. LEGENDA: BLT, Sovrascorrimento del Monte Baldo; BRT, Faglia del Monte Barro; Ca-VtF, Fronte Corno Alto-Val Trompia; CB, retroscorrimento di Castenedolo; CCT, sovrascorrimento di Capriano; CCB, retroscorrimento di Capriano; CH Colline di Castenedolo e Ciliverghe; CPPS, Strutture centro padane; CT, sovrascorrimento di Castenedolo; EAF, Arco Emiliano; FAF, Arco Ferrarese; GB, Retroscorrimento della Gonfolite; MAF, Arco del Monferrato; MN Monte Netto; PF, Faglia di Piadena; NGF, Faglia di Nave-Gussago; SGS, Sistema delle Giudicarie Meridionale. La mancata individuazione di faglie capaci nel settore della Brianza è in parte da ricondursi alla bassa qualità del dato di sismica a riflessione in questo settore. «Milano belt» indica il limite esterno della fascia deformativa, di competenza alpina (modificata da FANTONI* et alii, *2004);* b) *Carta della sismicità dell'area studio (GUIDOBONI* et alii, *2007, modificato). Le etichette indicano i terremoti più significativi che hanno colpito l'area. Il sisma di Monza del 26 Novembre 1396, pur essendo di notevole entità (Io VIII MCS), necessita di ulteriori approfondimenti circa la localizzazione dell'epicentro macrosismico.*

