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ALESSANDRO CORSINI (*), MAURO MARCHETTI (*) & MAURO SOLDATI (*)

HOLOCENE SLOPE DYNAMICS IN THE AREA OF CORVARA IN BADIA (DOLOMITES, ITALY): CHRONOLOGY AND PALEOCLIMATIC SIGNIFICANCE OF SOME LANDSLIDES

ABSTRACT: CORSINI A., MARCHETTI M. & SOLDATI M., *Holocene slope dynamics in the area of Corvara in Badia (Dolomites, Italy): chronology and paleoclimatic significance of some landslides.* (IT ISSN 0391-9838, 2001).

The area of Corvara in Badia, located in the Dolomites (NE Italy), is characterised by mountain groups over 3000 m high (Sella and Puez-Gardenaccia) which are connected to valleys located at about 1500 m in altitude by means of steep slopes. Besides the lithological, neotectonic and climatic characteristics of the area, the high relief energy has favoured intense gravitational slope modelling throughout the Holocene.

The study, which aimed at the reconstruction of the geomorphological evolution of the slopes surrounding the village of Corvara in Badia, has implied the geomorphological, stratigraphic and chronological analysis of landslide processes, in particular of those affecting the Col Alto-Pralongià slope, situated uphill of the village. The research has also investigated lacustrine deposits found in the surroundings of Corvara in Badia and downstream of the village, which are due to events of valley damming linked to a landslide detached form the Puez-Gardenaccia group (Col Maladat landslide). In particular, the analysis has made use of stratigraphic data obtained from boreholes, and of chronological data derived from radiocarbon dating of wood and peat remnants collected from the cores and from excavations carried out close to the surface.

The study has pinpointed that the triggering of the large complex landslides affecting the Col Alto-Pralongià slope (Col Alto landslide, Arlara landslide and Corvara landslide) occurred in the early Holocene and that subsequent phases of intense slope movements took place on the same slope during the Subboreal-Subatlantic. The ^{14}C data gathered from landslides affecting the Col Alto-Pralongià slope have also permitted the various areas progressively involved in the movements to be identified and the chronology of deposits making up actual landslide accumulations to be reconstructed. Finally, it was also proved that the plain of Corvara in Badia was affected by lacustrine deposition during the Preboreal-Atlantic and again, but to a lesser extent, during the Subboreal-Subatlantic. The evidence of a significant temporal correlation between the development of mass movements on the Col Alto-Pralongià slope and the evolution of the Col Maladat landslide was therefore proved.

Even if the landslides investigated are clearly influenced by geological factors, a cause-effect relationship seems to exist between the phases of slope dynamics outlined by the research and the climatic and environmental changes which have characterised the Holocene. The age of trigger of the landslides investigated corresponds to the early Holocene, a period that many Authors consider to be characterised by a rapid increase of temperature (followed by permafrost melting) and of precipitation. In the study area, this climate change caused in-depth infiltration and percolation of water, also favoured by the geological nature of the bedrock. A subsequent phase of slope instability, witnessed by the dating of several landslide events, corresponds to the climatic deterioration of the Subboreal - early Subatlantic periods, which has probably caused a large amount of meteoric water to be available on slopes.

KEY WORDS: Landslides, Dam lakes, Climate change, Italian Dolomites.

RIASSUNTO: CORSINI A., MARCHETTI M. & SOLDATI M., *Dinamica olocenica dei versanti nell'area di Corvara in Badia (Dolomiti, Italia): cronologia e significato paleoclimatico di alcuni fenomeni franosi.* (IT ISSN 0391-9838, 2001).

L'area di Corvara in Badia, ubicata nelle Dolomiti, è caratterizzata da gruppi montuosi di oltre 3000 m di quota (Sella e Puez-Gardenaccia) che si raccordano con ripidi pendii a vallate poste a circa 1500 m. L'elevata energia del rilievo, oltre alle caratteristiche litologiche, neotettoniche e climatiche dell'area, hanno favorito un intenso modellamento gravitativo dei versanti nel corso dell'Olocene.

