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Late Quaternary fault movements in the Mt. Baldo-Lessini Mts. sector of the Southalpine area (northern Italy)

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Abstract

Paleoseismological investigations have been performed at Mt. Baldo and in the Lessini Mts. in order to collect quantitative data on the activity of minor faults showing geomorphic evidence of recent activation. The 4.5-km-long, NNE-SSW trending Naole fault was responsible for the formation of a narrow depression at the top of Mt. Baldo, bordered by a continuous bedrock (carbonate) fault scarp to the west. The extensional activity along this minor fault is probably due to gravitational deformations (lateral spreading) in response to the warping of the Mt. Baldo anticline. A 1.5-km-long graben is instead related to the 2.5-km-long, NNW-SSE trending Orsara fault (Lessini Mts.) which was responsible for the formation of bedrock (carbonate) fault scarps. This minor fault is part of a complex structural framework made of few-km-long faults which show evidence of Quaternary activity. Two trenches have been excavated across the Naole fault which showed the occurrence of displacement events subsequent to 17435-16385 BP (cal. age) and probably prior to 5455-5385/5330-5295 BP (cal. age). Two other trenches have been excavated across the Orsara fault whose analysis indicated that the most recent displacement event occurred between 20630-19795 BP and 765-675 BP (cal. age). The upper chronological limits of the displacements give some indications about the minimum elapsed time since the last fault activation (about 5,300 years for the Naole fault and 5-8 centuries for the Orsara fault). Both 1) the maximum expected magnitude of the earthquakes which may originate along the Mt. Baldo thrust and 2) the identification of a main fault responsible for the displacements along the complex net of minor faults affecting the Lessini Mts. are still open questions. As for point 1 although historical earthquakes with magnitude 4.5-5 may be associated with the Mt. Baldo thrust, the investigations carried out in this area did not clarify whether larger magnitude earthquakes may be expected. As for point 2, the cause of the displacements along the Orsara (Lessini Mts.) fault may be related to the activity of a major blind fault (which, however, has never been identified), responsible for the uplift of the Lessini Mts. More generally, the obtained results demonstrate the limits of traditional paleoseismological analyses in Alpine areas whose erosional/depositional activity has been strongly conditioned by the Late Pleistocene glacial history. The lack of units younger than loess and colluvial sediments related to the Last Glacial Maximum makes it impossible to define narrower chronological constraints for the displacements and to estimate the number and size of the displacement events. Moreover, the rebound following the retreat of the thick glacial cover affecting the Alpine area may have induced stresses responsible for higher deformation rates after the Last Glacial Maximum. Higher surficial deformation rates could imply shorter recurrence intervals for faulting episodes and/or larger magnitude earthquakes. Therefore, paleoseismologically inferred data in Alpine areas may not correctly define the fault behaviour related to the present tectonic regime.

Keywords: active tectonics, paleoseismology, active fault, northern Italy

Introduction

Investigations into the recent tectonics of the Southalpine area began more than 20 years ago with the geomorphological analysis of bedrock fault scarps (Sauro, 1978). A great effort to collect data on Quaternary tectonics was made during the 'Progetto Finalizzato Geodinamica', sponsored by the National Research Council. Available data were summarised on the 'Neotectonic Map of Italy' (CNR-PFG, 1987) and in a number of works reporting maps of Quaternary and active faults at regional scale (e.g. Zanferrari et al., 1982; Slejko et al., 1989; Castaldini & Panizza, 1991). After this experience, however, investigations were almost interrupted for a decade and few recent publications indicate a renewed interest for this issue (e.g. Ferrarese et al., 1998; Galadini & Galli, 1999; Benedetti et al., 2000).

The result of this peculiar research history is that available data on Quaternary faulting can only be derived from investigations made more than 10 years ago.

Numerous factors render, however, the identification of Alpine faults affected by recent activity problematic. One of these factors is the strong exogenic modelling related to the Late Pleistocene glacial action and postglacial fluvial erosion. The thick glacial tongues have been responsible for the erasing of geomorphic evidence of Quaternary tectonics, while the Holocene river erosion rates (Late Pleistocene river terraces may be tens of metres suspended over the present valley bottoms) are larger than the documented slip rates of active faults (generally lower than 1 mm/yr, according to Castaldini & Panizza, 1991).

Other problems are related to the deformation affecting high mountainous areas. The effects of gravitational stresses are, indeed, well documented in the Alpine chain and many observed Holocene deformations are reported as deep-seated gravitational movements, although differently interpreted in terms of indirect causes (tectonic uplift, fault activity, postglacial slope decompression, valley overdeepening; Forcella & Orombelli, 1984; Cavallin et al., 1987; Mortara & Sorzana, 1987; Forcella & Sauro, 1988; Reitner et al., 1993; Giardino, 1996; Giardino & Polino, 1997; Sébrier et al., 1997; Forcella & Tibaldi, 1998). Gravitational movements along shear planes produce forms which are similar to those related to fault activity. Moreover, they sometimes occur along pre-existing faults, generating misleading evidence of recent tectonics.

The effects of the post-glacial rebound on the activation of Italian Alpine faults has been marginally addressed (e.g. Forcella & Tibaldi, 1998), and although there is worldwide increasing evidence of the major role played by the glaciation-deglaciation cycles on the fault activity (Stewart et al., 2000 and references therein), nothing is known about this issue in the Italian Alpine sectors.

Finally, the central-eastern Southalpine sector (in which the investigated areas are located) has been and is affected by a compressive regime (Doglioni & Bosellini, 1987; Slejko et al., 1989; Castellarin et al., 1992; Bressan et al., 1998; Caporali & Martin, 2000). As a result of this regime, folds and thrust faults have developed since the Cenozoic. However, the main active structures are usually blind thrusts and surficial geological investigations have provided data on the recent deformation only in few cases (Ferrarese et al., 1998; Aoudia et al., 2000; Benedetti et al., 2000).

Due to all these problems (not completely addressed in the 80s), new investigations into the characteristics of the Alpine active tectonics are necessary. In this light, the Mt. Baldo-Lessini Mts. sector (located east of Lake Garda, in the Verona province) may represent a test area to check previous hypotheses, since evidence of recent fault activity has already been reported in the literature (Sauro, 1978; Forcella & Sauro, 1988; Cavallin et al., 1988a and 1988b).

Previous hypotheses on the recent fault activity were, however, not supported by modern paleoseismological investigations. Therefore paleoseismological analyses have been performed in the Mt. Baldo-Lessini Mts. sector by trenching along bedrock fault scarps whose formation has been related (by the above mentioned authors) to recent fault activity, in order to collect chronological data on the displacements. Results of these analyses will be presented together with a discussion about the causes of the observed deformations.

Neotectonic and active tectonic framework

The building of the Alpine chain is due to the Africa-Europe convergence (Dewey et al., 1973; Castellarin, 1981; Laubscher & Bernoulli, 1982; CNR-PFG, 1983; Doglioni & Bosellini, 1987; Polino et al., 1990), which is manifest in a structural evolution involving the activity of thrust faults since the Miocene (Doglioni & Bosellini, 1987; Castellarin et al., 1992). Significant uplift has been documented to have occurred since the Pliocene (Zanferrari et al., 1982).

The area between Lake Garda and the Lessini Mts. is affected by faults related to two different structural domains (Fig. 1). Mainly NNE-SSW trending thrusts and transpressional structures (Giudicarie fault system) can be recognised in the western portion, while structures related to the left-lateral transcurrent Schio-Vicenza fault (NW-SE trending) affect the easternmost portion.

The present Alpine landscape has also been strongly conditioned by geomorphic processes related to the Quaternary glaciations (e.g. Carton & Soldati, 1992; Petrucci & Cavazzini, 1992). Evidence of the erosional/depositional effects of ice sheets developed at the Last Glacial Maximum is widespread in all the Alpine valleys, where deposits and landforms are generally not older than the upper Late Pleistocene.

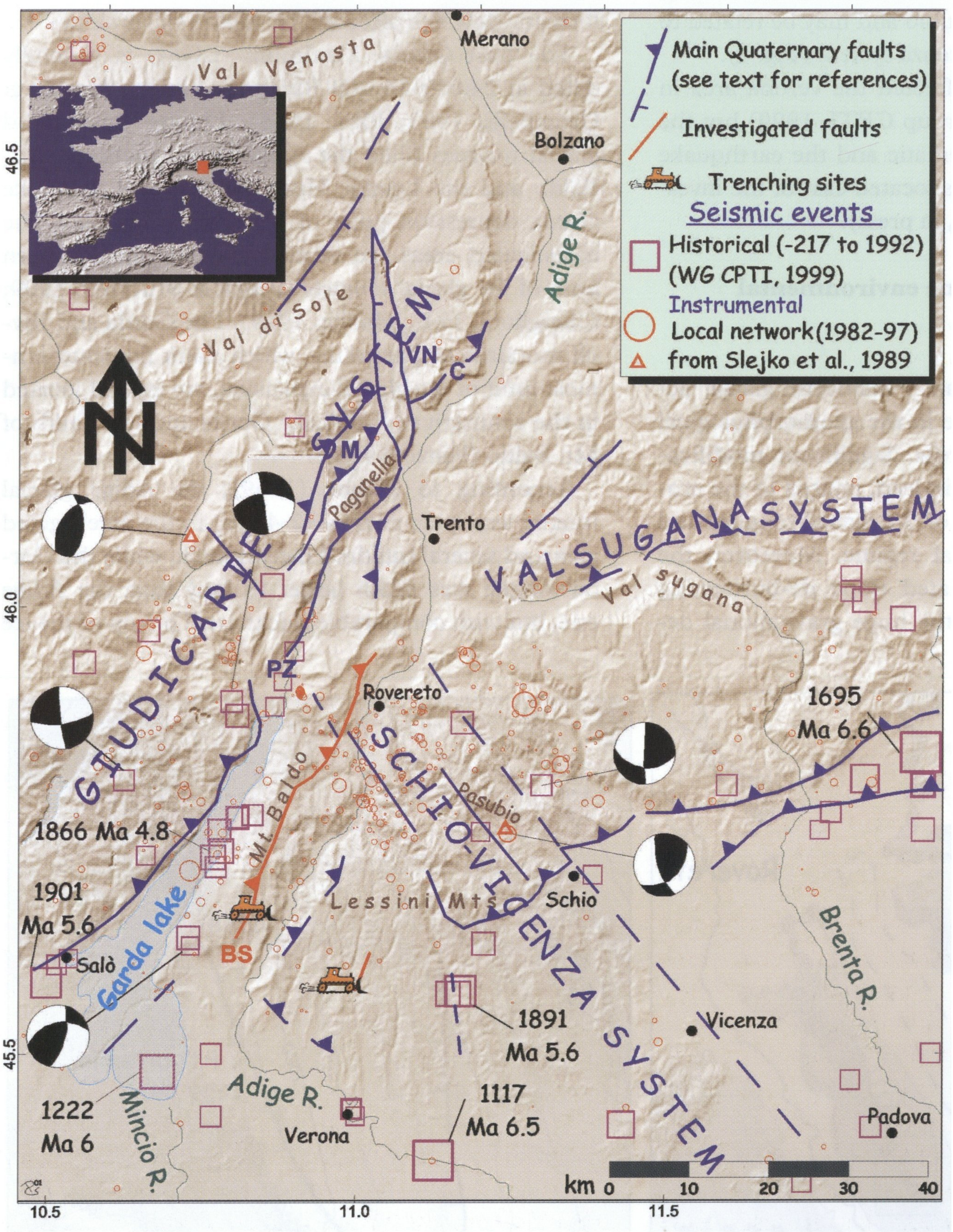

Fig. 1. Seismotectonic framework of the central Southalpine area. The main structures defined in the literature as being active during the Quaternary are reported, together with the seismic events which affected the region. Historical earthquakes (epicenters macroseismically determined) are taken from Working Group CPTI (1999); events of the 1982-1997 period are taken from instrumental recordings of the Trentino-Alto Adige seismic network of the Provincia Autonoma di Trento. The epicentre of the 1117 earthquake has been reported on the basis of the epicentre location proposed by Magri & Molin (1986), which is more consistent with the data reported in Galadini et al. (in press). Focal mechanisms are taken from Slejko et al. (1989). The dates of the most relevant earthquakes are also reported. Capital letters indicate specific fault names: C, Cortaccia thrust; VN, Val di Non structures; M, Molveno thrust; PZ, Paganella-Zambana thrust; BS, Mt. Baldo-Mt. Stivo thrust.