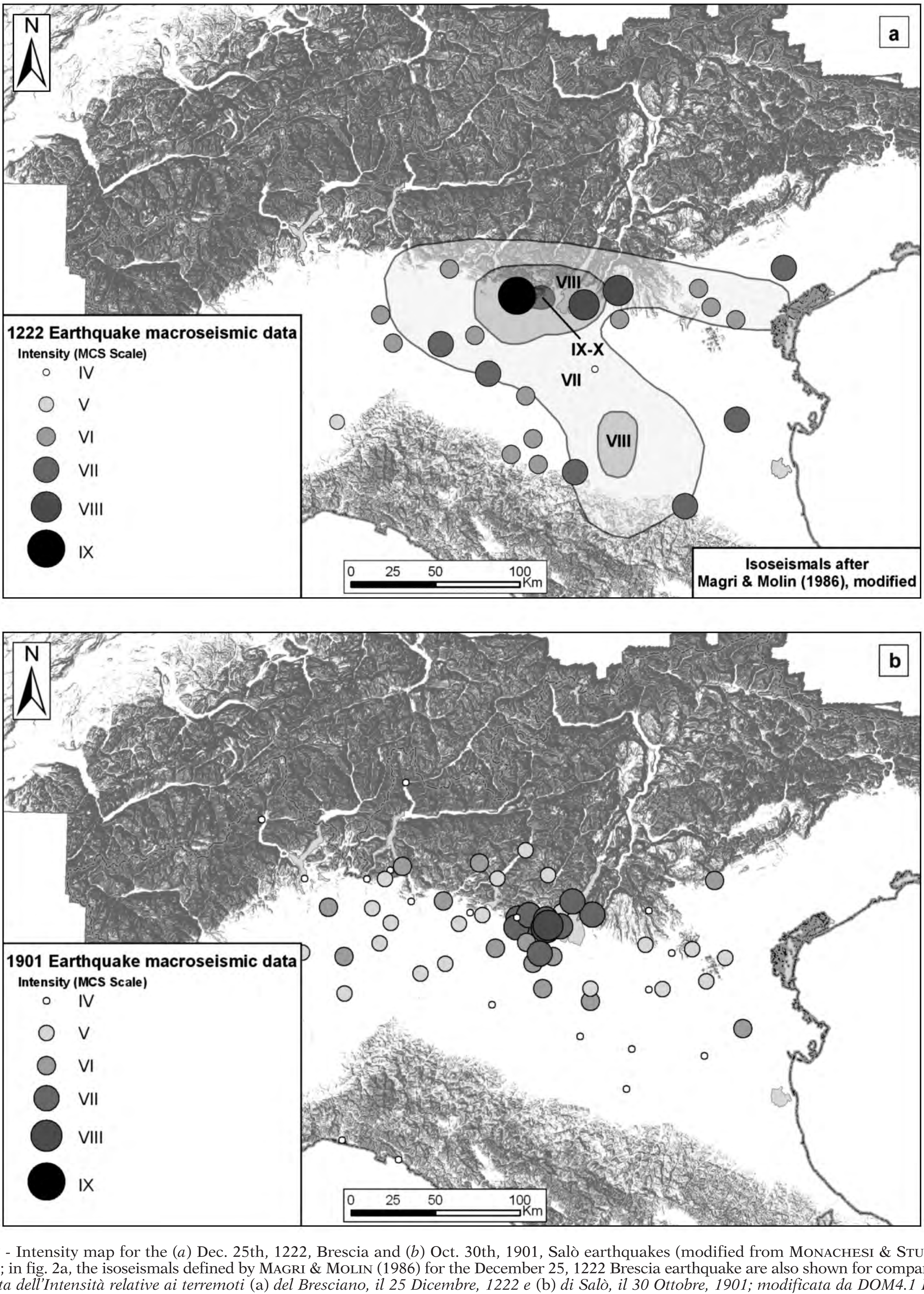

Fig. 2 - Intensity map for the (*a*) Dec. 25th, 1222, Brescia and (*b*) Oct. 30th, 1901, Salò earthquakes (modified from MONACHESI & STUCCHI, 1997); in fig. 2a, the isoseismals defined by MAGRI & MOLIN (1986) for the December 25, 1222 Brescia earthquake are also shown for comparison. – *Carta dell'Intensità relative ai terremoti* (a) *del Bresciano, il 25 Dicembre, 1222 e* (b) *di Salò, il 30 Ottobre, 1901; modificata da DOM4.1 INGV Catalogue (MONACHESI & STUCCHI, 1997); in fig. 2a sono anche mostrate, per confronto, le isosisme relative al terremoto di Brescia del 25.12.1222 così come costruite da MAGRI & MOLIN (1986).*

seismic hazard is still poorly constrained because the geological evidence of past earthquakes has not been explored yet in a systematic way. No comprehensive structural investigation of the seismogenic sources has been conducted until now, and very limited paleoseismological research has been pursued (GALADINI *et alii*, 2005).

Moderate tectonic activity, locally expressed by low slip and uplift rates, a structural style characterized by «blind» fault-related folds (e.g., LETTIS *et alii*, 1997), inducing subtle topographic deformations, and comparatively high velocity of sedimentation and erosion due to important glacial morphogenesis affecting the area during the late Quaternary; all of these factors have contributed to making it very difficult to discriminate, in this landscape, the tectonic signal related to capable faults and folds.

As a consequence, relevant seismic events in this area still lack positive association with well defined seismogenic structures. It is still unclear, for instance, which is the causative tectonic source of local damaging seismic events, such as the December 25, 1222, Io = IX MCS, Brescia earthquake (the macroseismically estimated magnitude for this event ranges from Me 6.2 to 6.5; e.g., MAGRI & MOLIN, 1986; GUIDOBONI, 1986; SERVA, 1990; GUIDOBONI & COMASTRI, 2005; fig. 2a).

In order to start filling the current gap in the knowledge of capable fault behaviour for the study region, we first model the geometry and Pleistocene growth of the Castenedolo anticline, selected as a representative example of the relations between earthquakes and tectonic sources in the Lombardia Southern Alps. Then we derive constraints for the evaluation of the slip-rates of the causative thrust beneath the anticline, and for the assessment of the related source parameters. Based on this information and the comparison with other relevant nearby sites, we argue that some tectonic structures of the Brescia area, already interpreted in the literature as active during the Quaternary (in particular by DESIO, 1965; BARONI & CREMASCHI, 1986; CURZI *et alii*, 1992), should be considered capable of producing earthquakes of the same order of magnitude as the Christmas 1222, Brescia, seismic event.

2. GEOLOGICAL AND SEISMOLOGICAL BACKGROUND

The Northern Po Plain and adjacent Southalpine margin in Lombardia accommodated significant crustal shortening during the Neogene. The deformation reached its peak during the Miocene, when the most external structural belt of the central Southern Alps (the so-called «Milano belt»; i.e., FANTONI *et alii*, 2004) began to develop (fig. 1a). The main collisional and deformative event seems to taper within the Tortonian («Lombardic Tectonic Phase»; e.g., SCHUMACHER *et alii*, 1996). Nevertheless, Plio-Pleistocene tectonic shortening went on acting in this sector of the Adria plate northern margin (CHUNGA *et alii*, 2007; SILEO *et alii*, 2007; and references therein). A compressional style of active crustal deformation is in fact consistent with the available GPS data, which indicate shortening rates, measured with a fixed point in the Western Alps, along vectors oriented NNE-SSW, in the range of 2.2 mm/yr in the Friuli area and ca. 1.1 mm/yr near Lake Iseo (e.g., SERPELLONI *et alii*, 2005), due to the ongoing counterclockwise rotation of the Adria plate.

The present-day tectonic activity is testified by the local historical and instrumental seismicity (i.e., the December 25, 1222, Io = IX MCS, Brescia; the November 26, 1396, Io = VIII MCS, Monza; the May 12, 1802, Io = VIII MCS, Soncino; the October 30, 1901, Io = VIII MCS, Salò; and the November 24, 2004, Ml 5.4, Io = VIII MCS, Salò, earthquakes; fig. 1b; GUIDOBONI, 2002; BURRATO *et alii*, 2003; GUIDOBONI & COMASTRI, 2005). In particular, the focal mechanism for the November 24, 2004, Salò earthquake (e.g., BAER *et alii*, 2005; MICHETTI *et alii*, 2005; PESSINA *et alii*, 2006) shows a compressional solution. This recent seismic event has recalled the not negligible level of seismic hazard of the study region, and has demonstrated how even a relatively moderate seismic event could cause today considerable damage in a highly vulnerable and densely populated anthropic environment like the one corresponding to the Brescia metropolitan area and its province. It is also noteworthy that the November 24, 2004, Salò earthquake displays epicentral location and a macroseismic field strongly consistent with another earthquake that struck this area at the beginning of the last century: the October 30, 1901, Salò earthquake (Io VIII MCS).