La ricerca, finalizzata alla ricostruzione dell'evoluzione geomorfologica dei versanti circostanti Corvara in Badia, ha comportato l'analisi geomorfologica, stratigrafica e cronologica dei fenomeni franosi, in particolare di quelli che interessano il versante Col Alto-Pralongià, situato a monte dell'abitato. Sono stati studiati inoltre i depositi lacustri rinvenuti in corrispondenza ed a valle di Corvara in Badia, dovuti a episodi di sbarramento determinati da una frana che si distaccò dalle pendici del Gruppo Puez-Gardenaccia (la frana di Col Maladat). In particolare, l'analisi si è avvalsa dei dati stratigrafici ricavati da sondaggi meccanici e

(*) *Dipartimento di Scienze della Terra - Università degli Studi di Modena e Reggio Emilia - Largo S. Eufemia 19, 41100 Modena - Italy.*

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dei dati cronologici derivanti dalla datazione radiometrica di resti di legno e torbe rinvenuti all'interno sia dei sondaggi sia in scavi in prossimità della superficie.

Lo studio ha evidenziato che l'innesco delle principali frane, di stile complesso, che si sviluppano sul rilievo Col Alto-Pralongià (frana di Col Alto, frana di Arlara e frana di Corvara) avvenne all'inizio dell'Olocene e che sucessive fasi di intensa dinamica gravitativa interessarono il versante durante il Subboreale-Subatlantico. Inoltre, i dati ^{14}C relativi alle frane del Col Alto-Pralongià hanno permesso di individuare le aree progressivamente coinvolte nei dissesti e ricostruire la cronologia dei depositi degli accumuli di frana attuali. Si è potuto constatare, infine, che la piana di Corvara in Badia fu interessata da condizioni di tipo lacustre nel corso del Preboreale-Atlantico e nuovamente, in minor misura, nel corso del Subboreale-Subatlantico. Sussiste pertanto una significativa correlazione temporale tra l'evoluzione dei fenomeni franosi del Col Alto-Pralongià e quella della frana di Col Maladat.

Pur essendo evidente l'influenza dei fattori geologico-strutturali sullo sviluppo dei fenomeni franosi, sembra comunque esservi un rapporto di causa-effetto tra le fasi di dinamica gravitativa delineate dalla ricerca e le variazioni climatiche ed ambientali che hanno caratterizzato l'Olocene. L'epoca di innesco delle frane studiate coincide infatti con l'inizio dell'Olocene, un periodo che da vari Autori è considerato caratterizzato da rapido innalzamento della temperatura (con conseguente scioglimento del permafrost) e da aumento delle precipitazioni. Nell'area studiata, ciò causò fenomeni di infiltrazione e percolazione profonda dell'acqua, favoriti dalla natura geologica del substrato. Un successivo periodo di instabilità dei versanti, testimoniato dalla datazione di numerosi eventi franosi, avvenne in corrispondenza col deterioramento climatico del periodi Subboreale e Subatlantico inferiore, che ha probabilmente reso disponibile sui versanti una grande quantità di acque meteoriche.

TERMINI CHIAVE: Frane, Laghi di sbarramento, Variazioni climatiche, Dolomiti.

INTRODUCTION

This paper is part of a series of investigations recently carried out in the Italian Dolomites in order to reconstruct the temporal recurrence of landslides from the Lateglacial to date and define the relationships between these mass wasting processes and the climatic changes already known in literature. In particular, these investigations were carried out between 1996 and 1999 within the framework of national (Cofin 97 and 99, CNR 05, Vigoni) and European (Environment and Climate - Newtech) research projects and were concentrated in the study area surrounding the village of Corvara in Badia.

The research made use of detailed geomorphological surveys and stratigraphic analyses of the Quaternary deposits; the latter was carried out on cores from boreholes made in collaboration with the Autonomous Province of Bolzano and on surfaces observable thanks to excavation activities for building purposes. An essential contribution to research was also provided by a series of radiometric dating carried out on organic finds found in superficial materials such as landslide accumulations and lacustrine deposits.

The interpretation of the chronological data collected and the study of the geomorphological evolution of the area also took advantage of the knowledge acquired in adjacent areas with similar physiographic and geological characteristics (e.g. Cortina d'Ampezzo), in which relationships between landslide recurrence and climatic changes have been hypothesised (Panizza & *alii*, 1996, 1997; Soldati, 1999), in agreement with the most recent results attained at a European level (see Matthews & *alii*, 1997). Nevertheless, in order to correctly define the paleoclimatic significance of the landslides thus dated, the possible influence of other geological causes, in particular neotectonic and lithological ones, was also taken into account.