Evidence of Quaternary activity along faults affecting the area between Lake Garda and the Lessini Mts. has been reported mainly on the basis of geomorphological data (Sauro, 1978; Sauro & Meneghel, 1980; Zanferrari et al., 1982; Baroni, 1985; Carton & Castaldini, 1987; Cavallin et al., 1988a and 1988b; Castaldini & Panizza, 1991). The freshness of bedrock fault scarps and the presence of long escarpments along the major tectonic structures have been used to identify recent faults. The high density of landslides, in particular along the structures related to the Giudicarie system (Fig. 1), has also been reported as an evidence of recent tectonic activity (Cavallin et al., 1988c).

Evidence of recent activity is most convincing in the Lake Garda area, where the displacement of Late Pleistocene-Holocene deposits and landforms has been documented (Baroni, 1985; Carton & Castaldini, 1987; Castaldini et al., 1988; Castellaccio & Zorzin, 1996). Further evidence can be found in the Mt. Baldo and the Lessini Mts. sector of the Southalpine chain (see below).

A low-to-moderate seismicity affects the Mt. Baldo-Lessini Mts. sector (Fig. 1) and a few seismic events have occurred in the past with M≤5.0 (e.g. Working Group CPTI, 1999). The few historical earthquakes (derived from Working Group CPTI, 1999) and the instrumental seismicity (derived from the local network of the Trento Province) indicate a NNE-SSW alignment of epicentres in the western portion of the area, consistent with the Giudicarie system (Fig. 1). Low-magnitude events are clustered in the Lessini Mts.-Mt. Pasubio and may be related to the activity of the Schio-Vicenza system (Fig. 1).

A stronger earthquake affected the Verona area in 1117 (Me=6.5; Working Group CPTI, 1999) but the epicentre location is problematic and the earthquake may be related to structures located east of the investigated area (Galadini et al., in press).

Late Pleistocene-Holocene environmental history

As previously reported, Late Pleistocene glacial action has had a primary role in the geomorphological evolution of the Alpine areas. Significant modifications to the landscape are, indeed, related to the erosional/depositional activity of the glacial tongues and the subsequent fluvioglacial regime. Moreover, the glacial retreat and the related slope de-buttressing have been responsible for the huge gravitational deformations which affected the Alpine valley slopes.

The Last Glacial Maximum (LGM) is generally dated at 24,000-16,000 BP in the eastern Alps (e.g. Orombelli, 1983; Fliri, 1988). During this period glacial tongues filled the Adige Valley (between Mt. Baldo and the Lessini Mts., Fig. 2a) and the Lake Garda depression (west of Mt. Baldo, Fig. 2a). The investigated areas are located close to the southern limit of the glacial tongues (Penck & Brückner, 1909; Castiglioni, 1940; Habbe, 1969). The Garda and Rivoli morainic amphiteatres, which mark the southernmost limit of the glacial expansion, are indeed located in the southern part of Lake Garda and just south of Mt. Baldo (Venzo, 1961).

According to Habbe (1969), the Adige glacial tongue was quite narrow (2-4 km) in the investigated area and several hundred metres thick, while the Garda tongue was much larger (8 km) than the Adige one, but with comparable thickness. The top of the ice

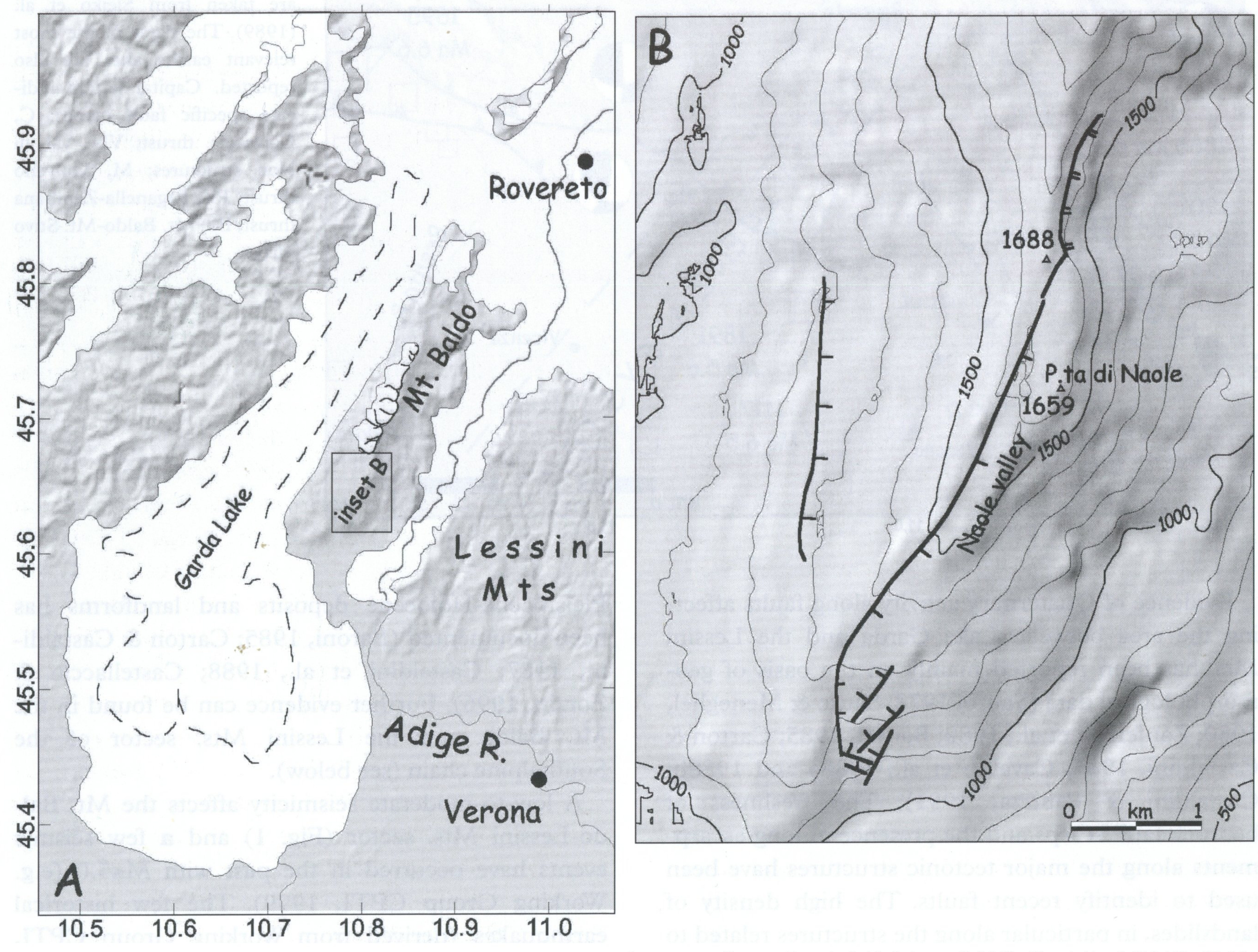

Fig. 2. a) Glaciers in the Lake Garda-Adige Valley area during the LGM, according to Penck & Brückner (1908), Castiglioni (1940), Habbe (1969); the Lessini Mts. and Mt. Baldo were not covered by the main valley glaciers; the latter was affected by minor glacial cirques at elevations of 2,000-2,200 m a.s.l.; b) detail of the Naole area (southern part of Mt. Baldo); uphill-facing scarps related to deep seated gravitational deformations are reported together with the trace of a landslide scarp (double dash) affecting the northern sector of the Naole area; the longest uphill-facing scarp borders the NNE-SSW linear trough (Naole Valley) where the paleoseimological investigations have been performed (see Fig. 4 for the trench site locations).

tongues was located at about 500 m a.s.l. west and east of Mt. Baldo. The crest of this ridge ranges between 1,500 and 2,200 m a.s.l. and therefore significant portions of the mountain slopes were not affected by the main glaciers. On the summit of Mt. Baldo some glacial cirques are, however, visible at elevations ranging between 2,000 and 2,200 m (Fig. 2a); these cirques fed minor glacial tongues draining towards Lake Garda (Habbe, 1969). Glacial action did not affect the southern part of the Mt. Baldo crest (1,500-1,600 m a.s.l.), where the Naole Valley (the narrow NNE-SSW trending depression in which paleoseismological investigations have been made, see below) is located (Fig.2b).

In contrast, the Lessini Mts. plateau was not affected by local LGM glacial tongues (Fig. 2a) and its western flank was bounded by the southern portion of the Adige glacier.

Based on the available data (Penck & Brückner, 1909; Castiglioni, 1940; Habbe, 1969), the whole landscape of the investigated area during the LGM was made of the two main glaciated valleys (Adige and Garda) from which the reliefs of Mt. Baldo and Lessini Mts. were emerging.

The environmental history of the southern sector of Mt. Baldo and of the Lessini Mts. has been outlined by Magaldi & Sauro (1982) and Sauro & Zampieri (1999a).

During the LGM, the mentioned areas were characterised by a steppe-like environment. Winds were responsible for the deposition of loess derived from the silty portion of the glacial deposits affecting the proglacial areas of the Adige Valley and Lake Garda. At the same time, erosion of the carbonate slopes was responsible for the deposition of scree in the depressions.

After the LGM, glacial tongues retreated and at about 13000 BP the ice cover was absent in significant portions (tens of kilometres) of the main glacial valleys (see Venzo, 1961, for the Garda glacier and Casadoro et al., 1976 and Bondesan, 1999, for the Piave glacier, about 100 km east of the Adige valley).

In the Lessini Mts. and the southern sector of Mt. Baldo, soils began to develop over the loess deposits related to the LGM (Magaldi & Sauro, 1982). In the Naole Valley (southern sector of Mt. Baldo) the present darkish soil (described by Magaldi & Sauro, 1982) formed over the loess deposits and has been found just below the ground surface in one of the excavated trenches (see below).

Paleoseismological investigations

Mt. Baldo- Naole Valley

Mt. Baldo is an east-verging compressive structure whose surficial expression comprises a number of thrust planes affecting Meso-Cenozoic carbonate units emerging along the western flank of the Adige river valley (Fig. 3a). Evidence of recent activity of this structure has been reported in some works (Magaldi & Sauro, 1982; Zanferrari et al., 1982; Carton & Castaldini, 1985; Forcella & Sauro, 1988) and can be summarised in the following points: 1) Pleistocene tilting of the karstic plateau affecting Mt. Baldo (Magaldi & Sauro, 1982); 2) vertical displacement of the karstic plateau between the southern and central portion of Mt. Baldo (Magaldi & Sauro, 1982); 3) recent activity along secondary faults indicating a differential growth of the structure and tilting towards west (Carton & Castaldini, 1985; Forcella & Sauro, 1988; Cavallin et al., 1988a; Castellaccio & Zorzin, 1996); 4) alignment of the Mt. Baldo structure with the active Sirmione-Garda fault, located SSW of Mt. Baldo and affecting Lake Garda (e.g. Carton & Castaldini, 1985).

Finally, a moderate seismicity (Mmax=4.8; Working Group CPTI) has been related to the activity of the southern Giudicarie system (Fig.1; Panizza et al., 1981; Slejko et al., 1989). In the eastern sector of Lake Garda, the areas damaged by historical earthquakes (1866, 1868, 1876, 1877, 1932; Monachesi & Stucchi, 1998) are located above the westward prolongation of the Mt. Baldo thrust at depth (Fig. 3). The damage affecting small areas suggests that the earthquakes originated at low depth. The damage distribution of the largest earthquake (1866, Ma=4.8 according to Working Group CPTI, 1999) is elongated in a NNE-SSW direction (Fig. 3b). All these points indicate that the reported seismicity may have been triggered by the activation of the Mt. Baldo thrust.