It is important to remark, however, that historical data in Eastern Lombardia keep track of earthquakes much stronger than those linked to the Salò seismogenic source. For instance, the already mentioned December 25, 1222, event (fig. 2a) is unquestionably an earthquake at least one order of magnitude larger (Io = IX MCS; Me in the range 6.2-6.5), than the 1901 and the 2004 Salò events (cfr. fig. 2a and fig. 2b). Uncertainties associated with Middle Ages earthquakes, even if very well studied as in Italy (e.g. SERVA, 1990; BOSCHI *et alii*, 1995; 2000; GUIDOBONI & COMASTRI, 2005), cause a significant lack of precision concerning epicentral location. Nevertheless, the recent critical review of several contemporary accounts (GUIDOBONI, 2002; GUIDOBONI & COMASTRI, 2005; fig. 2a) definitely confirms that the macroseismic epicentre of the 1222 earthquake lies within the southern sector of the Brescia diocese of the time, corresponding to the present-day piedmont belt of Brescia and adjoining Po Plain.

Notwithstanding the very well defined historical evidence for ancient destructive earthquakes, a clear knowledge and characterization of the capable tectonic structures in the area is, as already stated, still lacking. This surely increases the uncertainties related to the study of the macroseismic field of these strong and ancient earthquakes, and the proper identification of their causative faults.

3. SEISMOGENIC STRUCTURES IN THE BRESCIA AREA

As a matter of fact, geological, geomorphological and geophysical evidence of Pleistocene active tectonics between Lake Garda and Lake Iseo exists, and has been already underlined by several Authors. BERRUTI (1982) indicated, based on careful analyses of borehole stratigraphic logs, a probable Quaternary activity of a compressive tectonic structure (Nave-Gussago Fault) crossing E-W the lower Trompia Valley. The Nave-Gussago Fault cuts through an alluvial fan (just north of the village of Bovezzo), and apparently displaces recent terraces with several meters of vertical offset. In the adjoining pied-

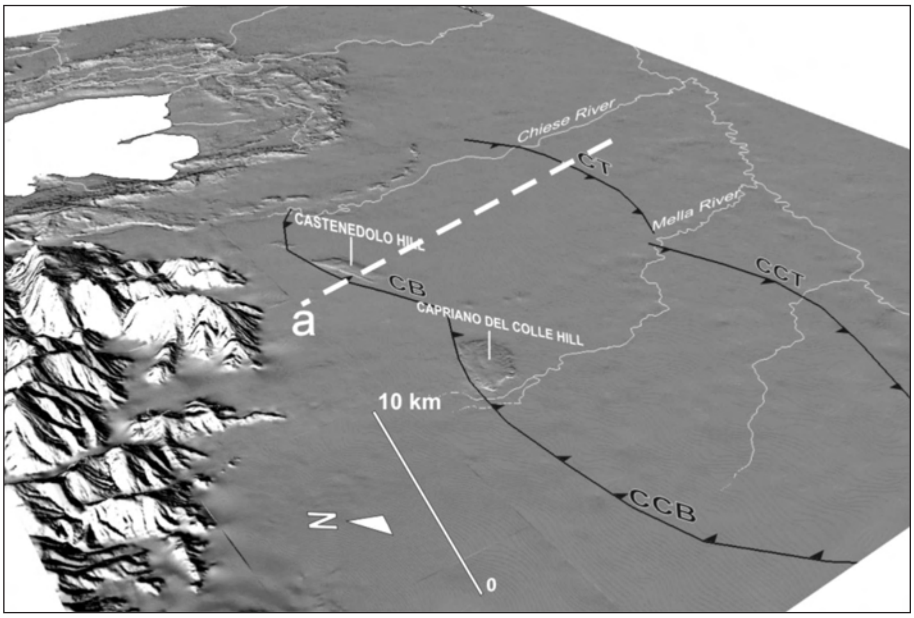

Fig. 3 - Digital Elevation Model of Castenedolo and Capriano del Colle Hills area. LEGEND: CB, Castenedolo backthrust; CCB, Capriano del Colle backthrust; CCT, Capriano del Colle thrust; CT, Castenedolo thrust. The dashed white line defines the trace of the seismic profile in fig. 4. – *Modello Digitale del Terreno dell'area occupata dai rilievi di Castenedolo e di Capriano del Colle. LEGENDA: CB, Retroscorrimento di Castenedolo; CCB, Retroscorrimento di Capriano del Colle; CCT, Sovrascorrimento di Capriano del Colle; CT, Sovrascorrimento di Castenedolo. La linea bianca tratteggiata indica il tracciato della linea sismica rappresentata in fig. 4.*

