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LANDSLIDE ACTIVITY IN RESPONSE TO ALPINE DEGLACIATION: THE CASE OF THE BELLUNO PREALPS (ITALY)

ABSTRACT: PELLEGRINI G.B., SURIAN N. & ALBANESE D., *Landslide activity in response to alpine deglaciation: the case of the Belluno Prealps (Italy)*. (IT ISSN 1724-4757, 2006).

In the Late Pleistocene, when the Piave glacier retreated from the end moraine system areas towards the Dolomitic region, several large landslides took place in the Belluno Prealps. The chronology of such landslides is mainly based on spatial relationships between mass movements and glacial or fluvial features, but poorly based on radiometric dating. The aim of this study is improving the existing data set on landslide chronology to clarify the relationship between deglaciation and landslides, that is the sensitivity of an alpine environment to climatic changes.

The research is based on different types of data (geomorphological field survey, geophysical investigations, drillings, radiometric dating and pollen analysis) and focused on four large gravitational phenomena (Fadalto, Madonna del Parè, Masiere di Vedana and Marziai landslides). Different strategies were adopted in order to date mass movements, according to the environmental conditions in which they occurred. In some cases landslide debris reached a valley bottom free of ice and dammed the valley, whereas in others mass movement took place during deglaciation. Therefore investigations were addressed to define the age of landslide deposits, of lacustrine sediments upstream of accumulation zones and of glacial sediments of specific deglaciation phases. Obtaining chronological information through radiocarbon method turned out a difficult task, mainly for the scarcity of organic matter suitable for dating. Also OSL method did not give satisfactory results. Notwithstanding such dating problems, the use of different data and evidence (geomorphological, stratigraphical, geophysical, and palynological) has allowed a quite accurate definition of landslide chronology. For instance, according to pollen types and concentration it is possible to establish that the landslides occurred during the first phases of deglaciation. The main conclusions are: (a) all the examined mass movements took place between 17,000 and 15,000 years BP; (b) there is a clear relationship between landslides and the climatic changes that occurred during the last glacial-interglacial transition; (c) reaction time of slopes to glacier retreat was relatively short. Finally, we do not exclude the hypothesis that tectonics could have played a role as for slope instability during a period of glacial unloading and lithospheric rebound.

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KEY WORDS: Mass movements, Climatic changes, Piave glacier, Late Pleistocene, Southern Alps.

RIASSUNTO: PELLEGRINI G.B., SURIAN N. & ALBANESE D., *Effetti della deglaciazione alpina sull'attività delle frane: esempi nelle Prealpi bellunesi (Italia)*. (IT ISSN 1724-4757, 2006).

Durante il Pleistocene Superiore, quando il ghiaccio del Piave si ritirò dagli anfiteatri morenici verso l'area dolomitica, si verificarono numerose grandi frane nelle Prealpi bellunesi. La cronologia di queste frane era basata su correlazioni stratigrafiche e morfologiche con forme e depositi glaciali e fluviali, mentre solo raramente su datazioni radiometriche. Il presente studio si propone di migliorare l'esistente quadro cronologico al fine di esaminare le relazioni esistenti tra la deglaciazione ed i movimenti gravitativi, e quindi la risposta di un ambiente alpino ad un'importante variazione climatica.

La ricerca, basata su vari metodi d'indagine (rilevamento geomorfologico, indagini geofisiche, sondaggi meccanici, datazioni radiometriche, analisi polliniche), si è focalizzata su quattro grandi fenomeni gravitativi (le frane di Fadalto, della Madonna del Parè, delle Masiere di Vedana e di Marziai). A seconda delle condizioni ambientali in cui si sono verificate le frane sono stati adottati differenti approcci d'indagine. In alcuni casi infatti le frane sono avvenute quando il ghiacciaio si era già ritirato, ed hanno provocato lo sbarramento del fondovalle; in altri si sono verificate quando il ritiro della massa glaciale era ancora in atto. La ricerca è stata rivolta a definire l'età dei depositi di frana, dei sedimenti lacustri presenti a monte degli accumuli di frana e dei depositi glaciali relativi a specifiche fasi della deglaciazione. Fondamentalmente a causa dello scarso contenuto di sostanza organica rinvenuto in tutti i depositi, solo alcune delle varie datazioni ^{14}C realizzate hanno fornito risultati significativi. Anche il metodo OSL non ha portato risultati soddisfacenti. Nonostante i problemi nell'impiego di questi comuni metodi di datazione, si è riusciti ugualmente a ricostruire, grazie all'integrazione con altri dati ed evidenze (geomorfologiche, stratigrafiche, geofisiche, palinologiche), una cronologia piuttosto affidabile degli eventi franosi. Ad esempio in base all'analisi pollinica si è potuto stabilire che le frane si sono verificate durante le prime fasi della deglaciazione alpina. Le principali conclusioni cui si è giunti sono: (a) tutti i fenomeni gravitativi esaminati hanno avuto luogo tra 17.000 e 15.000 anni BP; (b) esiste una chiara relazione tra gli eventi franosi e la variazione climatica che ha determinato la fusione dei ghiacciai pleistocenici; (c) da parte dei versanti c'è stato un tempo di risposta relativamente molto breve al ritiro delle masse glaciali. Infine non si esclude l'ipotesi che la tettonica possa aver condizionato l'instabilità dei versanti in un periodo caratterizzato da diminuzioni di carico (scomparsa di grandi masse glaciali) e da isostasia glaciale.

TERMINI CHIAVE: Frane, Variazioni climatiche, Ghiacciaio del Piave, Pleistocene Superiore, Alpi Meridionali.

INTRODUCTION

It is well known that climate has considerably changed during the different periods of Earth history. Present morpho-climatic systems, as those of temperate regions, have been established only few thousand years ago. In fact, about 20,000 years ago, during the last glacial expansion, climate was very different from what it is at present. As regards slope geomorphological evolution, such climate changes have induced new geomorphic processes and variations in evolution trends.

In the study area (Belluno Prealps, Eastern Alps) research was carried to point out the effects of climate changes on slope evolution, focusing in particular on gravitational processes. The response of vegetation associations to climate changes has also been taken into account, since vegetation is a fundamental feature for reconstructing environmental variations.

In the Late Pleistocene, when the Piave glacier retreated from the Lapisina Valley, the Quero Canyon and the «Vallone Bellunese», several landslides took place (Pellegrini & Surian, 1996; Pellegrini, 2000) (fig. 1). The landslide deposits are found both on the valley bottom and on the slopes, and they generally cover glacial sediments of the last glaciation. Some of these landslide deposits have been buried by Holocene fluvial deposits while others have not been and therefore could be of a younger age. Most of these landslides are very large and likely to have occurred within a short period of time. In the Late Pleistocene, climatic changes induced the complete melting of very large glaciers in a time span of few thousand years. Therefore, as shown in several studies carried out in different European regions (e.g. Matthews & *alii*, 1997; Borgatti & *alii*, 2001), a strong relationship between landslides and climate changes may exist in this study area too.