The summit of the Mt. Baldo southern portion is displaced by a 4.5-km-long normal fault, creating a narrow NNE-SSW trending linear trough (Naole Valley; Figs. 2, 3 and 4). Moreover, uphill-facing scarps have been detected on both the eastern and western slopes of Mt. Baldo, close to the Naole Valley (Fig. 2). Recent activity along the Naole fault has been reported in numerous works based on the presence of a fresh and continuous bedrock (carbonate) scarp (e.g. Magaldi & Sauro, 1982; Cavallin et al., 1988a; Forcella & Sauro, 1988). The formation of the scarp was previously attributed to 'gravity tectonics' affecting Mt. Baldo in response to the activation of the compressive structure (Cavallin et al., 1988a; Forcella & Sauro, 1988; Castellaccio, 1993).

In some places, the fault plane is exposed along the bedrock scarp bordering the Naole Valley (Fig. 4) and displays a low degree of karstic weathering; Forcella & Sauro (1988) hypothesised, therefore, a Holocene age for the last fault activation.

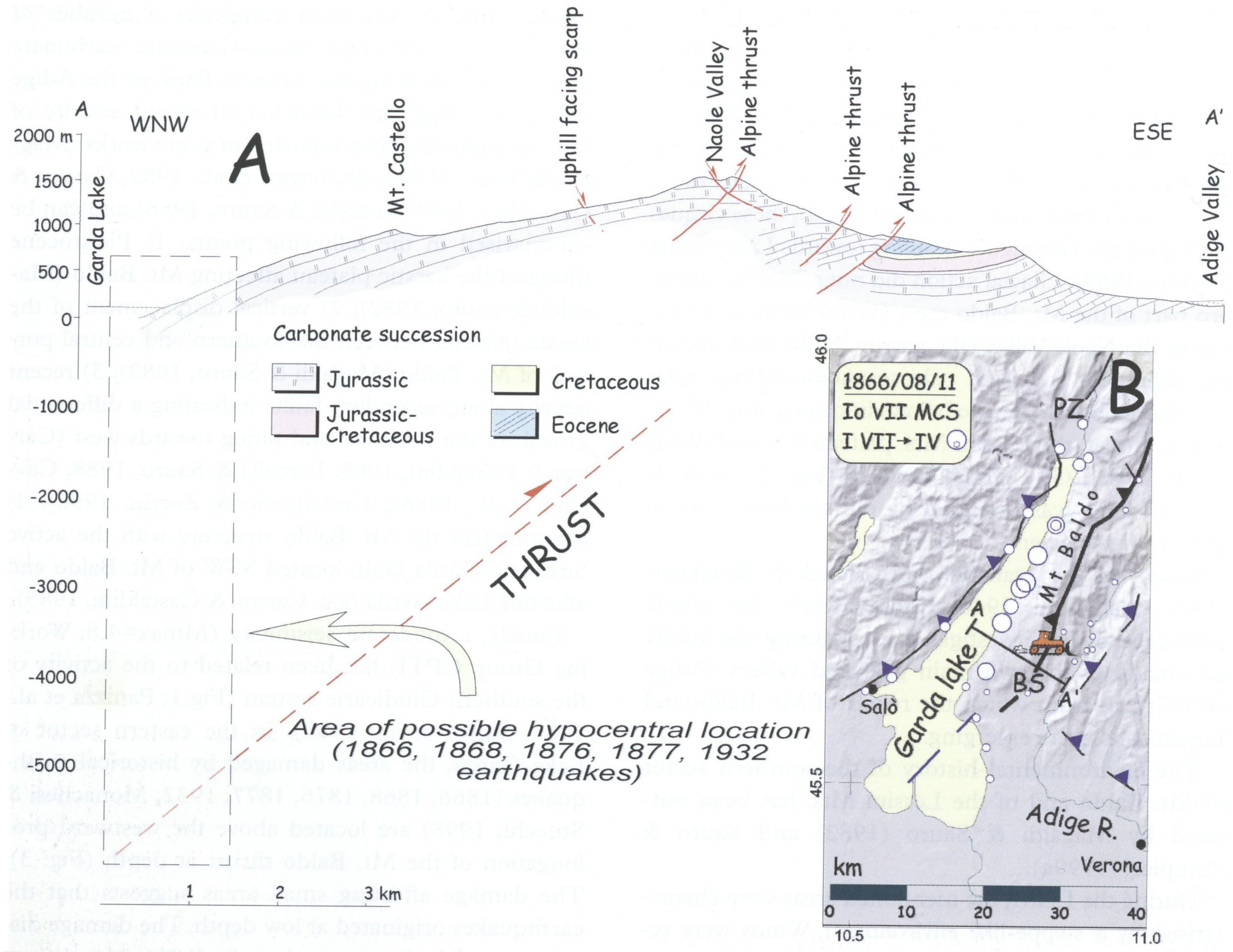

Fig. 3. a) geological cross-section of Mt. Baldo with the possible projection at depth of the main thrust plane and the area of the hypocentral locations of the 1866, 1868, 1876, 1877 and 1932 earthquakes and b) Intensity datapoints related to the 1866 earthquake (Ma=4.8, according to Working Group CPTI, 1999).

Because the scarp displays an almost constant height and the depression is closed, the origin of the scarp cannot be related to erosion and the fault activity is the most probable cause of the present morphology.

Fieldwork identified two sites for the excavation of trenches along the fault (Fig. 4). At both sites, the scarp appeared to be scarcely weathered and it was considered likely to find datable deposits.
The main fault plane (exposed in both trenches) places the carbonate bedrock in contact with slope deposits. Wind-blown deposits and a paleosol gave the possibility to obtain chronological constraints by means of radiocarbon dating (Tab. 1).

Samples for 14C have been analysed by Beta Analytic Inc. (Miami, USA); all the collected samples were suitable for accurate radiometric analysis. However, sample NAO-5 contained only about 0.3% carbon in the combusted material, while the content was higher for the other samples (e.g. about 2% for NAO-2 and NAO-6). The bulk organic carbon has been analysed after removing all carbonates or rootlets. The conventional radiocarbon ages obtained (all standard analyses) have been calibrated by Beta Analytic (if conventional ages were younger than 19000 BP) by using the INTCAL98 database reported in Stuiver et al. (1998). Ages reported in the text represent the 1 Sigma calibrated results (68% of probability).

Site 1
Faintly layered slope deposits (unit 1) made of carbonate clasts in sparse sandy matrix were exposed in the southern trench wall (Fig. 5). Pebbles are angular with average dimension ranging between 1 and 10 cm. Sparse boulders (up to 50 cm) were also detected in the lower part of the unit. The deposition of unit 1 indicates erosion of the western valley slope. According to Magaldi & Sauro (1982), these deposits resulted from gravitational transport of clasts produced by criogenic processes acting along the slope.

Layers of unit 1 are dipping (30°) towards west

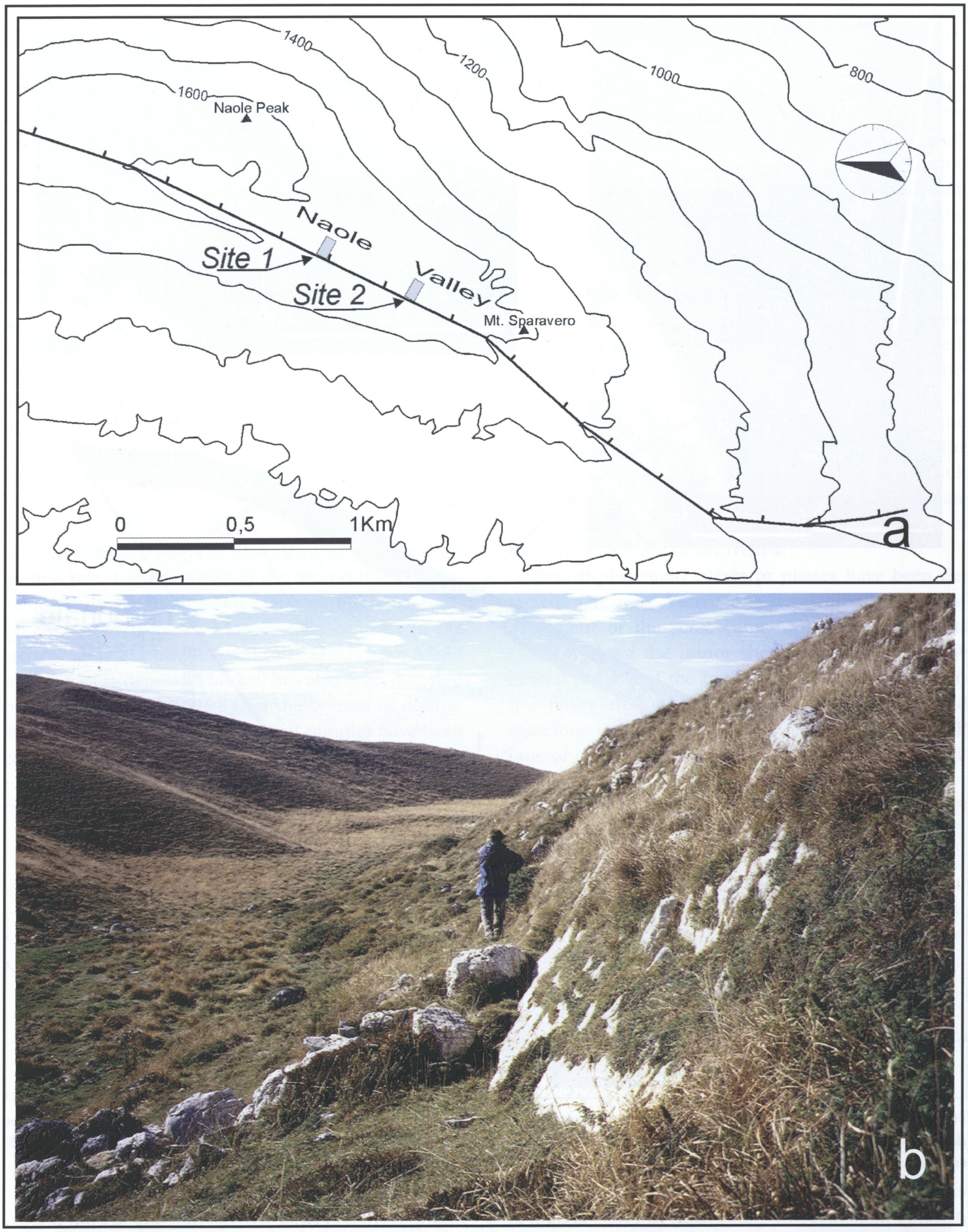

Fig. 4. a) Plan map of the Naole Valley area and trench location and b) bedrock fault scarp bordering the Naole depression at the top of Mt. Baldo.

(Fig. 5), i.e. against the slope, while the original dip may have been 20-30° towards the valley. This testifies to a significant tilt of the deposits.