mont belt, DESIO (1965) already pointed out the occurrence of some isolated hills (Castenedolo, Ciliverghe and Monte Netto hills) whose presence cannot be explained by glacial or fluvioglacial morphogenic processes (fig. 3). These hills were in fact interpreted as the culmination of growing anticlines associated to underlying thrusts (DESIO, 1965; BONI & PELOSO, 1982; BARONI & CREMASCHI, 1986; CASTALDINI & PANIZZA, 1991; CURZI *et alii*, 1992, CARCANO & PICCIN, 2002).

Starting from this state of knowledge, we conducted a systematic revision of the available data, new field mapping, and new study of the data obtained by ENI E&P for oil exploration. In particular, the high quality ENI E&P data available in the Castenedolo area allowed us to conduct a detailed structural analysis of the blind south-vergent thrust («CT» in fig. 3 and 4), and of the linked secondary backthrust («CB» in fig. 3 and 4) whose culmination is represented by the Castenedolo Hill. Both these structures show evidence for Quaternary activity, based on their syn-growth sedimentary record (fig. 4 and fig. 5). Since the Castenedolo area is located within the epicentral area of the December 25, 1222, seismic event, we focused our investigation on the seismic reflection profile imaging the CT and CB structures, and the associated fault related folds. In the following section, we conduct uplift rate calculations as a first proxy for fault slip rate quantifications.

4. FOLD UPLIFT RATES CALCULATIONS

1. METHODOLOGY

In order to detail the Quaternary development of the Castenedolo fault-related folds, we made use of the syntectonic sedimentary record associated with each structure. In particular, we revised the mapping of four stratigraphic sequence boundary surfaces (dated at ca. 1.6 Ma, 1.2 Ma, 0.89 Ma, and 0.45 Ma), belonging to the Quaternary infilling of the Po Basin. These markers are characterized by a regional extent and by good stratigraphic and age constraints (CARCANO & PICCIN, 2002; MUTTONI *et alii*, 2003).

If sedimentation takes place during the growth of a fold, cumulative displacement will decrease upward within the stratigraphic interval deposited during deformation. In contractional fault related folds, these syntectonic strata typically thin across fold limbs towards structural highs.

The crestal structural relief (see MCCLAY, 1992 for the structural terminology adopted here) at a specific time T has been obtained by subtracting the thickness of all the growth beds deposited on the anticline crest prior to time T from the thickness of the same growth beds in the basin adjacent to the anticline. Uplift rates have then been calculated as the difference between the structural relief relative to the top and to the bottom of a specific growth bed (SUPPE *et alii*, 1992; MASAFERRO *et alii*, 2002).

The geometries of growth structures are primarily controlled by the geometry of the underlying fault and by the relative rates of sedimentation and uplift (SUPPE *et alii*, 1992). Variations in the ratio between sedimentation and uplift rates, can either enhance or mask the thinning of the strata, and therefore have to be carefully considered.

2. CASTENEDOLO FOLD UPLIFT RATES

We applied this approach to evaluate Pleistocene uplift rates of the fold located just South of Castenedolo Hill and related to a south vergent thrust (CT in fig. 4). We selected this structure because (1) the stratigraphic and structural features of the growth strata are well imaged, and (2) the seismic line shows a complete section of the growth strata, from the oldest beds preserved over the pre-growth units to the youngest beds near the topographic surface. As already stated, this fold is related to the growth of an underling Miocene thrust which has experienced a successive Pleistocene reactivation.

The Pleistocene syndepositional growth history of this anticline can be divided into three tectono-sedimentary episodes (fig. 5) based on the fold uplift rates, sedi-