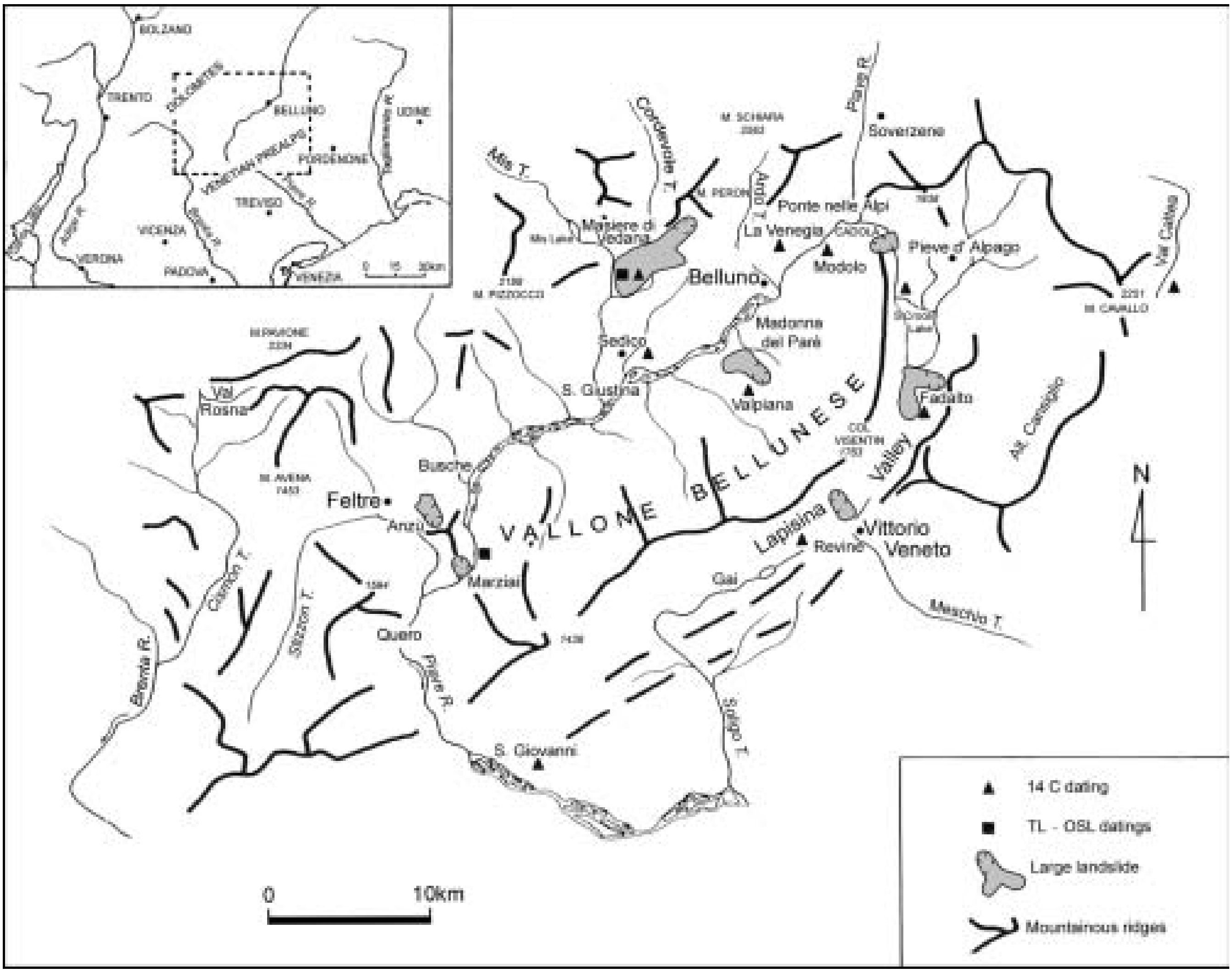


FIG. 1 - Location of the study area and of the large landslides examined.

In the Belluno Prealps there is still a lack of knowledge about climate and event chronology in order to establish a reliable relationship between landslides and climatic changes. The aim of this study is to analyse slope geomorphological evolution along some prealpine valleys where large landslides took place and to reconstruct the environmental characteristics of the area during the Lateglacial and the Holocene. In particular, after a detailed survey and mapping of the main landslides, the research has focused on the following aspects: 1. obtaining new dating of landslides through radiometric, sedimentological and dendrochronological analyses; 2. analysing temporal relationships between deglaciation and landslides, that is the reaction time of slopes following the retreat of glaciers; 3. obtaining a reconstruction of paleoenvironment in the study area through pollen analysis; 4. evaluating influence of climatic changes on occurrence of landslides; 5. evaluating influence of other factors on landslides.

GENERAL SETTING

The study area is located in the Southern Alps and specifically in the central and lower parts of the Piave River basin (fig. 1). The main features of the study area are the Vallone Bellunese, the Lapisina valley and the Quero Canyon. The Vallone Bellunese is a large longitudinal valley which corresponds to a syncline structure with a WSW-ENE direction. This valley separates the Belluno Dolomites, in the northern part, from the Venetian Prealps, in the southern part. The Lapisina valley, in the eastern sector, and the Quero Canyon, in the western sector, are two transverse valleys crossing the anticlinal ridge of the Venetian Prealps.

Besides Quaternary deposits, the stratigraphic sequence includes marine and terrigenous formations of the Upper Triassic-Messinian age. Older formations are made of thick sequences of dolomites which are overlayed by pelagic limestones. The younger rocks, found in the Belluno, Alpago and Vittorio Veneto synclines, are mainly sandstone and argillaceous rocks. This region is tectonically active and one of the most active areas of Northeastern Italy (Zanferrari & *alii*, 1982; Slejko & *alii*, 1987). The main tectonic features are the Bassano-Valdobbiadene-Vittorio Veneto fault and the Belluno fault, which are thrusts with a WSW-ENE direction.

The morphology of this area is strictly controlled by geological structures, the main of which corresponds to the Belluno syncline. During the Pleistocene, the main valleys (Piave, Cordevole, Mis and Lapisina) were almost completely filled with glaciers (e.g. the glacier was about 800 m thick in the Vallone Bellunese) which deeply modelled the slopes and the bottoms of these valleys. During and after the retreat of the Pleistocene glacier slope processes were very active as suggested by many landslides and valley floor sedimentation. Large landslides dammed the valley bottom at several places causing the formation of lakes and changes in the course of the Piave River (Pellegrini, 1994; Pellegrini & Surian, 1996). The lake upstream of the Fadalto landslide still exists (Santa Croce Lake), whereas the lake upstream from the Marziai landslide was filled during the Lateglacial. Other large landslides are the Mt. Peron landslide (Masiere di Vedana near Belluno), which took place during the deglaciation when the valley bottom was still occupied by ice, the Cadola landslide and the Madonna del Parè landslide.