Unstratified reddish-brownish clayey-silty sediments (unit 2) were exposed in the lower portion of the trench wall. A sample of silty clay was taken from

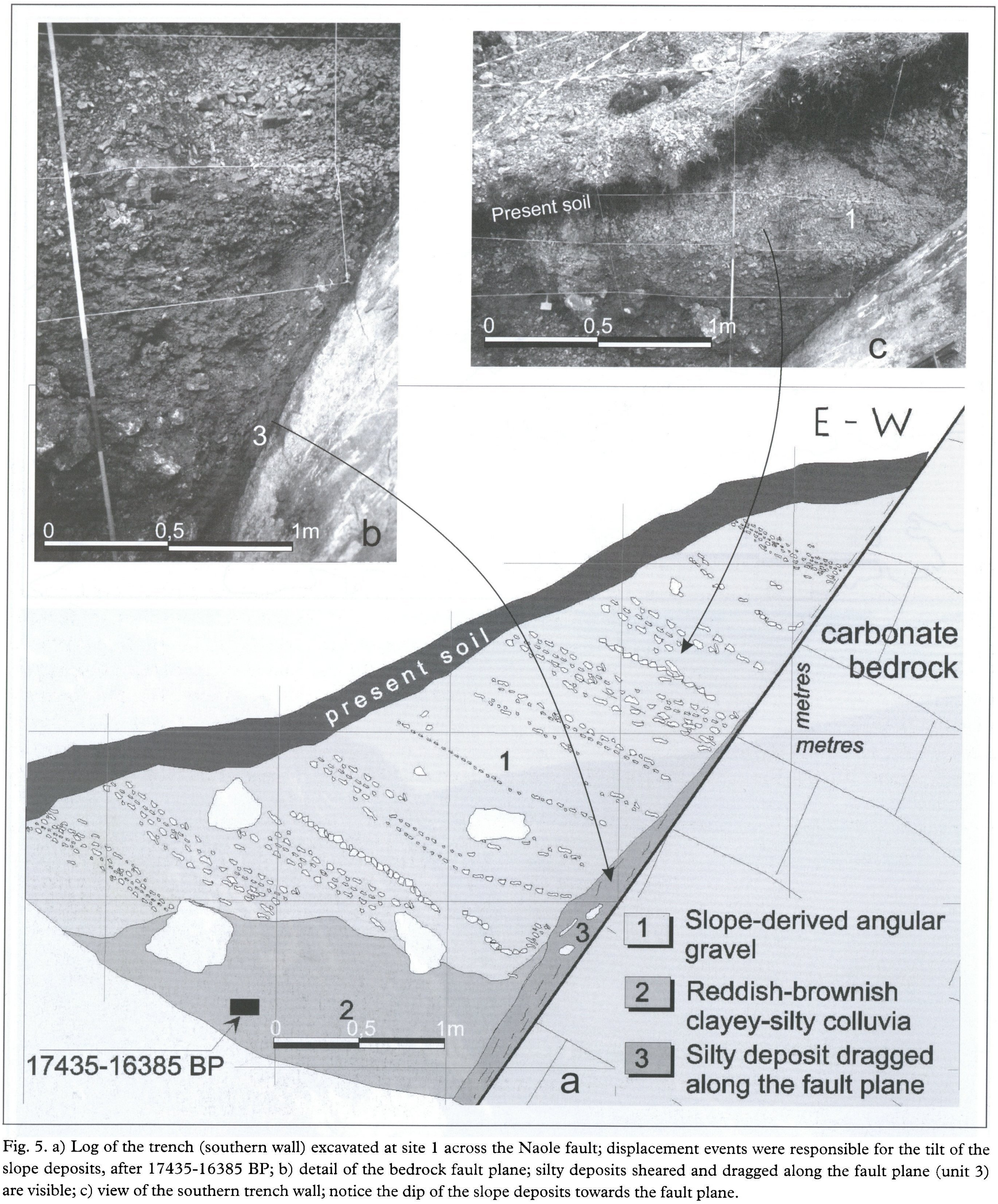

Fig. 5. a) Log of the trench (southern wall) excavated at site 1 across the Naole fault; displacement events were responsible for the tilt of the slope deposits, after 17435-16385 BP; b) detail of the bedrock fault plane; silty deposits sheared and dragged along the fault plane (unit 3) are visible; c) view of the southern trench wall; notice the dip of the slope deposits towards the fault plane.

the area indicated in Figure 5 and the bulk sediment has been radiocarbon dated at 17435-16385 BP (cal. age). Magaldi & Sauro (1982) analysed similar deposits (both for lithology and stratigraphic position) in the Mt. Baldo area and in the Lessini Mts. (Sauro, pers. com.). Based on detailed pedological analyses, Magaldi & Sauro (1982) related this unit to loess (i.e. windblown) deposits fed by the silty sediments exposed in the proglacial areas of the Garda and Adige glacial tongues. According to Magaldi & Sauro (1982), the loess accumulation phase was contemporaneous to the slope erosion indicated by the deposition of unit 1 (see also the description of site 2, below). The radiocarbon date confirms the previous conclusions of the authors who related these depositional events to the upper Late Pleistocene.

Unit 3 (Fig. 5) is a wedge of clayey-silty deposits (probably the same as unit 2) with sparse carbonate angular pebbles sheared and dragged along the bedrock fault plane.

As for the movement along the fault, tilting of the slope deposits (unit 1) testifies to at least one displacement event after 17435-16385 BP (age of unit 2). The strong amount of backtilting (50-60°) indicates a rotational sliding along a shear plane coinciding (at least at surface) with the fault plane exposed in the trench. This backtilting testifies to the occurrence of gravitational deformations whose expression (backtilting of slope deposits) is similar to other cases observed along mountain ranges affected by deep seated gravitational movements (e.g., for central Italy, Galadini et al., 1991; Bosi et al., 1993; Farabollini et al., 1995).

Site 2

Deposits similar to those described in the previous section have been detected in the second trench excavated along the fault plane, with a different stratigraphic order (Fig. 6). Moreover, in contrast to the trench at site 1, a blackish soil (unit 1) has been found over the loess deposit. This soil has also been detected by Magaldi & Sauro (1982) at the bottom of dolinas affecting the Naole Valley. Two soil samples have been collected from the lower part of unit 1 (in the areas indicated in Fig. 6) for radiocarbon dating and gave calibrated ages of 5290-5035/5005-4990 BP and 5455-5385/5330-5295 BP.

Unit 2 is made of reddish-brownish clayey-silty loess deposits similar to those already described for trench 1. A sample of clayey silt from this unit (bulk sediment) has been radiocarbon dated at 20710±300 BP. The colluvial deposits unconformably overlie unit 3, made of layered carbonate scree. The attitude of these slope deposits indicates a significant tilt also in this trench and the present dip is about 30° towards the fault plane (Fig. 6).

Although the described units are similar to those detected at site 1, the succession is clearly inverted, with the scree representing the lower unit. This further corroborates the conclusions by Magaldi & Sauro (1982), who related the deposition of loess and slope sediments to the same depositonal phase of the upper Late Pleistocene. Pebbles dragged by the fault movement have been observed along the carbonate fault plane. Minor fault planes affect units 2 and 3 in the central portion of the trench.

Two displacement events or phases have been detected. The most recent one is testified by the displacement of the scree (unit 3) and loess deposits (unit 2) along the minor shear planes affecting the central portion of the trench wall (Fig. 6). These minor faults are sealed by the paleosol (unit 1) and therefore the event occurred after 20710±300 BP (age of unit 2) and before 5455-5385/5330-5295 BP

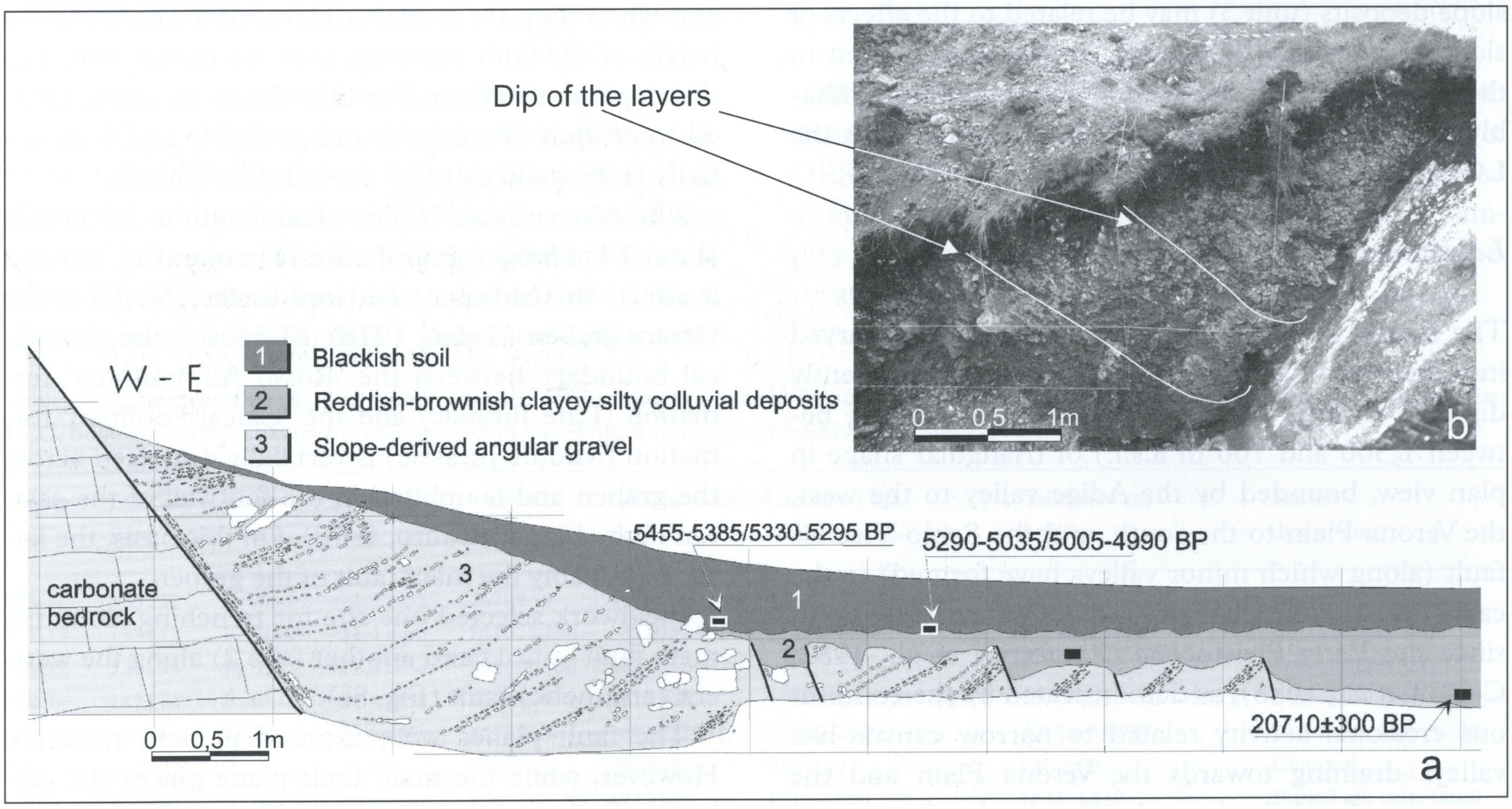

Fig. 6. a) Log of the trench (northern wall) excavated at site 2 across the Naole fault. Two displacement events have been detected at this site, the youngest having occurred between 20710±300 BP and 5455-5385/5330-5295 BP (cal. age); b) view of the southern wall of the trench excavated at site 2 across the Naole fault.

(oldest age of unit 1). It is not possible to define narrower chronological constraints, due to the fact that after the loess and scree deposition, the Naole Valley was only affected by the soil formation and did not experience any other depositional activity. Moreover, the date of unit 2 is related to the original glacial sediment, and testifies to an age preceding the wind-blown re-deposition inside the Naole Valley. This re-deposition may have occurred close to the LGM, on the basis of the environmental reconstruction proposed by Magaldi & Sauro (1982) and Sauro & Zampieri (1999a), but within a time span of several millennia following the date 20710±300 BP. However, it probably occurred before the beginning of the Bølling interstadial, about 13000 BP (e.g. Orombelli & Ravazzi, 1996), when the valley glaciers were far from the southern ice-limits of the LGM (e.g. Venzo, 1961; Casadoro et al., 1976; Bondesan, 1999) and, based on the traces of residential human frequentation (Broglio & Lanzinger, 1996), Mt. Baldo was no longer characterised by a steppe-like environment.

Finally, the occurrence of further displacements along the main bedrock fault after 5455-5385/5330-5295 BP cannot be ruled out, since sedimentary units sealing it have not been found.

A previous event is evident in the tilting of the slope deposits (unit 3) along the bedrock fault plane, before the deposition of unit 2 (dated at 20710±300 BP). As stated before, this deposition may have occurred between the reported age and the Bølling interstadial (began at 13000 BP). Therefore, considering that the slope deposits (unit 3) may be related to the effects of slope erosion in a periglacial environment related to the LGM (Magaldi & Sauro, 1982), the tilting probably occurred in a period close to or slightly after the LGM.

Lessini Mts. - Orsara Fault

The Lessini Mts. are basically a large plateau (carved into the Meso-Cenozoic carbonate succession) gently dipping towards south (with elevations ranging between 1,500 and 700 m a.s.l.) of triangular shape in plan view, bounded by the Adige valley to the west, the Verona Plain to the south, and the Schio-Vicenza fault (along which minor valleys have formed) to the east (Fig. 1). The plateau has been affected by uplift since the Early Pleistocene (Zanferrari et al., 1982; Carton et al., 1988), as demonstrated by the continuous erosional activity related to narrow canyon-like valleys draining towards the Verona Plain and the presence of sub-horizontal paleo-landsurfaces (suspended over the valley bottoms) testifying to ancient base levels (Castiglioni et al., 1988). Tilting of blocks separated by NNE-SSW and NNW-SSE striking faults occurred during the uplift together with 'horst and graben' style displacements indicating mainly extensional kinematics (Panizza et al., 1987; Carton et al., 1988). The area is affected by a large number of normal faults and related fault scarps (Fig. 7; Sauro, 1978; Magaldi & Sauro, 1982). Scarp formation has been in some cases related to fault activity (Sauro, 1978) due to the constant scarp height along hundreds of metres and the absence of erosional agents which may have been responsible for differential erosion along the fault plane. The faults are, however, generally not longer than 5 km, while a longer main fault has never been identified. This aspect implies some problems in terms of the role played by the faults in the structural framework of the Lessini Mts. that will be addressed in the discussion.