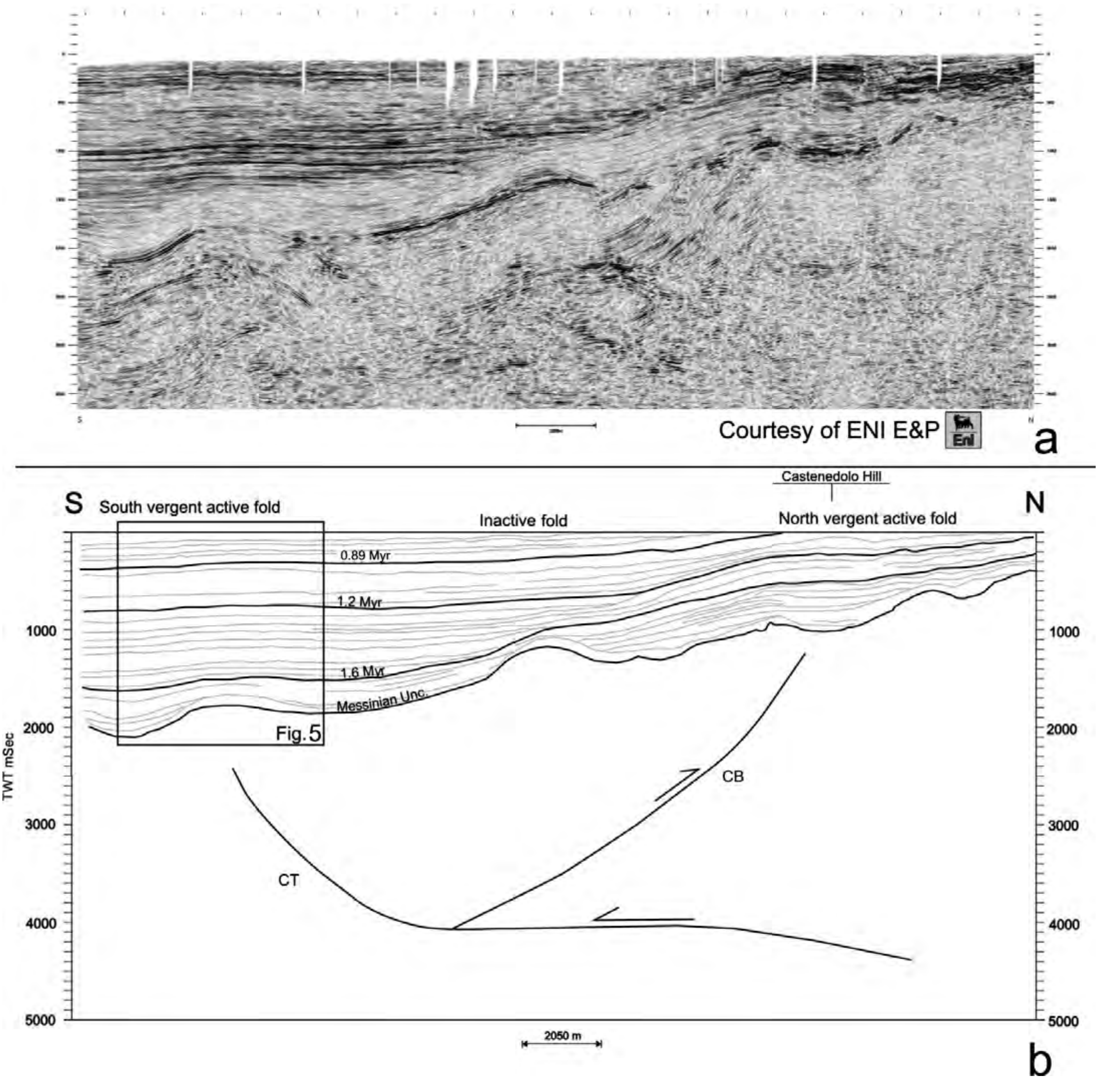

Fig. 4 - Seismic reflection data and structural interpretation along a profile passing through the Castenedolo structures (see fig. 1 or fig. 3 for location). CT: Castenedolo Thrust; CB: Castenedolo backthrust.
– Profilo sismico a riflessione ed interpretazione di una sezione passante per la struttura di Castenedolo (per la traccia del profilo v. fig. 1 o fig. 3). CT: Sovrascorrimento di Castenedolo; CB: Retroscorrimento di Castenedolo.

mentation rates and onlap/overlap geometry of the growth strata.

(1) The first episode ranges between ca. 1.6 Ma and ca. 1.2 Ma. Growth beds onlapping the fold limb and thinning as they approach the fold limb predominated during this period; the relative uplift rate is ca. 0.13 mm/yr. Sedimentary environment was characterized by a relative deep marine setting and *in situ* sedimentation rate was ca. 1.49 mm/yr.

(2) The second episode initiated ca. 1.2 Ma, and lasted until ca. 0.89 Ma. The maximum sedimentation rate recorded during fold amplification (ca. 2.43 mm/yr) was attained in this period, under a shallow marine setting. Within this time span no tectonic uplift occurred, as testified by the large number of overlapping, constant thickness, syntectonic beds.

(3) The inception of the last episode is at ca. 0.89 Ma. Sedimentation rates were very low during this event (0.3 mm/yr) because of the final establishment of continental environmental setting in the area. Thinning of growth strata is again predominant (uplift rate ca. 0.1 mm/yr).