METHODS

This research is based on different types of data (field survey, geophysical investigations, radiometric dating, pollen analysis) collected during the last years and refers to results of different studies dealing with the geomorphological evolution of this area (Pellegrini & Zambrano, 1979; Pellegrini & Zanferrari, 1980; Pellegrini, 1994; Pellegrini & Surian, 1994; Pellegrini & Surian, 1996; Surian, 1996; Bertoldi, 2000; Pellegrini, 2000; Surian & Pellegrini, 2000). Detailed geomorphological survey and mapping represent the fundamental tools for the study of the geomorphological evolution of slopes and, more in general, of forms and processes. The geomorphological survey allowed the distinction between active and inactive landforms and some paleogeographic reconstructions of the study area (Pellegrini, 2000). Where there are lacustrine deposits correlated with landslides, drillings were carried out. Cores from drillings were used to date landslides and for environmental reconstruction through pollen analysis. This latter analysis was also carried out on some other reference cores to improve the knowledge of environment and climate during Lateglacial-Holocene in this sector of the Alps. Aerial photographs interpretation supported geomorphological field surveys. Geophysical investigations and drillings were used to identify buried morphologies of the valley bottom and to reconstruct the stratigraphy of Quaternary sediments. Chronological data were obtained through radiometric dating (specifically ^{14}C and OSL), where the conditions were suitable, or by stratigraphic and geomorphological correlations.

DEGLACIATION IN THE BELLUNO PREALPS

In the Alps the last glaciation took place between 31,000 and 12,000 years BP, and the maximum expansion of glaciers (LGM) likely occurred between 21,000 and 18,000 years BP (Orombelli, 1983; Billard & Orombelli, 1986; Fliri, 1988; van Husen, 1997). During LGM the Piave glacier flowed towards the Venetian Plain in two branches. The western branch built the Quero end moraine system, whereas the eastern branch, passing through the Lapisina valley, built the Gai and the Vittorio Veneto systems. The maximum expansion of the glacier at Vittorio Veneto was dated around 17,670 ± 320 years BP (Bondesan, 1999), and was followed by a relatively rapid deglaciation phase. Modes and times of such deglaciation phase are now well defined by recent data (Pellegrini & *alii*, 2005a). The retreat of the glacier took place in some phases (three at least), well documented by lateral moraines, kame terraces and small marginal moraine systems. The first phase of retreat was dated ^{14}C 16,210 ± 50 years BP, whereas the complete melting of the Piave glacier in the Vallone Bellunese occurred before the Bølling interstadial and reasonably before 15,000 years BP. In fact, fluvial deposits date back to ^{14}C 13,160 ± 110 years BP at Sedico in the valley bottom (Pellegrini, 2000), and the pollen analysis and counting of rhythmic sediments in a lacustrine sequence at Modolo demonstrate that the glacier disappeared about 2,000 years before the beginning of the Bølling interstadial, commonly ascribed to about 13,300 years BP in the Southern Alps.

ANALYSIS OF LANDSLIDES

Fadalto landslide

The Fadalto landslide is located in the upper part of the Lapisina Valley (fig. 1). It is a complex landslide involving more than one type of movement (rock slide, rock avalanche, debris slump etc.) and different reactivations from the Late Glacial to the present (Pellegrini & Surian, 1996; Pellegrini & *alii*, 2004). The landslide regards the eastern slope of the Lapisina valley which is mostly made of Fadalto Limestone, a bioclastic calcarenite and calcirudite with layers dipping towards the valley bottom. The main scarp is about 7 km long with vertical walls reaching a height of 400 m, whereas the accumulation zone is about 1.6 km^2. The highest point of the scarp is 1400 m a.s.l. while the lowest point of the accumulation is 305 m a.s.l. Through geomorphological investigations different landslides were recognised in the accumulation zone and grouped into three landslide units. These units are (fig. 2): Col Brustolade - Col delle Vi, Col dei Masarei and Sassoi. Landslide debris cover the glacial deposits of the last glacial expansion. This gravitational phenomenon likely had a great impact on the evolution of this area during the Lateglacial, since it should be the main cause for the damming of the valley, the formation of the S. Croce Lake and the subsequent change in the course of the Piave River.

According to Venzo (1977) this landslide took place during the pre- Bölling when the Piave glacier was retreating from the valley. Our research tried to define the age of this phenomenon, by analysing both the deposits in the accumulation zone and the lacustrine sediments upstream of the landslide. The several ^{14}C datings obtained document that the landslide has had various reactivations during the Holocene; on the other hand they did not help defining the chronology of the main event (tab. 1) (Pellegrini & *alii*, 2004). In any case, as regards the main event, the chronology can be based on geomorphological and stratigraphical data. The most significant information was derived from drillings carried out on the edge of the S. Croce Lake. These drillings showed that the bedrock is covered initially by glacial deposits and then by lacustrine deposits (fig. 3). Since in this alpine area a long fluvial sedimentation phase took place during and after deglaciation (Surian & Pelle-