The Orsara valley is a small fault-controlled depression, not wider than 90 m, about 1.5 km long and bordered on both sides by NNW-SSE trending normal-oblique faults (Fig. 8; Sauro, 1978). The faults were responsible for the formation of bedrock (carbonate) scarps and the fault planes are sometimes exposed along the scarps showing tectonic striations (Sauro & Zampieri, 1999b). Also in this case, a Holocene scarp formation was hypothesised on the basis of the low karstic weathering of the fault plane (Sauro, 1978).

The two faults are exposed for an almost constant height (about 2 m) along the entire depression, both when they are located in the lowest part of the slopes and when they are at higher elevations. Therefore the height of the fault exposure is by no means linked to the slope morphology. For this reason an origin related to erosion processes is not probable and fault activity is the main cause of the scarp formation.

The eastern fault (whose total length is 2.5 km) is about 1 km longer than the western one (Fig. 8a) and it affects the carbonate bedrock further NNW of the Orsara graben (Sauro, 1978). Moreover, the geological boundary between the 'Rosso Ammonitico' formation (Late Jurassic) and the 'Calcare oolitico' formation (Middle Jurassic) is vertically displaced across the graben and is uplifted in the footwall of the eastern fault (Fig. 8d, Sauro, 1978). On this basis, the latter is probably the main fault of the graben.

Fieldwork selected one site for trenching along the main fault (site 1) and another (site 2) along the western (antithetic) fault (Fig. 8a).

The fault planes were exposed in both trenches. However, while the main fault plane places the carbonate bedrock in contact with slope deposits, the antithetic structure only affects the carbonate bedrock (see below).

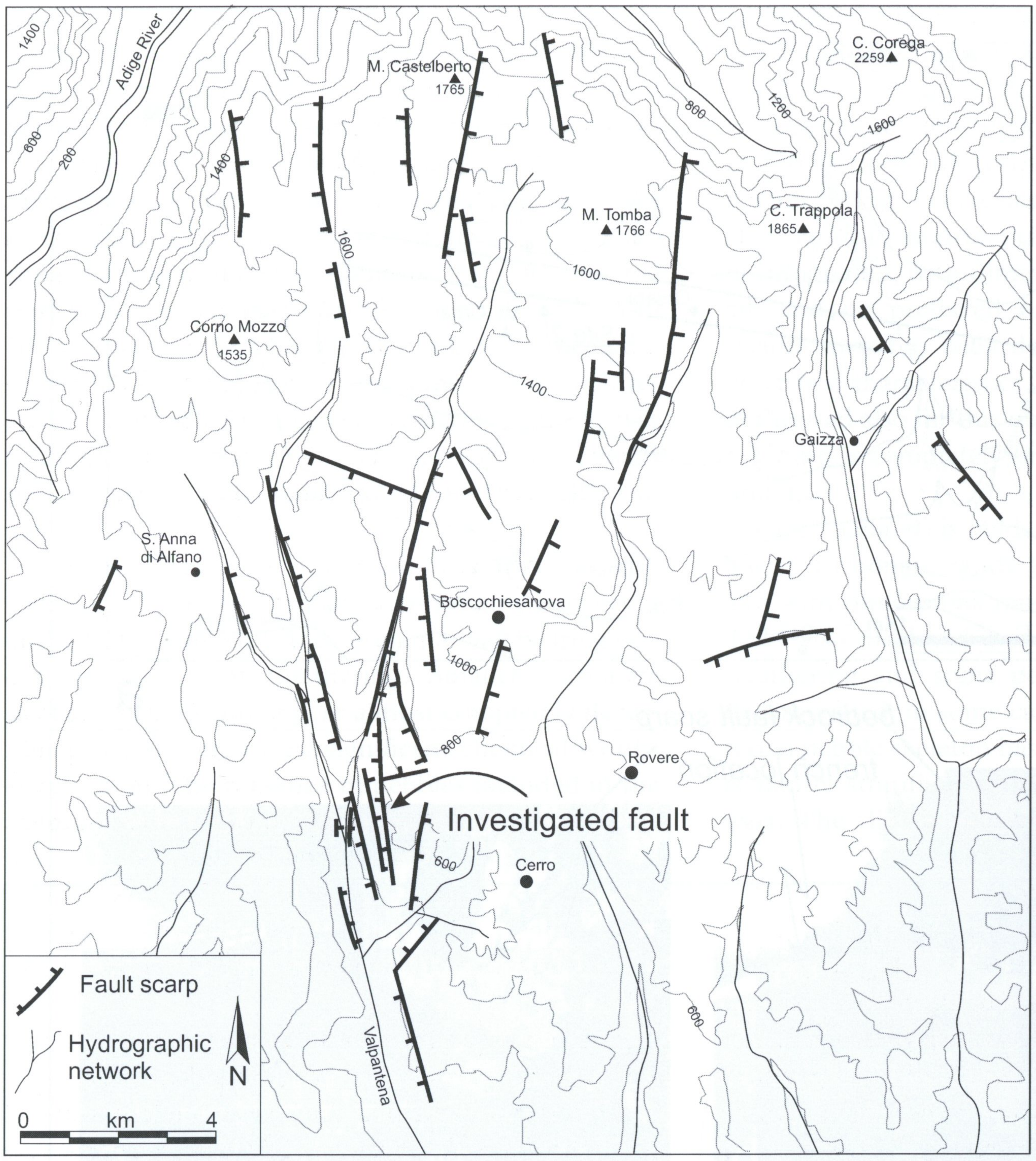

Fig. 7. Morphological sketch of the Lessini Mts. (redrawn from Sauro, 1978). Few-km-long bedrock (carbonate) fault scarps affecting longer Tertiary faults have been recognised in this Southalpine sector.

Samples for radiocarbon dating were collected at site 1 (Tab.1) from soils and colluvial deposits (see below) and analysed by following the same procedure described for the Naole Valley trenches. After pretreatment, sample ORS-2 (original weight 501 gms) yielded less final carbon than expected (0.15 gms) and required AMS analysis. Only one soil sample (ORS-12, see below) was collected for radiocarbon dating at site 2. Charcoal was collected in the case of ORS-7, while the other samples have been analysed as bulk sediments. Apart from ORS-2, the other samples provided plenty of carbon for accurate radiometric analysis.

Table 1. Radiocarbon dates of samples collected in the trenches excavated across the Naole and Orsara faults. R, radiometric technique; BLC, bulk/low carbon material procedure; AMS, accelerator mass spectrometry technique.

pSample	Lab.code Beta-	Analysis	C13/C12 Ratio	Measured age BP	Conventional age BP	Calibrated age 1σ BP	Calibrated age 2σ BP	Sample description
NAO2	133152	R, BLC	-24.3 o/oo	4470±50	4480±50	5290–5035/5005–4990	5305–4955/4925–4885	Buried soil (silty sand)
NAO3	133143	R, BLC	-24.4 o/oo	14100±250	14110±250	17435–16385	17740–16115	Loess (clayey silt)
NAO5	133153	R, BLC	-21.9 o/oo	20660±300	20710±300	–	–	Loess (clayey silt)
NAO6	133154	R, BLC	-24.4 o/oo	4600±70	4610±70	5455–5385/5330–5295	5570–5540/5475–5055	Buried soil (silty sand)
ORS2	137398	AMS	-23.6 o/oo	16950±90	16970±90	20630–19795	20735–19690	Colluvium (clayey silt)
ORS7	137399	R	-24.2 o/oo	890±60	900±60	915–740	940–690	Charcoal
ORS9	137400	R, BLC	-23.6 o/oo	1740±60	1770±60	1735–1600	1835–1540	Buried soil (silty sand)
ORS10	137401	R, BLC	-24.5 o/oo	800±60	810±60	765–675	900–855/810–660	Present soil (silty sand)
ORS12	137402	R, BLC	-23.7 o/oo	480±60	500±60	545–505	640–590/565–470	Present soil (silty sand)

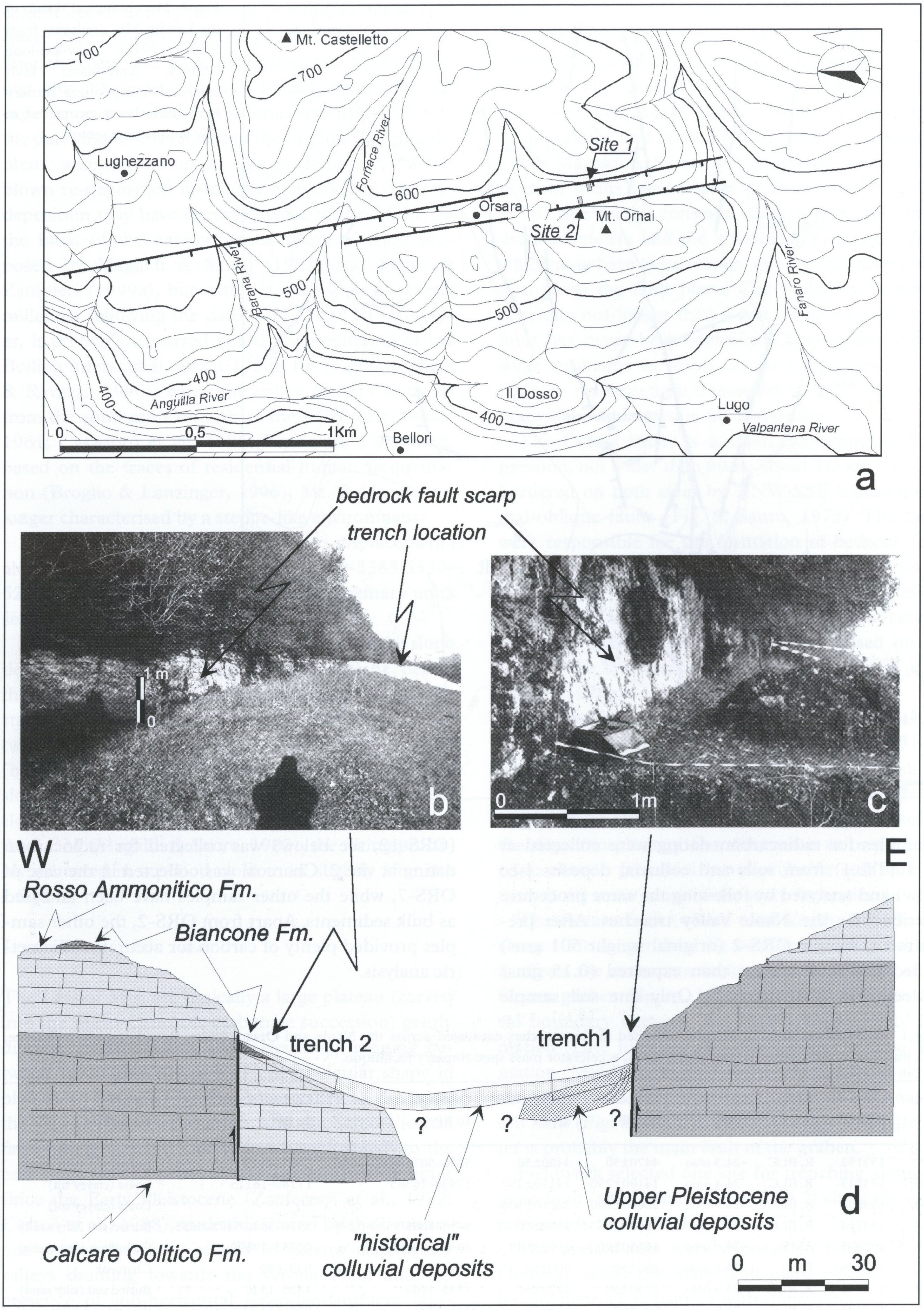

Fig. 8. a) Plan map of the Orsara area and trench location; b, c) bedrock fault scarps bordering the Orsara graben; d) schematic geological section through the Orsara graben.