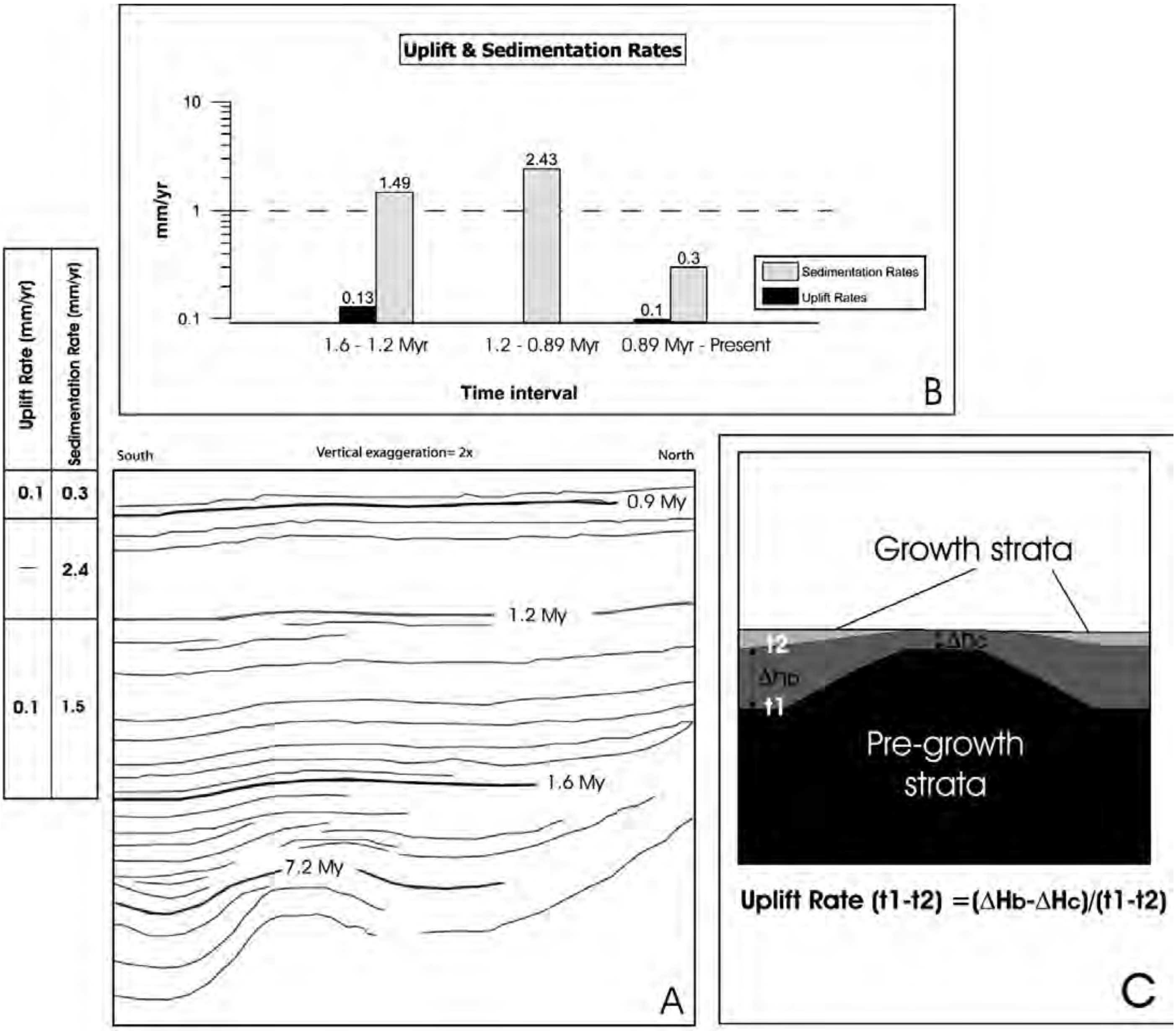

Fig. 5 - Detail of the interpretation of the seismic line in fig. 4 showing (*a*) the interpreted stratigraphic horizons (*b*) the calculated uplift and sedimentation rates relative to each chronological interval, and (*c*) the adopted methodological approach.
– *Dettaglio dell'interpretazione del profilo sismico in fig. 4 con l'indicazione degli orizzonti interpretati* (a) (b) *i tassi di sollevamento e di accumulo relativi ad ogni intervallo cronologico considerato e* (c) *l'approccio metodologico di calcolo utilizzato.*

5. DISCUSSION AND CONCLUSIONS

Uplift rates calculated and discussed above for the Castenedolo structure have highlighted that the evolution of this anticline was a discontinuous process characterized by several tectonic uplift pulses of different duration and intensity, separated by periods of variable extent in which no fold growth occurred. The Middle Pleistocene to present uplift rate is in good agreement with the one proposed by Scardia *et alii* (2006) for a nearby drilling site, based on magnetostratigraphic analyses. The Pleistocene growth history of this anticline and the comparison with other adjacent structures illustrate the style of the recent and ongoing compressional tectonic activity along the central Southalpine front. The calculated uplift rates can be used to geometrically estimate minimum slip rates and therefore to evaluate the source parameters of the local tectonic structures responsible for damaging earthquakes.