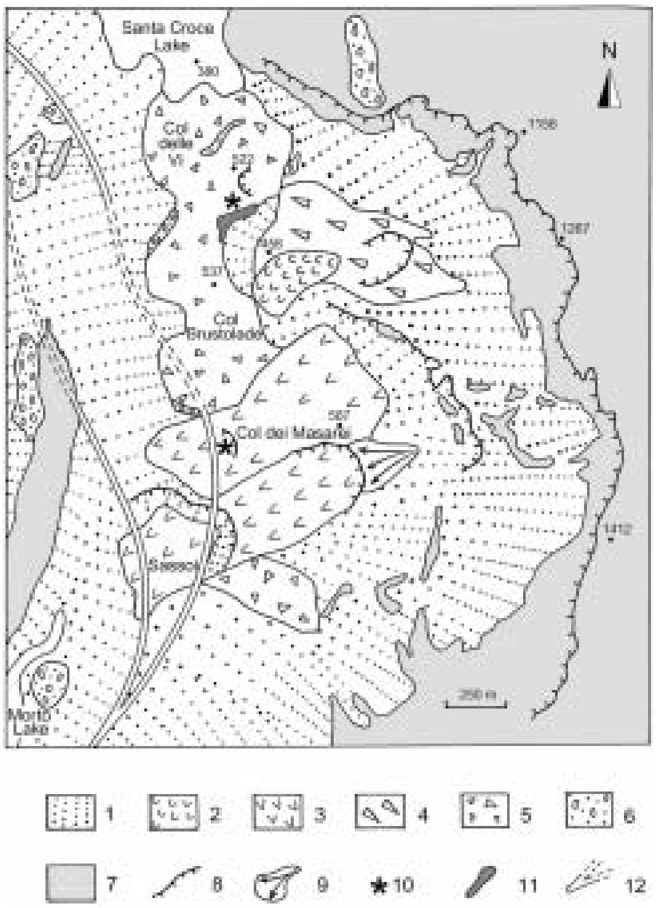
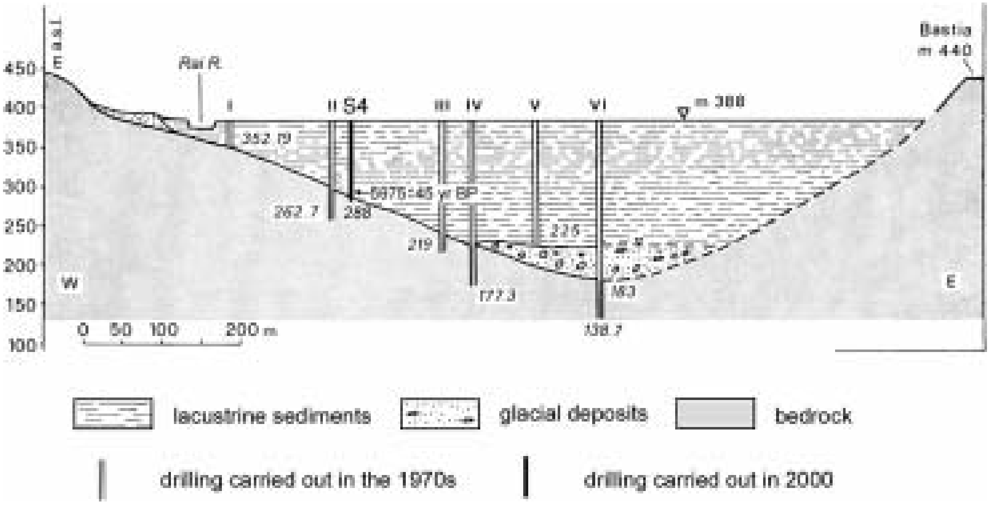


FIG. 2 - Geomorphological sketch map of the Fadalto landslide. Legend: 1: Slope debris; 2: Earth flow; 3: Rotational slide; 4: Rock avalanche; 5: Rock slide; 6: Glacial deposit; 7: Bedrock; 8: Landslide scarp; 9: Debris flow; 10: Site where ^{14}C datings were carried out (datings are listed in Table 1); 11: Area where rock avalanche deposits were exposed; 12: Motorway (from Pellegrini & *alii*, 2004).

TABLE 1 - Results of radiocarbon dating of the Fadalto landslide: ages, not calibrated, refer to the deposits of different landslide units and to the lacustrine deposits which are found upstream of the accumulation zone in the S. Croce area (see figure 2 for location of Col dei Masarei and Col delle Vi and figure 3 for drilling S4)

Sample lab. code	**Material**	**^{14}C age** years BP	**Location**	**Landslide type**
UD-238	Wood	640 ± 60	Col dei Masarei	Rotational slide
UD-262	Wood	840 ± 70	Col dei Masarei	Rotational slide
GX-24890	Wood	1005 ± 40	Col delle Vi	Rock avalanche
GX-24888	Wood	1140 ± 70	Col delle Vi	Rock avalanche
Beta-193335	Wood	1160 ± 60	Col delle Vi	Rock avalanche
GX-24889	Wood	1275 ± 40	Col delle Vi	Rock avalanche
GX-24887	Organic matter	5375 ± 95	Col delle Vi	Rotational slide
KIA14735	Wood	5915 ± 50	S. Croce Lake (drilling S4)	—
KIA14736	Wood	5975 ± 45	S. Croce Lake (drilling S4)	—

FIG. 3 - Cross section of the S. Croce valley, upstream of the Fadalto landslide. (modified from Pellegrini & Zambrano, 1979).



grini, 2000), such sedimentary sequence, where fluvial deposits are absent, is evidence that the Fadalto landslide dammed the valley just after glacier retreat, causing the formation of a lake. Some ^{14}C age obtained for the bottom of the lacustrine sequence, in a marginal position within the valley (see drilling «S4» in fig. 3), document a Holocene phase of lacustrine sedimentation but they do not define the age of the main gravitational phenomenon that dammed the valley (tab. 1).

Madonna del Parè and Masarei landslides

Near Dussoi, on the southern slope of the Col Visentin, there are two large landslides. One of them («Madonna del Parè») derived from vertical walls made of a bioclastic limestone of the «Flysch of Belluno» (fig. 4). The scarp is about 1 km long and its highest point is at 620 m a.s.l.; the lowest point in the accumulation zone, which is quite large, is at 380 m a.s.l. The accumulation is mainly made of large blocks that are up to 100 m^3, or more, in size. Layers dipping towards the valley bottom and joints with direction parallel to that of the slope are the internal causes of this mass movement. Considering structural conditions of the scarp and the nature of the landslide deposit, it can be inferred that the slope mainly underwent falls and, locally, topples. The second landslide («Masarei»), on the northeastern slope of San Pietro in Tuba, has different characteristics, as regards both the nature of the deposit and the type of movement. The accumulation is made of smaller blocks, compared to those of the Madonna del Parè landslide, and has an irregular morphology with several large depressions. Such morphology suggests that the mass movement likely took place when some dead ice was still on the slope. As for the type of movement, it can be identified as a slide.

Since it was not possible to obtain a direct dating of the landslide deposits, other deposits strictly connected to these gravitational phenomena were investigated. Specifically glacial sediments of the LGM were identified as a good chronological indicator since those sediments do not cover landslide deposits. Besides, the lateral moraines of the Piave glacier are cut by landslide deposits (fig. 4). The ^{14}C dating of the glacial sediments found at the bottom of the Valpiana peat-bog (834 m a.s.l.) provides a maximum age, 16,210 ± 50 years BP (Beta-191132), for the Madonna del Parè and Masarei landslides which are at a lower elevation compared to the peat-bog (fig. 4).

Masiere di Vedana landslide

The large accumulation zone of this landslide is at the confluence of the Cordevole valley with the Vallone Bellunese and it extends for 5.5 km (fig. 5). The landslide detached from the vertical walls of the Mt. Peron (1486 m a.s.l.) which are made of limestones of different Mesozoic formations. In the scar area layers are sub-vertical due to the presence of a thrust (the Belluno Line). The total rock mass is about 100 million m^3 (Abele, 1972) and is spread out over a large area (fig. 1). The maximum thickness of the accumulation observed is about 40 m (fig. 6). Within the accumulation zone two main sectors with different morphological and sedimentological characteristics were identified. In the sector which is farther from the slope there is a glacial-type morphology, with ridges and small depressions. The deposits are mainly made of «Calcare del Vajont», «Rosso Ammonitico» and «Calcari di Fonzaso», i.e. of rocks found in the scar area, and there are several large boulders some cubic metres in size. In the sector closer to the slope, there is a very irregular topography with frequent knobs and kettles. As for sediments two different areas can be distinguished in this sector: in the first area the debris in small or medium in size and is mainly made of «Calcare del Vajont», in the second one, closer to the scar area, debris is mainly made of «Calcari Grigi» and it is up to some tens of metres in size.