Site 1

Colluvial and slope deposits and a paleosol were exposed in the southern wall of the trench excavated at site 1 (Fig. 9). Unit 2, found in the western portion of the trench and mainly made of charcoal and combusted reworked material, is the remain of a pit used in the past to burn wood and testifies to the human frequentation of the area. A sample from the charcoal portion of this unit gave a radiocarbon age of 915-740 BP (cal. age). A dark brown soil (unit 3) has been detected below the ploughed soil (unit 1). The soil, resulting from the pedogenesis affecting unit 4, was sampled (about 500 gms) and analysed for radiocarbon dating as bulk sediment (1735-1600 BP; cal. age).

Unit 4 (Fig. 9) is a reddish-brownish silt with sparse cherty pebbles (dimensions ranging between 1 and 10 cm) with whitish external patinae bearing evidence of incipient weathering. Smaller carbonate pebbles (max. 3 cm) appear almost completely decarbonated, testifying to the significant chemical weathering action. The presence of pebbles included in the reddish-brownish silt, together with the total absence of stratification, supports the hypothesis of a colluvial origin for unit 3. A sample of silt (about 500 gms) has been collected (from the area indicated in Fig. 9) for radiocarbon dating (bulk sediment) and gave an age of 20630-19795 BP (cal. age).

Unit 5 (Fig. 9) is a slope deposit made of gravel in abundant silty matrix. Pebbles are angular, incipiently decarbonated, with dimensions ranging from 1 to 10 cm and no preferred orientation. No evidence of stratification has been detected. On the basis of the described characteristics, a colluvial origin may be hypothesised also for this unit.

Unit 6 is completely similar to the above described unit 4.

Unit 7 (Fig. 9) is made of carbonate pebbles in yellowish carbonate sandy matrix. Pebbles are angular and with dimensions ranging between 1 and 10 cm. They also displayed evidence of significant chemical weathering and some pebbles appeared completely decarbonated: in some cases, only the trace of the external pebble skeleton has been found. The entire unit is faintly stratified, with layers dipping towards the west. The dip larger than 70° and the presence of

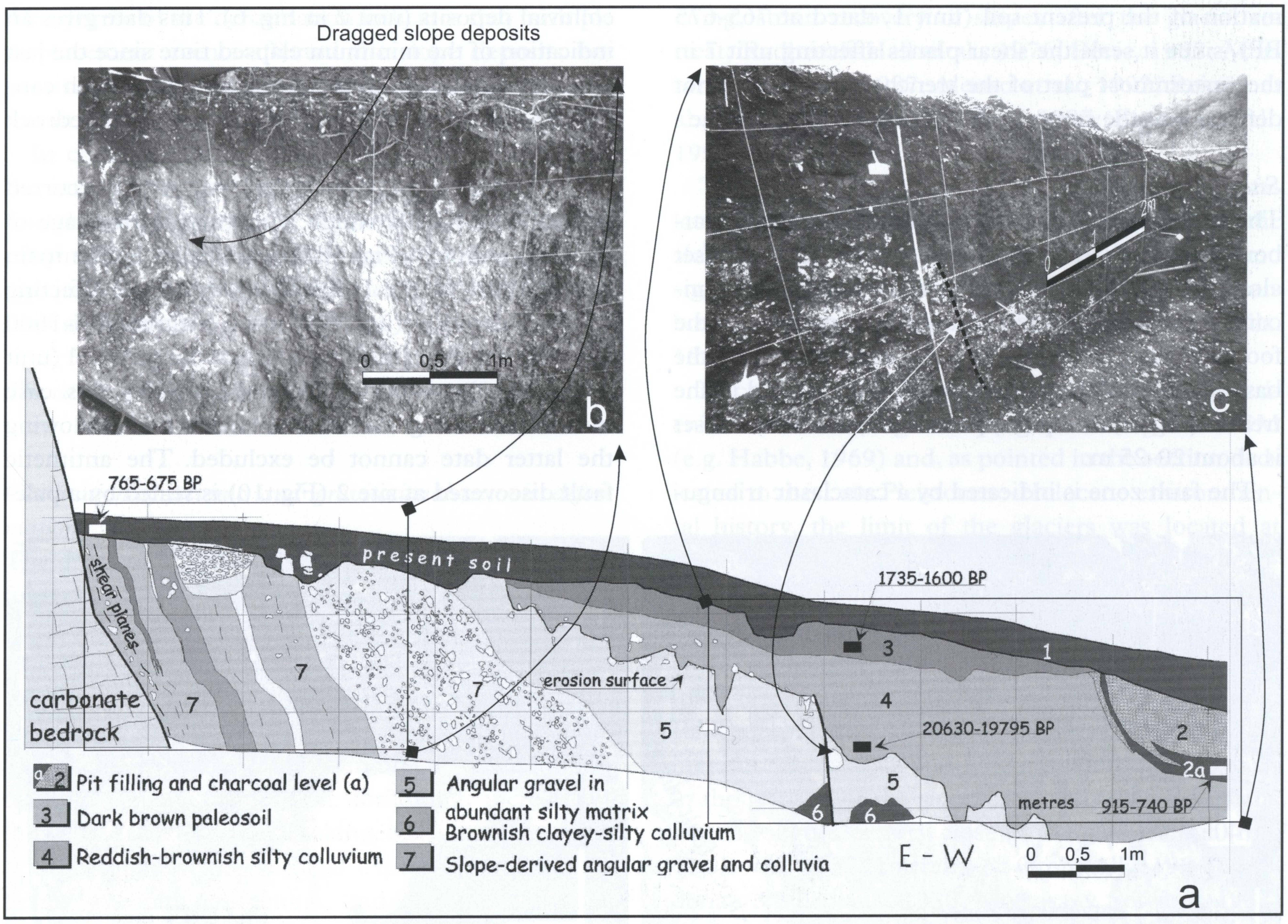

Fig. 9. a) Log of the trench (southern wall) excavated at site 1 across the Orsara fault. Pleistocene displacements were responsible for dragging the slope deposits along the fault, while the youngest displacement event occurred between 20630-19795 BP and 1735-1600 BP; b, c) views of the southern trench wall.

shear planes in the deposits close to the bedrock (Fig. 9) indicate that the present attitude resulted from the drag of unit 7 along the main fault.

The present soil (unit 1) is made of brownish sand with sparse pebbles. A sample (about 500 gms) has been collected from the area indicated in Figure 9 (in the lower portion of unit 1) for radiocarbon dating and gave an age of 765-675 BP (cal. age).

The main fault plane places the bedrock in contact with the strongly deformed slope deposits (unit 7). The attitude of this unit is the probable result of a number of shear episodes. Unfortunately, we have no indications about the age of the slope deposits and therefore we suggest a generic Pleistocene age.

The youngest event detected at this site is indicated by the displacement of the base of unit 3 along a minor shear plane affecting the central portion of the trench wall. This event occurred after 20630-19795 BP (age of unit 3) and before the formation of the paleosol (unit 2), dated at 1735-1600 BP. Narrower chronological constraints are not available due to the colluvial origin of unit 3 whose deposition age may be very different from the obtained radiocarbon age.

Fault movements are probably older than the formation of the present soil (unit 1, dated at 765-675 BP), since it seals the shear planes affecting unit 7 in the easternmost part of the trench wall and it is not deformed at the contact with the bedrock fault plane.

Site 2

The trench was almost entirely excavated in the carbonate bedrock in order to evaluate the vertical offset along the antithetic fault. In fact, the base of the Biancone Formation (Early Cretaceous) crops out in the footwall about 20 m above the trench site, while the basal portion of the same formation was found in the trench (Fig. 8; Zampieri, pers. com.); thus the offset is about 20-25 m.

The fault zone is indicated by a cataclastic triangular area bordered by the main fault plane to the west and an antithetic minor plane to the east (Fig. 10a). A reddish paleosol sealing the main fault plane was found in the northern trench wall (Fig. 10b) which has been radiocarbon dated at 545-505 BP (cal. age). Displacements along the fault (sealed by the paleosol) occurred before the above reported palesol age.

Discussion

Chronology of the displacement events

Radiocarbon dates indicate that some displacements at the investigated sites occurred close to and after the LGM. Considering that most of the obtained radiocarbon dates have been derived from colluvial or loess deposits (i.e. from units which may have deposited in the Naole Valley and in the Orsara graben after the primary deposition/formation to which the obtained dates are related), some displacements may also have occurred during the Holocene.

The youngest event detected at the Naole Valley occurred before 5455-5385/5330-5295 BP and has been identified along minor shear planes affecting colluvial deposits (unit 2 in Fig. 6). This date gives an indication of the minimum elapsed time since the last fault activation, if younger displacements (which cannot be excluded) did not affect the main bedrock fault.

The youngest event along the Orsara fault occurred before 765-675 BP, which is the radiocarbon age of the soil (unit 1 in Fig. 9) not deformed by the main bedrock fault at site 1. A minor shear plane affecting colluvial deposits (unit 5) moved before 1735-1600 BP, which is the radiocarbon age of the paleosol (unit 4 in Fig. 9) sealing it. However, also in this case movements along the main bedrock fault following the latter date cannot be excluded. The antithetic fault discovered at site 2 (Fig. 10) is sealed by a pale-

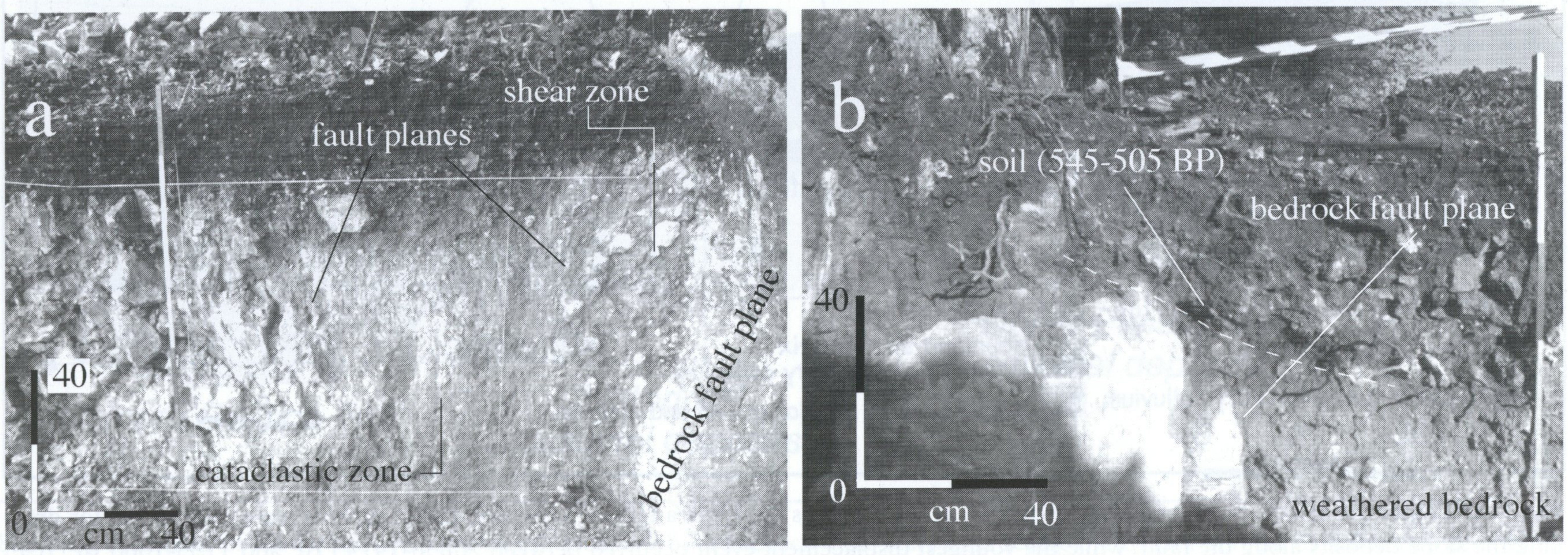

Fig. 10. a) View of the southern wall of the trench excavated at site 2 (Orsara fault); b) view of the northern wall of the trench excavated at site 2.

osol which has been dated at 545-505 BP. Therefore in the case of the Orsara structure the minimum elapsed time may be of 5-8 centuries.