Assuming that the fault length mapped in fig. 3 for the CB is a reasonable estimate of the «characteristic» coseismic rupture length, we can derive the maximum potential earthquake associated to the Castenedolo structure by means of the empirical relations described in Wells & Coppersmith (1994). These give us a value of Ms 6.0-6.3. Such a value is consistent with the calculated uplift rate for the Castenedolo anticline (taken here as a minimum value for the CB slip rate), and the available information on historical seismicity for the study area. To illustrate this point, we compare the Castenedolo source parameters with typical relations between slip rates, magnitude, recurrence interval and geomorphic expression of faults, as derived from an extensive worldwide database

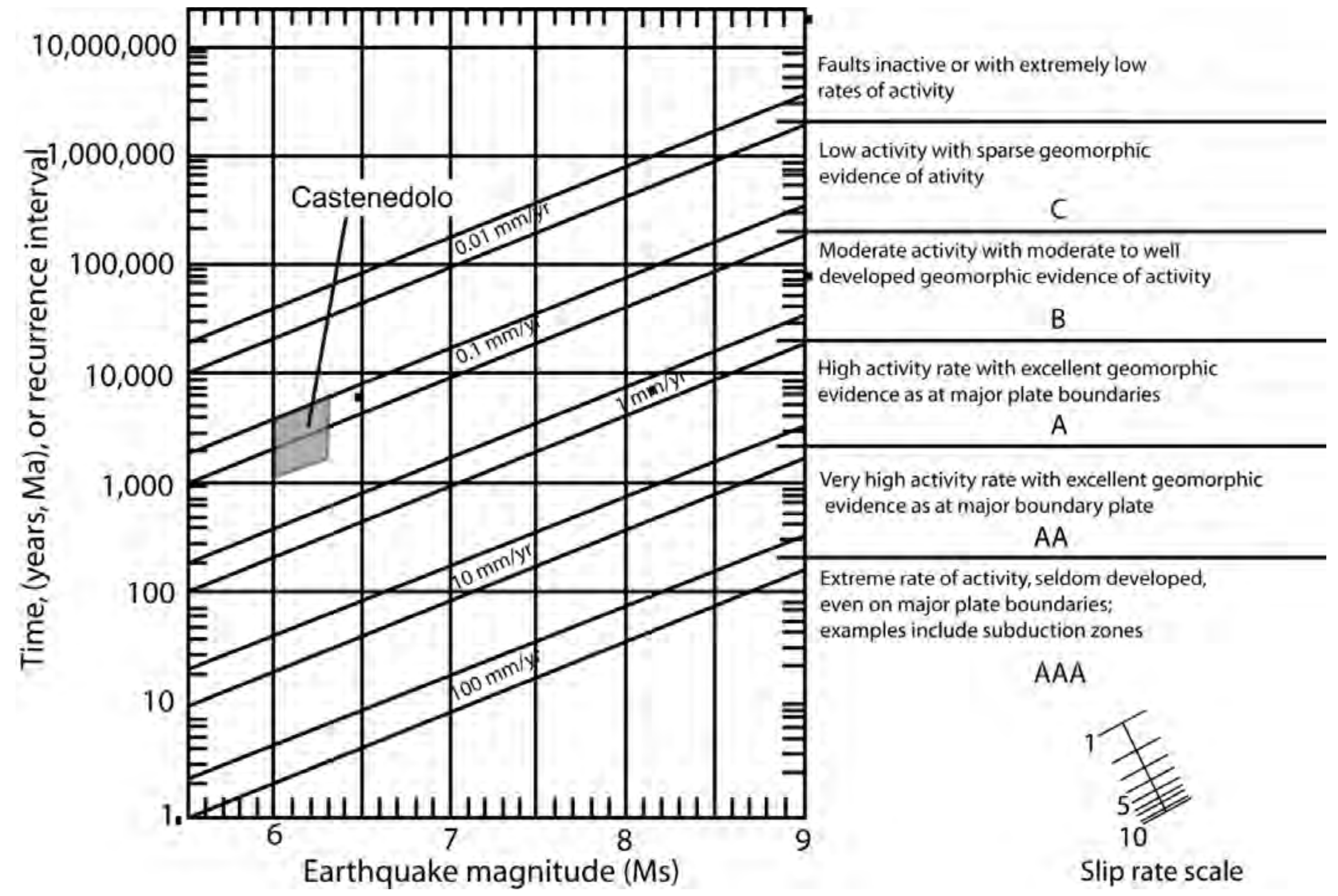

Fig. 6 - Diagram illustrating empirical relationships between earthquake Ms, seismogenic structure slip rate and typical earthquake recurrence intervals (modified from Slemmons & de Polo, 1986). A preliminary assessment of the fault parameters of a structure similar to the Castenedolo one, and consistent with the local seismotectonic framework, have been plotted (highlighted area), entering the uplift rates calculated in fig. 5 and the maximum expected earthquake Ms estimated from the rupture length mapped in fig. 1 through the empirical relations of Wells & Coppersmith (1994).