Several authors who analysed this mass movement argued that it took place when the Cordevole glacier was still in the valley bottom, but with its tongue already sepa-

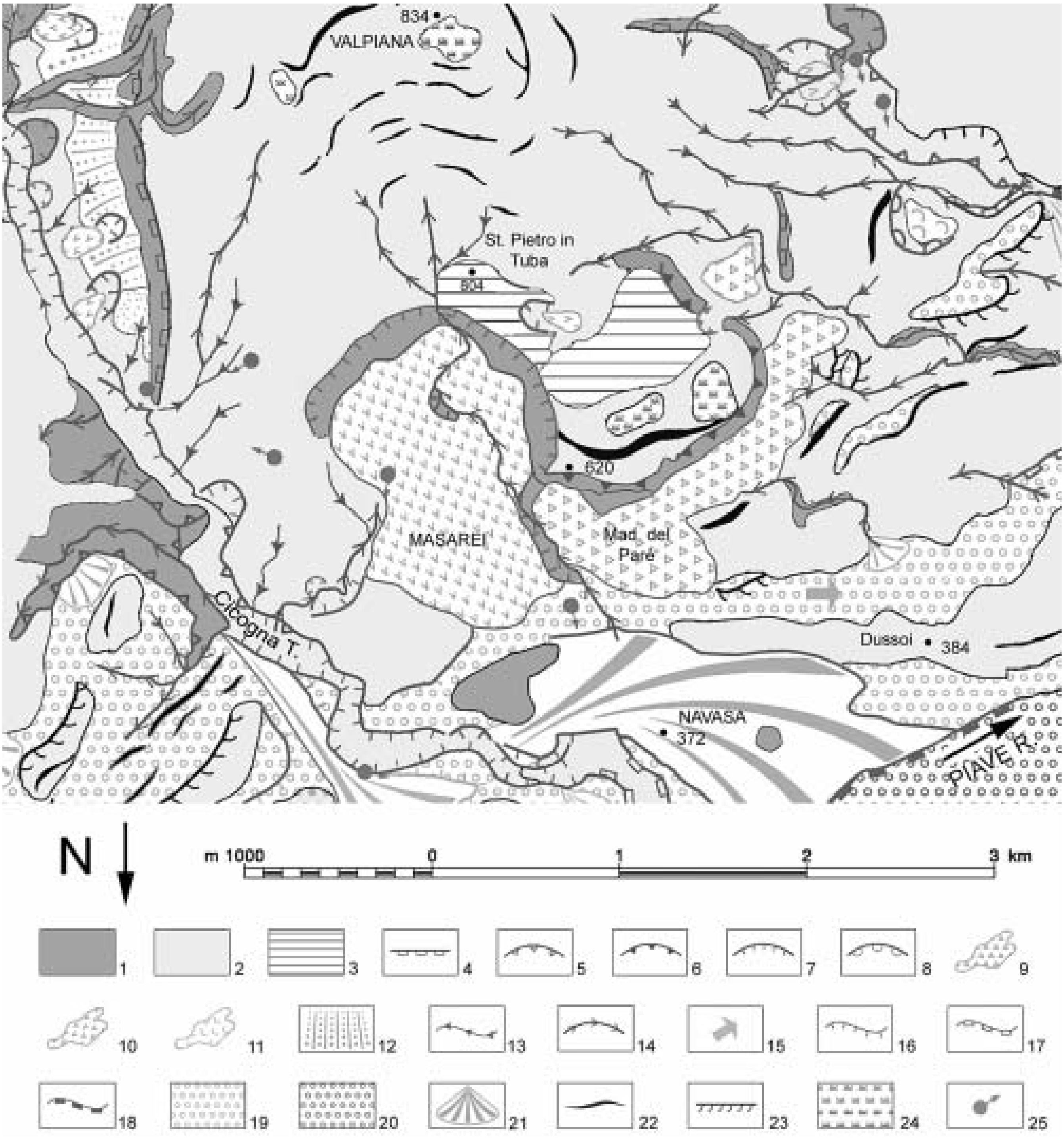


FIG. 4 - Geomorphological sketch map of the Madonna del Parè landslide. Legend: 1: Pre-Quaternary bedrock; 2: Glacial deposit; 3: Structural surface; 4: Structural scarp; 5: Degradational scarp; 6: Rock-fall scar; 7: Rock-slide scar; 8: Earth-flow scar; 9: Rock-fall scree; 10: Rock-slide scree; 11: Earth-flow scree; 12: Scree slope; 13: Gully; 14: Small «V»-shaped valley; 15: Palaeo-flow direction; 16: Fluvial scarp edge (height<5m); 17: Fluvial scarp edge (height = 5-10m); 18: Fluvial scarp edge (height>10m); 19: Old alluvial deposit; 20: Recent or present alluvial deposit; 21: Old alluvial fan; 22: Moraine ridge; 23: Kame edge; 24: Peaty deposit; 25: Perennial spring.

FIG. 5 - The Masiere di Vedana landslide: in the background the scar area (Mt. Peron), in the foreground the accumulation zone.

rated from the Piave glacier (Taramelli, 1883; Squinabol, 1902; Dal Piaz, 1912; Venzo, 1939). According to morphological, sedimentological and stratigraphical evidences a more detailed interpretation can be suggested for this mass movement. Such interpretation implies two main evolutionary phases. In the first phase the landslide, a rock fall, took place when the Cordevole glacier was still in the valley bottom and therefore the landslide material was transported by the glacier (evidence of this phase is found in the distal sector of the accumulation zone). The second phase occurred when the some dead ice was in the valley bottom, but the distribution of the material suggests that it is possible that the rock falls evolved in rock avalanches (Orombelli & Sauro, 1988).