The main problem is, however, related to the definition of the chronological interval during which the last displacement events may have occurred in both the investigated areas. Due to the lack of sediments younger than the LGM, the time interval of the event occurrence is, indeed, very large.

Both the investigated sites at the Naole Valley showed that the slope deposits were tilted. Tilting occurred before the deposition of the loess deposits (unit 2) at site 2 (Fig. 6), which in turn is displaced along minor shear planes. This indicates that two displacement events have affected the Naole Valley since 17435-16385 BP. The history of the tilting is, however, unknown, i.e. we do not know if the present dip of the slope deposits was obtained by means of only one or more events. This means that it is not posssible to exclude that more than two displacement events affected the Naole Valley.

In the case of the trench excavated at site 1 across the Orsara fault, Pleistocene slope deposits (unit 7 in Fig. 9) were evidently dragged along the fault plane. The degree of the deformation indicates that multiple displacement events affected the slope deposits but precise chronological constraints for the deposition of this unit are missing.

In conclusion, the peculiar depositional history at the investigated sites prevented the possibility to define the number and the recurrence interval of displacement events, nor did the investigations give precise information about the elapsed time since the last fault activation.

The cause of the deformation

Gravitational, tectonic and gravitational-tectonic deformations

The distinction among the three different kinds of deformation has been summarised by Hutchinson (1995). The two extremities of the range are related to pure external (gravitational) and pure endogenous (tectonic) forces. Gravitational-tectonic deformations are usually represented by deep-seated gravitational displacements whose origin is indirectly related to the tectonic activity (responsible for tilting, increase of the energy relief, seismic shaking, etc..).

Unfortunately, the surficial expression of gravitational, gravitational-tectonic and tectonic deformations along mountain slopes may be the same and the discrimination betweeen the different causes through the evaluation of the local structural characteristics and geological evolution is often impossible (see, for example, the discussion at the end of the paper by Forcella, 1984).

Taking into account these problems, the main question about the deformations affecting Mt. Baldo and the Lessini Mts. is whether the observed displacements are related to pure gravitational, pure tectonic or mixed causes.

In the case of Mt. Baldo, the recent deformation is indicated by a double-crested summit and uphill-facing scarps (affecting both the western and the eastern slopes; Fig. 2b). These geomorphic features are typical of deep-seated gravitational deformations, already studied in many parts of the world (e.g. Jahn, 1964; Zischinsky, 1969; Radbruch-Hall et al., 1976; Mahr, 1977). According to the available literature, non-tectonic factors conditioning the deep-seated gravitational deformations are mainly structural (soft bedrock layers in a multilayered bedrock, rigid blocks overlaying soft sediments, pervasive fracturation or schistosity; Mahr, 1977; Nemcok & Baliak, 1977; Forcella & Rossi, 1987; Sorriso-Valvo, 1988; Guerricchio et al., 1988; Guida et al., 1989) and geomorphic (slope oversteepening due to glaciation, valley deepening, strain recovery of slopes after the glacial retreat; Radbruch-Hall et al., 1976; Bovis, 1982; Mortara & Sorzana, 1987; Alonso et al., 1992; Reitner et al., 1993; McCalpin & Irvine, 1995; Forcella et al., 1998).

The deformation affecting Mt. Baldo cannot be related to peculiar structural conditions, since the slopes are entirely made of carbonate rocks and no significant soft layers have been recognised in the carbonate succession (e.g. Servizio Geologico d'Italia, 1969).

In contrast, the valleys limiting Mt. Baldo experienced the flow of glacial tongues during the LGM (e.g. Habbe, 1969) and, as pointed in the section dedicated to the Late Pleistocene-Holocene environmental history, the limit of the glaciers was located at about 500 m a.s.l. Many works dealing with deep-seated slope deformations in previously glaciated areas indicate the glacial modelling and the removal of lateral support by now-melted valley glaciers as the main factors triggering gravitational movements (e.g. Radbruch-Hall et al., 1976). However, the available literature shows that this kind of deformation occurs in the portion of the slope previously covered by the glacial tongues or very close to the glacial limit (Fig. 11; Bovis, 1982; Forcella & Orombelli, 1984; Bordonau & Vilaplana, 1986; Mortara & Sorzana, 1987; Alonso et al., 1992; Reitner et al., 1993; Bellotti et al., 1995; McCalpin & Irvine, 1995; Forcella et al., 1998; Onida et al., 2000).

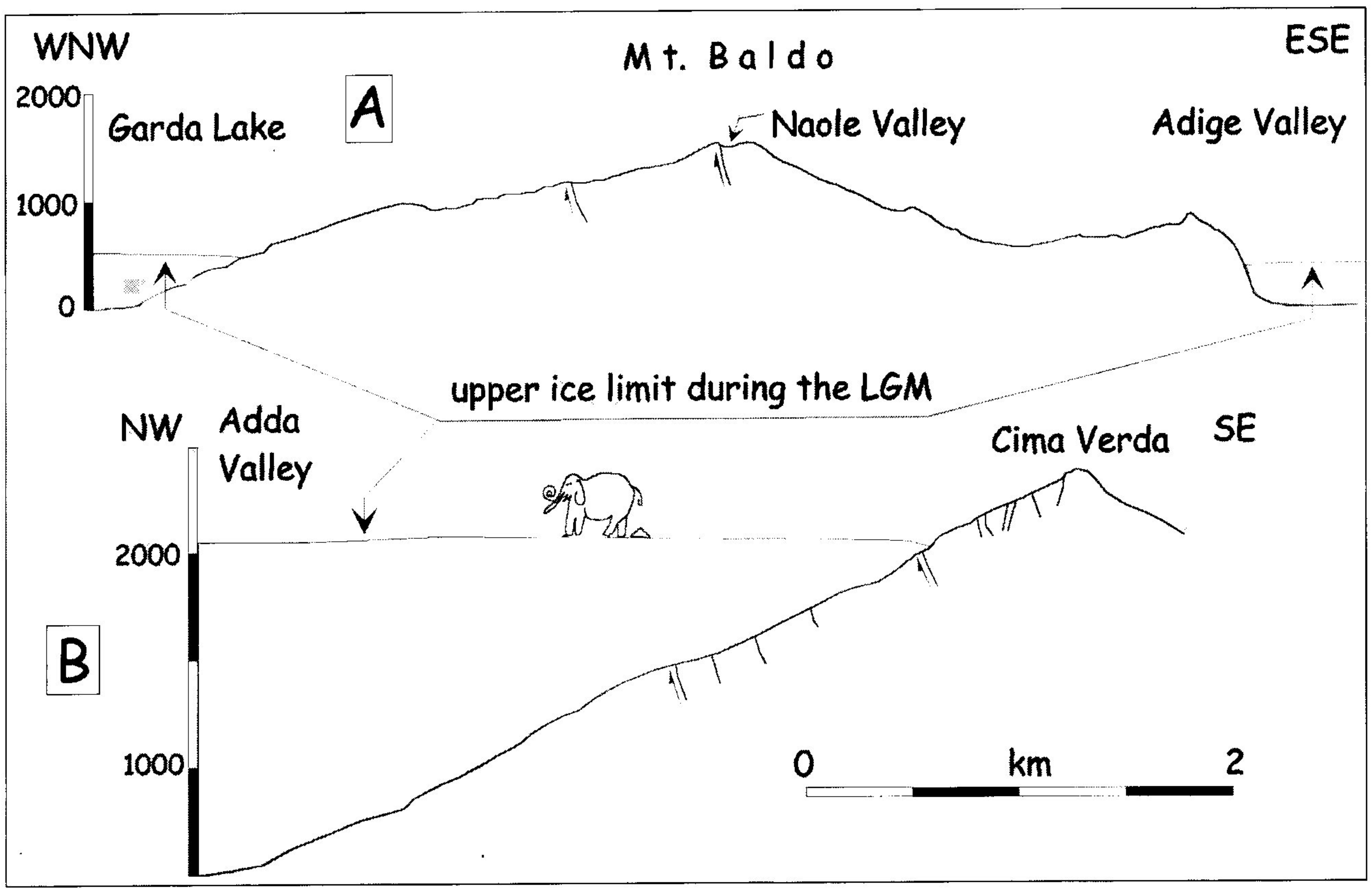

Fig. 11. a) Topographic profile across Mt. Baldo with the location of the shear planes responsible for the formation of uphill-facing scarps and the position of the upper ice limit during the LGM; b) topographic profile across the Cima Verda sector of the Adda Valley (central Alps) showing the location of the shear planes responsible for the formation of uphill- and downhill-facing scarps and the position of the upper ice limit during the LGM; this area is affected by a well known deep seated gravitational movement (Onida, 1999, from which data necessary to draw the section have been derived). Figure a) suggests that the deep seated gravitational deformations affecting Mt. Baldo have probably not been conditioned by the de-buttressing effect due to the glacial retreat. In contrast, this effect has probably been the main cause of the deformations affecting the SE slope of the Adda Valley (Onida, 1999).

In contrast, the deformation affects portions of the Mt. Baldo slopes located at about 1000 m above the upper ice limit during the LGM and no evidence of deformation has been detected in the lower portion of the slope which may be related to the effects of the glacial retreat (Fig. 11). Therefore, the Lake Garda and Adige valley ice tongues did not have the classical glacial buttressing effect on the slopes which experienced gravitational deformations.

The summit of the Mt. Baldo chain was affected by some minor glacial cirques (Fig. 2) feeding tongues which drained towards Lake Garda. These cirques are, however, located 4 km north of the Naole Valley and no relationship can be defined between the observed gravitational deformations and the presence of the small cirques and the related glacial tongues.

Therefore, the two main causes responsible for gravitational deformations along slopes of glacial valleys (i.e. the valleyward squeezing of ductile rocks overlain by brittle rocks and the end of the glacial buttressing action against the slope) cannot be invoked for Mt. Baldo.

Attention has been dedicated in Italy to the problem of the relationship between deep-seated gravitational deformations and tectonic activity (Dramis, 1984; Cavallin & Tornaghi, 1987; Guerricchio et al., 1988; Dramis & Sorriso-Valvo, 1994). Dramis & Sorriso-Valvo (1994) have shown that a close relationship may exist between the triggering of lateral spreading (i.e. the deformation observed at Mt. Baldo, the double crest and the uphill-facing scarps indicating extension perpendicular to the divide) and the growth of anticlinal structures (with or without a thrust fault) formed in compressional regime. Basically, a slight warping of the structure may be responsible for breaking the rocks at the extrados of the fold and triggering deep-seated slope deformations. A similar evolution has been hypothesised for the gravitational movement affecting Mt. Cornagiera (central Alps) by Cavallin & Tornaghi (1987), and coseismic deformations with similar forms have been described after the 1980 El Asnam (Algeria) earthquake (Philip & Meghraoui, 1983).

The low seismicity in the area just west of Mt. Baldo (Figs. 1 and 3), the tilting and vertical displacement which affected the karstic plateau during the Quaternary (Forcella & Sauro, 1988) and the lack of the structural and geomorphic conditions responsible for triggering pure gravitational deformations may suggest that the model of the lateral spreading related to the warping of the Mt. Baldo structure may account for the displacements which affected the Naole Valley after 17435-16385 BP. This kind of deformation (conditioned by the tectonic activity) should be defined, therefore, as gravitational-tectonic (e.g. Hutchinson, 1995).

Investigations along this kind of structures do not allow for hypotheses on the maximum expected magnitude which may be associated with the active structure. Therefore, also for the definition of this fundamental parameter, the effectiveness of paleoseismological investigations is limited. Historical catalogues (e.g. Working Group CPTI, 1999) indicate that the Mt. Baldo thrust may have been responsible for earthquakes with Ma = 4.8, but it is not possible to exclude that larger earthquakes may occur as a result of its activation.

In contrast, no evidence of gravitational deformation has been found in the case of the Orsara graben, since the faults do not affect a mountain crest or slope. The displacements observed along the Orsara fault have, therefore, to be considered as the result of tectonic activity. The interpretation of the recent tectonic activity of the entire Lessini Mts. sector is, however, problematic (see below).