– *Diagramma rappresentante le relazioni empiriche tra Ms, fagliazione superficiale cosismica per evento e tempi di ritorno tipici (da Slemmons & de Polo, 1986, modificata). I parametri di strutture sismogenetiche simili a quella di Castenedolo (rappresentati dall'area evidenziata) e caratterizzanti questo contesto sismotettonico, sono stati calcolati a partire dai tassi di sollevamento e dalla massima Magnitudo attesa (Ms) stimata a partire dalla lunghezza di rottura della faglia, secondo Wells & Coppersmith, 1994.*

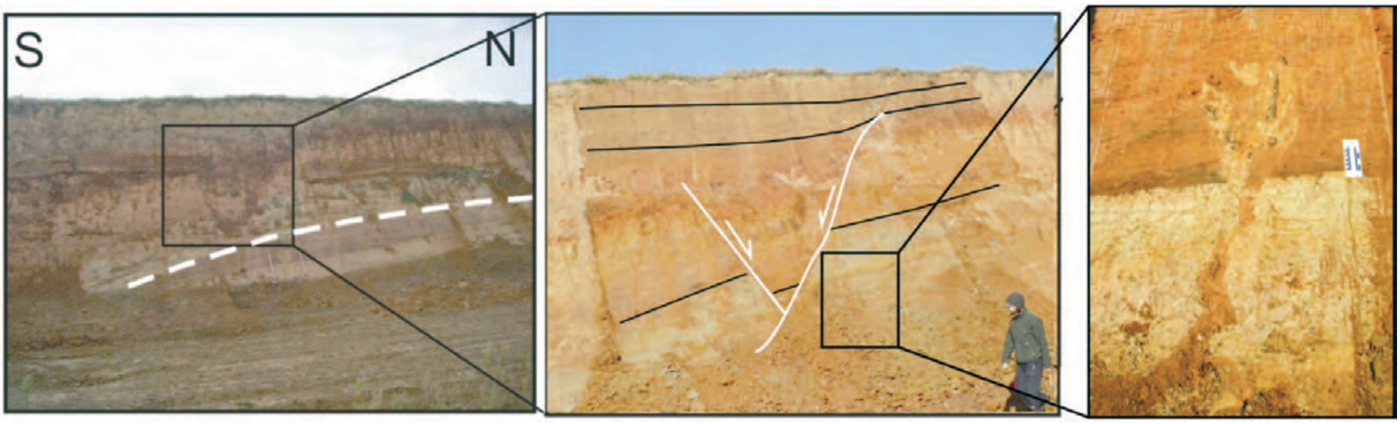

Fig. 7 - Secondary capable faults/folds affecting a Late Quaternary sequence just south of Brescia (e.g., Berlusconi *et alii*, 2007): *a*) the sequence gently folded in an anticline; *b*) bending-moment faults affecting the anticline crest up to the topographic surface, and *c*) a paleoliquefaction sand and gravel dike cutting through silt strata.

– *Pieghe e faglie secondarie capaci interessanti una sequenza del Pleistocene Medio-Superiore situata poco a Sud di Brescia (e.g., Berlusconi* et alii, *2007):* a) *assetto a blanda anticlinale della sequenza;* b) *deformazioni fragili del tipo bending-moment faults sviluppatasi sulla cresta dell'anticlinale e* c) *paleo-liquefazione costituita da un dicco di sabbie grossolane e ghiaie espulse verso l'alto all'interno di limi sabbiosi.*

(Slemmons & De Polo, 1987; Michetti *et alii*, 2005), and summarized in fig. 6.

The Castenedolo structure, moving at a slip rate of ca. 0.1 mm/yr and capable of producing a maximum magnitude in the order of ca. Ms = 6.0-6.3, should be characterized by long recurrence intervals (greater than 1000 yr). Seismic events such as the December 25, 1222, earthquake might be therefore considered as «characteristic earthquakes» of Castenedolo-like structures.

These observations allow us to define the parameters of a consistent seismic landscape (*sensu* Michetti *et alii*, 2005) relative to the Southern Alps of Lombardia. The footprints of recent tectonic activity, expressed through recurrent coseismic movements on capable faults, should therefore be recognizable in the present topography and stratigraphic record. This hypothesis has been recently confirmed by new observations of Late Pleistocene to Holocene surface faulting and coseismic paleoliquefaction features in a quarry located few km South of Brescia (fig. 7).

It is therefore evident that the available seismotectonic models and seismic hazard estimates for this region, which to a large extent are merely based on the seismicity record (e.g., Meletti *et alii*, 2000; Stucchi, 2004), should be carefully re-evaluated. A systematic structural and paleoseismological study of all the structures identified in fig. 1 has to be considered the first necessary step in this line. Research has to be aimed at the definition of source parameters based on geological evidence, including the systematic identification in the field of all the environmental effects of past earthquakes, and the assessment of the influence of active crustal shortening on the landscape and sedimentary record.

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