Over several years large volumes of sediments have been excavated from this landslide. Such quarrying activity has allowed the analysis of different exposures and the reconstruction of the following stratigraphic sequence (from the bottom to the top): 1) bedrock; 2) conglomerate; 3) paleosol; 4) glacial deposit; 5) glaciolacustrine sediments, TL dated at 19,700 ± 3000 years BP; 6) glacial deposit; 7a) landslide deposit transported by the glacier («Marocca del Cordevole») made of «Calcari di Fonzaso», «Rosso Ammonitico» and «Calcare del Vajont»; 7b) landslide deposit made of large blocks of «Calcare del Vajont» and «Calcari Grigi» (fig. 6). It was not possible to obtain a direct age of the landslide deposits, but the stratigraphic relationships show that (a) the deposits must be younger than the last glacial expansion and (b) the age of the landslide deposits («7a» and «7b» in fig. 6) should be quite close to that of the glacial deposits («6» in fig. 6) since paleosols or erosional surfaces were not observed between

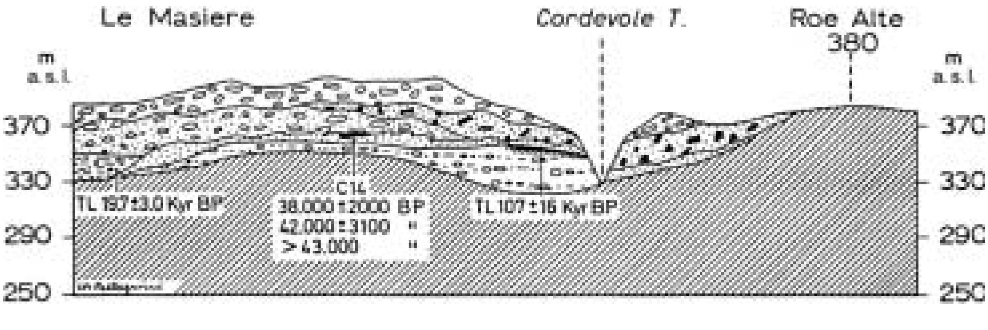


FIG. 6 - Stratigraphic section of the Masiere di Vedana landslide. 1: Bedrock; 2: Roe Conglomerate; 3: Paleosol; 4: Glacial deposit; 5: Glaciolacustrine deposit; 6: Glacial deposit; 7a) landslide deposit transported by the glacier («Marocca del Cordevole») made of «Calcari di Fonzaso», «Rosso Ammonitico» and «Calcare del Vajont»; 7b) landslide deposit made of large blocks of «Calcare del Vajont» and «Calcari Grigi». (modified from Pellegrini & Surian, 1994).

the two deposits. Such stratigraphic evidences and geomorphological analyses suggest that the gravitational phenomenon occurred during one of the first phases of deglaciation, and specifically when the Cordevole glacier was already separated from the Piave glacier. This phase has been recently dated between 16,210 ± 50 and 15,000 years BP (Pellegrini & *alii*, 2005a).

Marziai landslide

The Marziai landslide is in the Quero Canyon, a transverse valley of the Piave River. The landslide scar is on the southern slope of Mt. Miesna (774 m a.s.l.), it is about 1 km long and its highest point is at 675 m a.s.l. (fig. 7). The gravitational phenomenon regarded the Vajont Limestone, with layers lightly dipping towards the slope. Among the internal causes leading to the fall of the rock mass we must mention joints with ENE-WSW direction, that is parallel to the slope. The accumulation zone is in the valley bottom between C. Putin (238 m a.s.l.) and C. Toffoli (246 m a.s.l.) and is mainly made of blocks, some of which of large size. Only a small part of the landslide deposits outcrops since these deposits were covered by lacustrine and fluvial sediments. In fact, like the Fadalto landslide described above, the Marziai landslide dammed the valley bottom causing the formation of a lake that was filled in a relatively short time (fig. 8). This paleogeographic reconstruction was obtained through a detailed geomorphological survey which showed the presence of other large landslides in this area, in particular of the one known as Collesei di Anzù on the northern slope of Mt. Miesna. (Pellegrini & *alii*, 2005b).

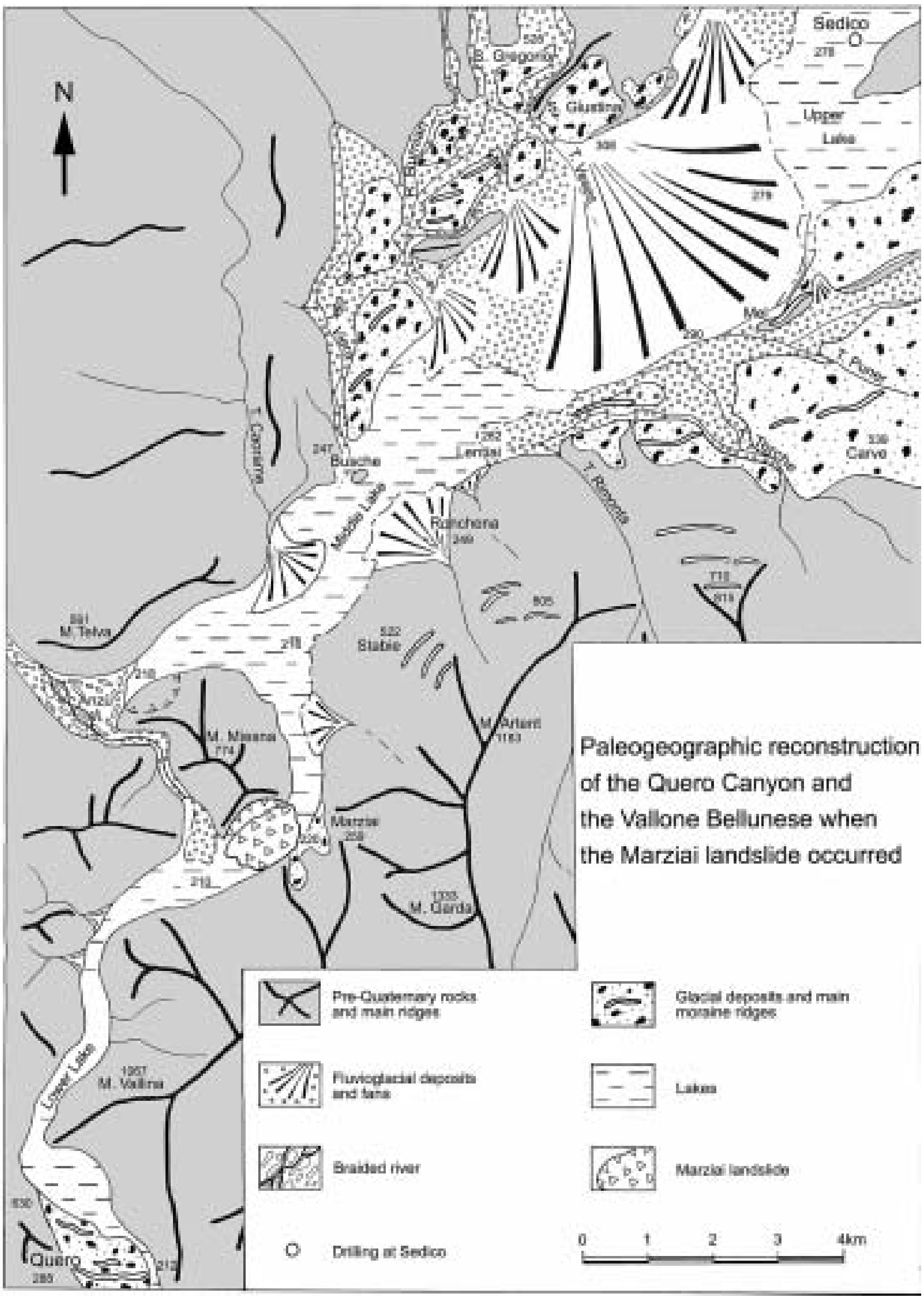
The lacustrine sediments upstream of the accumulation zone were investigated in order to date such phenomenon. Spatial distribution and thickness of such sediments were reconstructed through several drillings and vertical electrical soundings: lacustrine sediments extend for at least 5 km upstream of the landslide and have a maximum thickness of about 110 m (fig. 9). In 2001 and 2004 some drillings were carried out with the specific purpose of collecting samples for ^{14}C and OSL dating and pollen analysis. Unfortunately ^{14}C and OSL results were not useful to improve the chronology of this phenomenon. In fact the ^{14}C age of the sampled lacustrine sediments was too old (26,170 ± 150 and 31,760 ± 240 years BP), probably due to the presence of organic sediments transported and deposited into the lake. On the other hand the pollen analysis, carried out in different levels of the whole lacustrine sequence, showed low pollen concentration and the presence of species such as pine trees and artemisia, which are typical of a cold and steppic climate (fig. 10). Since the lacustrine sediments are covered exclusively by fluvial deposits and nowhere by glacial ones, there is a clear evidence that the lacustrine sedimentation, and therefore the landslide, took place after the LGM and, according to the pollen analysis, during the first phases of deglaciation (between 17,000 and 15,000 years BP).