Tectonic activity: open problems

The deformation investigated in the Naole Valley probably testifies to the persistent activity of the Mt. Baldo thrust during the Late Pleistocene (-Holocene?). Based on the available structural literature, the whole NNE-SSW trending Giudicarie system has been affected by a transpressional kinematics, responsible for the activity of thrusts with variable strike-slip components (Doglioni & Bosellini, 1987; Avanzini, 1992; Castellarin et al., 1992; Prosser, 1998 and 2000; Castellarin & Cantelli, 2000). This activity is consistent with the available data on the present-day kinematics inferred by focal mechanisms (Panizza et al., 1981; Slejko et al., 1989) and GPS measurements (Caporali & Martin, 2000). These data indicate strike-slip and compressive kinematics along the NNE-SSW trending structures (Fig. 1) and a NW-SE shortening (inferred from the changed length of baselines) in the investigated area.

The hypothesised warping of the Mt. Baldo structure (causing the investigated gravitational deformations) seems therefore to be consistent with the regional kinematic framework.

In contrast the kinematic framework of the deformation affecting the Lessini Mts. is, in our opinion, unclear. Recent activity involving few-km-long faults in the Lessini plateau (Fig. 7) basically results from the re-activation of parts of longer fault systems which formed graben-like depressions during the early Tertiary (Zampieri, 1995 and 2000). However, the mechanism responsible for the re-activation of short fault segments is unknown.

Similar deformations (occurred during the Holocene) have been described for an Andean plateau of Ecuador by Ego et al. (1996), who related the displacements to the elastic rebound following ice melting. A similar origin cannot, however, be invoked for the Lessini Mts., since this area was not covered by glaciers (Fig. 2; Penck & Brückner, 1909, Castiglioni, 1940; Habbe, 1969).

We have no conclusive data to hypothesise which mechanism was responsible for the activation of few-km-long fault segments. Our preliminary hypothesis is that the surficial deformation may result from the activation of a blind major fault, responsible for the uplift of the Lessini Mts. and related displacements along minor normal faults. The extensional kinematics along NNE-SSW and NNW-SSE faults may be consistent with an uplift related to the activity of a fault of the Giudicarie system.

A more general problem is represented by the role that glacio-seismotectonics (i.e. the influence of glacial rebound stresses on the crustal deformation and seismicity; see Stewart et al., 2000) played in the recent tectonic history of the investigated area. Evidence of a direct relationship between fault activity and post-glacial rebound has been found for areas affected by large ice covers (Fennoscandia and North America; Wu et al., 1999; Stewart et al., 2000 and reference therein), while this kind of relationship is less clear for smaller glaciated areas such as the Swiss Alps (Schaer & Jeanrichard, 1974; Gudmunsson, 1994; Beck et al., 1996). As for the Italian Alps the effect of the post-glacial rebound on the activation of faults has been marginally addressed by Forcella & Tibaldi (1998), who rejected this mechanism as being responsible for the post-LGM re-activation of two few-km-long faults in the central Alps.

These remarks indicate that almost nothing is known about the importance of glacio-seismotectonics in the recent tectonic history of the Alps. The problem is, however, by no means trivial, since the deglaciation may be responsible for high horizontal compressive stresses close and perpendicular to the retreating ice-limit (Stewart et al., 2000 and references therein). Deglaciation-induced stresses interfere with the tectonic stress. In the case of the Southalpine area, we know that the southern Alpine glacial limit (towards the Po and Veneto Plains) coincided with the limit between the Alps and the mentioned plains (Fig. 12).

This area is affected by the main compressive structures for which evidence of recent activity is available (e.g. Castaldini & Panizza 1991). Therefore, for the central-eastern Southalpine area, the limit of the ice tongues and the Quaternary thrusts almost coincide, and the tectonic compressive stress could be roughly parallel to the horizontal compressive stress induced by the deglaciation (Fig. 12). This may result in an increased compressive stress (Stewart et al.,

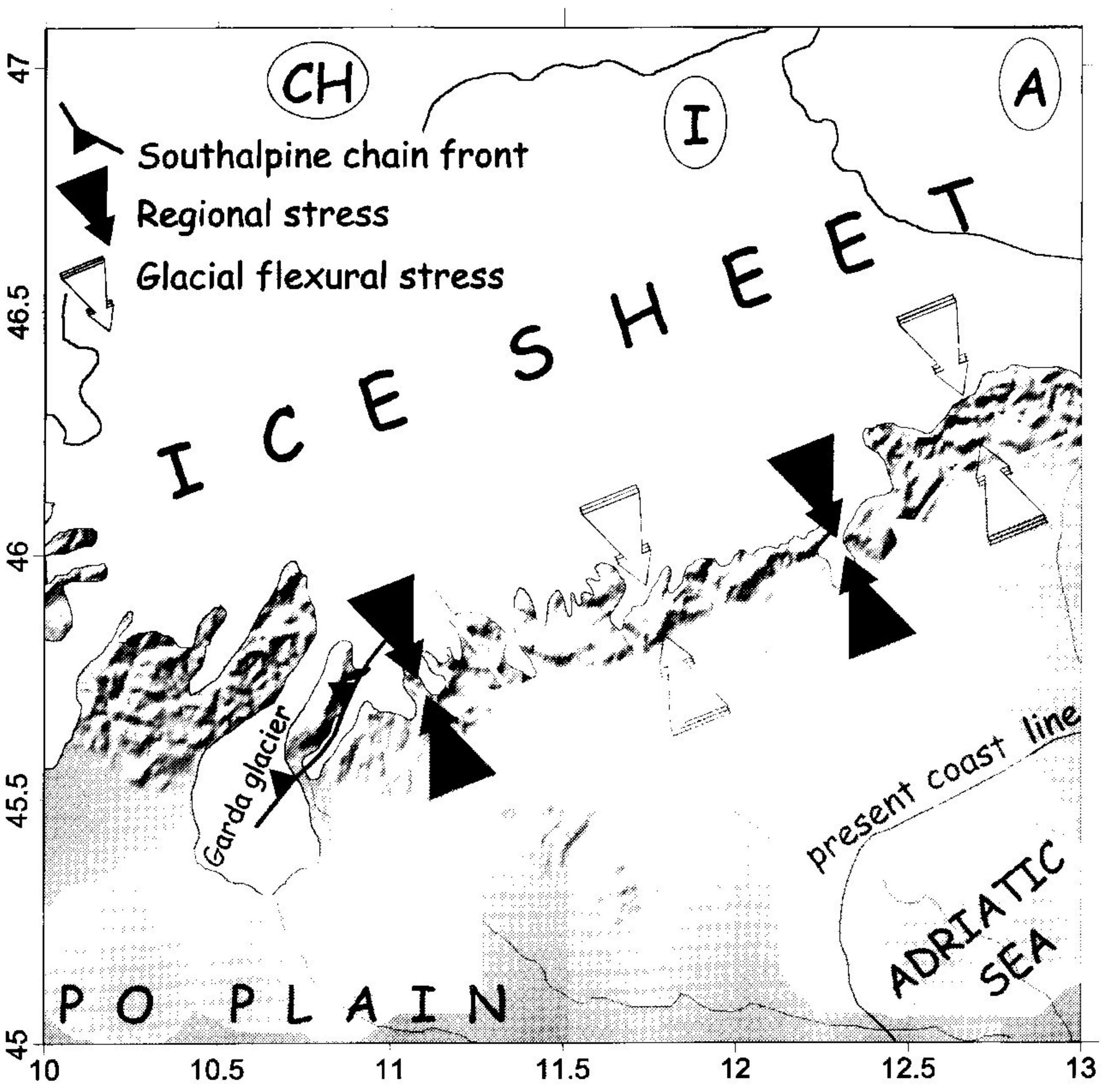

Fig. 12. Morphological sketch of NE Italy during the Last Glacial Maximum. The highest peaks of the inner Alpine sectors (not represented in figure) were not covered by glaciers. The southern ice limit was close to the active thrusts bordering the Southalpine chain. The glacial retreat and related post-glacial rebound may have induced a NW-SE horizontal compressive stress perpendicular to the ice limit. Tectonic and glacially induced stresses may have been parallel in the investigated area, thus resulting in an increased horizontal total compressive stress.

2000 and reference therein), which may be in turn responsible for increasing the 'intensity' of the tectonic activity, reducing recurrence intervals between faulting episodes, and increasing the seismicity both in terms of earthquake frequency and magnitude. In this light, the deglaciation may have increased the NW-SE tectonic compressive stress in the Mt. Baldo sector, and the lateral spreading which affected the Naole Valley area with the tilting of the slope deposits (close to the LGM or slightly after it) may be the effect of an increased deformation experienced by the Mt. Baldo structure.

More generally, although there is evidence of strong present-day tectonic activity in the Southalpine area (demonstrated by the number of earthquakes with M=6-6.5; Working Group CPTI, 1999) which is probably not related to deglaciation, Late Pleistocene (after the LGM) and early Holocene activity may have been conditioned by the glacial retreat. This implies that enhanced evidence of Late Pleistocene-Holocene tectonic activity may be detected in the field (as the result of the deglaciation stress), which probably does not reflect the present-day deformation. Therefore, due to the possible deglaciation effects, paleoseismological information may be considered not fully reliable to define the present-day Alpine fault behaviour if based on investigations of the Late Pleistocene (after the LGM)-early Holocene displacement history.

Conclusions

Paleoseismological investigations performed at Mt. Baldo and in the Lessini Mts. (central Southalpine chain) indicated that displacement events occurred close to and after the Last Glacial Maximum in the Naole Valley and along the Orsara fault. The deformation in the Naole Valley has been interpreted as the result of gravitational lateral spreading in response to the warping of the Mt. Baldo structure (basically an anticline with east-verging thrust faults). The Orsara fault is, instead, a 2.5-km-long normal fault and is part of the complex structural pattern (made of few-km-long faults) related to the recent tectonic evolution of the Lessini Mts.

Investigated faults have been affected by displacement events following 17435-16385 BP and probably occurred before 5455-5385/5330-5295 BP in the Naole Valley and occurred between 20630-19795 BP and 765-675 BP along the Orsara fault. The lack of deposits younger than the Last Glacial Maximum at the investigated sites prevented the definition of narrow chronological constraints for the observed displacements. Moreover, the trench analyses did not allow for a distinction in the number and size of the displacement events. The upper chronological limit of the displacements indicates that the minimum elapsed time since the last fault activation may be about 5,300 years for the Naole fault and 500-800 years for the Orsara fault.

Some outstanding questions remain unanswered: 1) the maximum expected magnitude of the earthquakes which may originate from the activation of the Mt. Baldo fault, due to the fact that investigations have been performed along a secondary structure affected by gravitational spreading and 2) the identification of a main fault in the Lessini Mts. responsible for the displacement along a complex pattern of secondary faults similar to the Orsara structure.

The problems arisen from the investigations performed at Mt. Baldo and in the Lessini Mts. clearly indicate that paleoseismological analyses in Alpine areas cannot give an amount of information similar to that obtained in other areas affected by active tectonics. In particular, the Late Pleistocene glacial history has an outstanding role in hindering the definition of the Alpine active tectonic framework for two main reasons:

1) the thick glacial tongues which filled the Alpine valleys and the subsequent fluvioglacial deposition were the main factors affecting landscape model-

ling (with erosion and deposition rates higher than the active fault slip rates); this means that a) the geological evidence of fault activity and the displacement history may often be limited to the very short time span of few millennia and b) the traces of the activity may be very faint and difficult to detect;

2) the rebound due to the retreat of the glacial cover which affected the Alpine chain during the Late Pleistocene may have induced horizontal compressive stresses close to the retreating ice limits which, in the case of the central-eastern Southalpine sector, may have been coaxial with the tectonic stress; in such a case, an increase in the deformation rates may have occurred along the southern Alpine compressive belt following the LGM.

Although the problems of the post-glacial rebound in the Italian Alps have not been analytically addressed so far, the process outlined at point 2 may further reduce the effectiveness of paleoseismological investigations in Alpine areas. Paleoseismologically inferred parameters describing the characteristics of the fault activity (e.g. recurrence interval, elapsed time since the last fault activation, slip rate) may, indeed, reflect the response of a fault to a state of stress different from the present one.

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