DISCUSSION AND CONCLUSIONS

The study area, in the central-lower part of the Piave River basin, includes several gravitational phenomena which have taken place from the Lateglacial to date. Some of these phenomena have been characterised by various reactivations. This research focused on larger landslides which had remarkable effects on the morphology of valley

FIG. 7 - The Marziai landslide (the dashed line shows the scar); in the foreground the Marziai village and the Piave River.

FIG. 8 - Geomorphological sketch map of the Marziai landslide (Quero Canyon).



bottom and on stream courses. Different strategies were adopted in order to date such landslides, according to the environmental conditions in which the landslides occurred. In some cases the landslide debris reached a valley bottom free of ice and dammed the valley (Fadalto and Marziai landslides), whereas in others mass movement took place during deglaciation (Masiere di Vedana, Madonna del Parè and Masarei landslides). In the former case, both the landslide deposits and the lacustrine sediments upstream of the accumulation zone were investigated to obtain chronological data. Landslide deposits may be well preserved and exposed, for instance in the Fadalto landslide, but also almost completely buried or reworked, like in the Marziai landslide. Dating lacustrine sediments does not give a direct age of the mass movement but a minimum age that can be quite close to the real age when dating is carried out at the bottom of the lacustrine sequence or when the basin was filled in a short period of time. In the case of

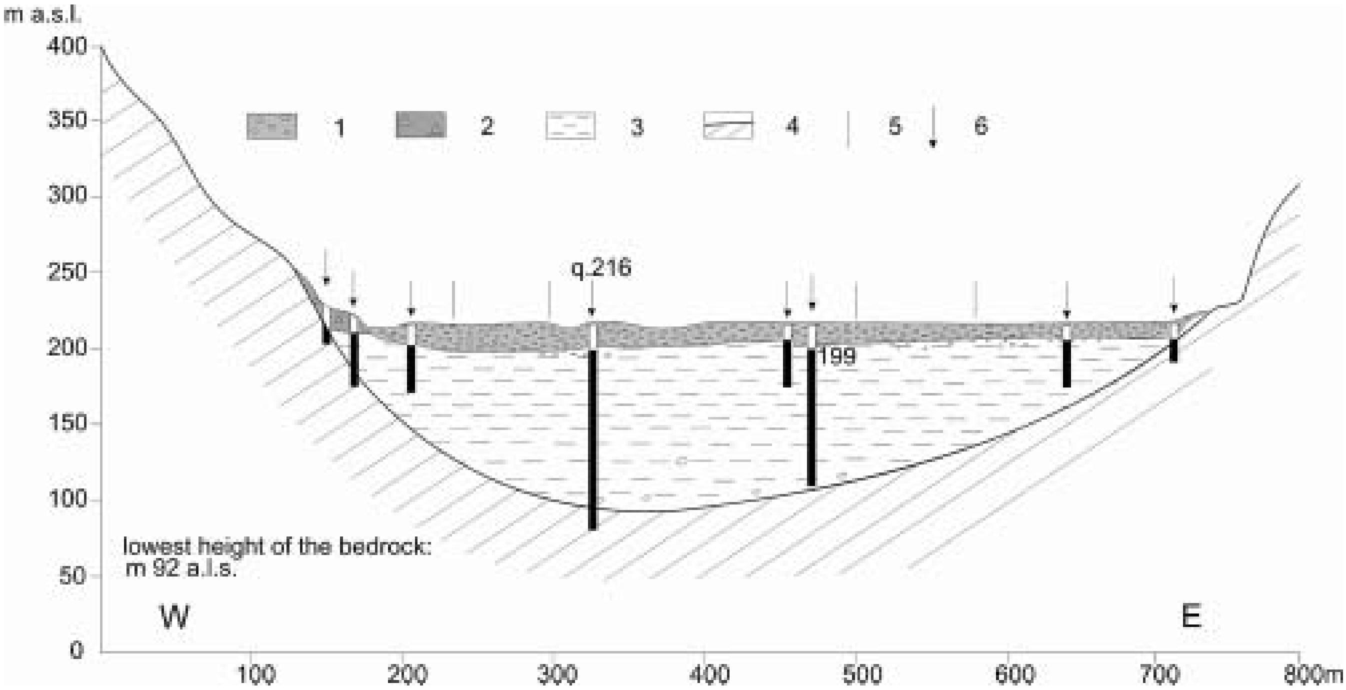


FIG. 9 - Cross section of the Piave valley, upstream of the Marziai landslide. 1: Fluvial deposit; 2: Scree slope; 3: Lacustrine deposit; 4: Bedrock; 5: Vertical Electrical Sounding; 6: Drilling.

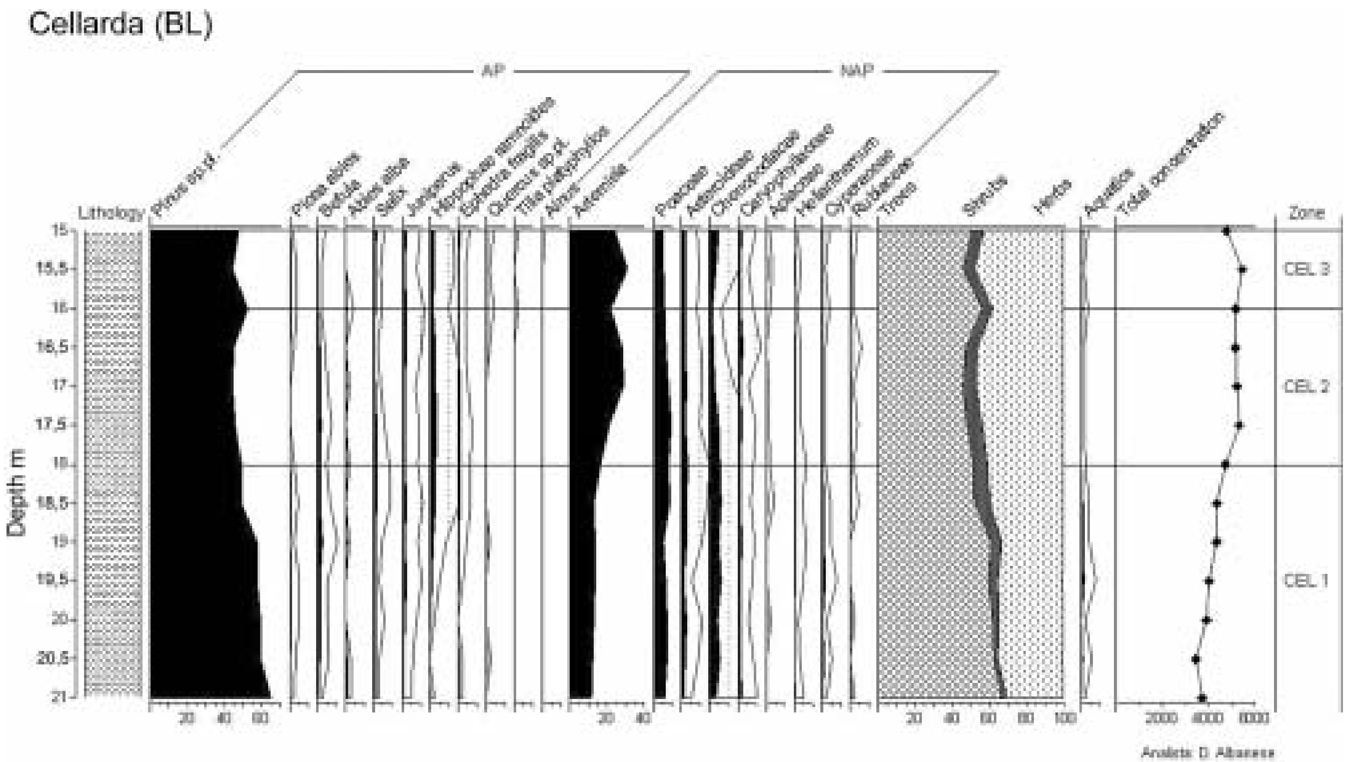


FIG. 10 - Pollen analysis of lacustrine sediments at Cellarda, upstream of the Marziai landslide (samples come from a drilling).

landslides occurring when ice masses were still in place, investigations were also addressed to define the age of the specific deglaciation phase, by dating glacial (e.g. Madonna del Parè and Masarei landslides) or glaciolacustrine sediments (Masiere di Vedana landslide).

The results of the research show that establishing landslide chronologies through radiocarbon, OSL or other methods can be quite difficult when dealing with LGM or Lateglacial events. Some of the issues that came out from the analysis of the single landslides are as follows. A first issue is the scarcity both in lacustrine and landslide deposits of organic matter suitable for radiocarbon dating. Such scarcity is due to environmental conditions: the pollen analyses carried out at Marziai (fig. 10) and Valpiana (near Madonna del Parè and Masarei landslides) show that lacustrine deposition occurred in proglacial or in recently deglaciated areas with sparse vegetation. This issue came out clearly in the study of the Marziai landslide. Even though several drillings were carried out, in one case sampling more than 80 m of lacustrine sediments (fig. 9), the organic matter found was very little. Two AMS datings were performed but results were not significant since the ages obtained were too old. Likely, the organic matter used for dating came from older sediments that were transported and deposited into the lacustrine basin. Similar unsatisfactory results were given by OSL dating that is commonly a suitable method for dating lacustrine sediments: OSL ages were too old according to geomorphological and stratigraphic evidence in this area. Therefore the chronology of the Marziai landslide is actually based on the geomorphology of the area around the mass movement, on the stratigraphical data and, most important, on the pollen analysis of the lacustrine sediments.

As for organic matter within landslide deposits, similar difficulties as those just described were found. This is due to the fact that mass movements took place when climate was still cold, there was a sparse vegetation on the slopes and valley bottoms, and glaciers were likely still in place. In the study cases, suitable samples for dating the main landslide events were not found, even though very large exposures have allowed an analysis of the whole accumulations, from the bedrock to the ground surface (e.g. Fadalto and Masiere di Vedana landslides). On the other hand, organic levels and wood remains that document Holocene reactivations of such mass movements were found and dated (Pellegrini & *alii*, 2004).

Notwithstanding problems with radiometric dating, use of different data and evidence (geomorphological, stratigraphical, geophysical, palynological) has allowed a quite accurate definition of landslide chronology. According to such data and evidences, all the examined mass movements occurred between 17,000 and 15,000 years BP, that is from the beginning of deglaciation in the Piave valley to the complete melting of glaciers in the Vallone Bellunese (Pellegrini & *alii*, 2005a). It is evident a strong relationship between the gravitational phenomena and the alpine deglaciation, which was due to remarkable climatic changes. Considering modes and times of glacier retreat (glaciers retreated from the end moraine system areas towards the Dolomitic region with a velocity of about 10 m/year, at least during the first two thousands years), the slopes of the Quero Canyon and Lapisina valley were the first to be affected by the melting of ice masses and by the absence of glacial pressure. Only later such melting had a direct effect on the slopes of upstream areas as those around Masiere di Vedana and Madonna del Parè. Therefore it is possible that the Marziai and the Fadalto landslides took place some time before the Masiere di Vedana and Madonna del Parè landslides. As for reaction time of slopes to glacier retreat, it can be concluded that these phenomena occurred in a relatively short period, that is not more than 2000 years.

As mentioned before, this area is tectonically active and there are regional faults, such as the Bassano-Valdobbiadene-Vittorio Veneto and the Belluno thrusts which border the Venetian Prealps to the south and to the north respectively. In addition to the lack of glacier mass support (Panizza, 1973), it is reasonable to suggest that those tectonic structures could have played a certain role on slope instability during a period of glacio-isostatic adjustment (Ehlers, 1996; Hetzel & Hampel, 2005). At present only data on recent uplifting are available for this area (Balestri & *alii* (1988) calculated an uplifting of 1.6 mm/year at Ponte nelle Alpi) and more geological and palaeoseismological data would be needed for evaluating if glacial unloading and/or lithospheric rebound could have induced an increase in slip rates during the Late Pleistocene. In conclusion, both in the case fault activity changed or not during and after deglaciation period, climatic changes, that induced the complete melting of large glacier masses, were the main causes for slope instability, producing gravitational phenomena of very high magnitude, never equalled after that period in this prealpine area.

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