GEOGRAPHIC SETTING

The area of Corvara in Badia is located in the central part of the Dolomites (Italian Eastern Alps), in the Autonomous Province of Bolzano (South Tyrol), and corresponds to the southernmost sector of the Alta Badia district. The mountain ridges culminate in the dolomite peaks of Puez-Gardenaccia (3025 m a.s.l.) and Sella (3151 m) in the western sector and in the marly pyroclastic peaks of Piz la Villa (2078 m), Col Alto (1980 m) and Pralongià (2571 m) in the eastern sector (fig. 1). Access to the area is possible through the Gardena Pass (2121 m), the Campolongo Pass (1679 m) to the southwest and the narrow gorge of the Gadera stream to the north, between the villages of Corvara in Badia and La Villa. The valley floors, on which the main watercourses flow (Pissadù stream, Rutorto stream and, from their confluence, Gadera stream), range in altitude between over 2000 m near the passes and about 1500 m near the northern boundary of the study ar-

FIG. 1 - Location of the Corvara in Badia area.

ea. The slopes are usually subvertical in the upper part of the ridge (in correspondence with the dolomite peaks) and moderately inclined in the mid-lower part.

GENERAL GEOLOGICAL AND GEOMORPHOLOGICAL FEATURES

The area of Corvara in Badia is geologically illustrated by Sheet no. 11 «Mt. Marmolada» of the Italian Geological Map at a 1:100,000 scale (Servizio Geologico d'Italia, 1970) and Sheet no. 028 «La Marmolada» of the Italian Geological Map at a 1:50,000 scale (Servizio Geologico d'Italia, 1977). In this area well known formations crop out, which have been exhaustively described in literature (Leonardi, 1967; Brondi & *alii*, 1977; De Zanche & *alii*, 1993; Bosellini, 1996): they make up the sedimentary sequence of the Dolomites in the Upper Permian-Norian interval (Servizio Geologico d'Italia, 1977). The mountain groups of Puez-Gardenaccia and Sella are constituted by massif or stratified *dolostones* from the Upper-Middle Triassic (Dolomia Cassiana, Dürrenstein Formation and Dolomia Principale) and, subordinately, by *marls* and *pelites* from the Upper Triassic (Raibl Formation) (fig. 2). The Pralongià ridge and the upper part of the slopes located beneath the Sella and Gardenaccia dolomite cliffs are made up of lithological complexes, prevalently with a ductile mechanical behaviour and made up of alternating sequences of Upper-Middle Triassic *calcarenites*, *marls* and *pelites* (S. Cassiano Formation) and Middle Triassic *pyroclastic arenites* and *siltites* (La Valle Formation). The crest of the Piz La Villa-Col Alto ridge is made up of Middle Triassic *arenites* and *pyroclastic conglomerates* and *lavas* (Fernazza Formation; Pillow Lavas) which are affected by a dense network of joints with a substantially brittle mechanical behaviour. In the north-western sector of the Piz La Villa-Col Alto ridge, and in the lower portion of the northern and eastern slopes of the Puez-Gardenaccia ridge, rock types displaying different kinds of mechanical behaviour crop out; they are mainly Upper Permian-Lower Triassic *limestones*, *sandstones* and *marls* (Bellerophon Formation; Werfen Formation; Richthofen Conglomerate; Contrin Formation; Livinallongo Formation).

From the structural standpoint, in the Corvara in Badia area paleotectonic elements linked to the Upper Permian-Triassic extensional phases are found («Badioto-Gardenese ridge» and Passo Gardena line, fig. 2; Bosellini, 1965, 1968, 1996) together with displacement structures such as folds, faults and overthrusts resulting from the Tertiary Alpine compressive phases (Leonardi, 1967; Doglioni & Bosellini, 1987; Doglioni, 1990; Bosellini, 1996). Among the latter, west-verging features related to the Cattian-Aquitanian Mesoalpine compressive phase are found (Doglioni, 1987; Doglioni & Bosellini, 1987) and also south-verging features linked to the Serravallian-Tortonian Neoalpine compressive phase (Castellarin & *alii*, 1992) (fig. 2). Furthermore, some of the structures which developed during these tectonic stages were also reactivated during the Plio-Quaternary, in relation with ESE-verging late compressive phases (Castaldini & Panizza, 1991; Castellarin, 1996). This is testified by the Neogene extension fault affecting the Sella Group with a N-S direction along the Val di Mesdì and the Neogene subvertical dislocation with a NNW-SSE direction recognisable along the lineament passing through the Gardenaccia plateau, the Fraina Maradagna stream, Braida Fraida and Passo Incisa (fig. 2). On the basis of several congruous geomorphological elements (among which also the deep-seated gravitational deformations affecting the Col Alto-Pralongià slope should be mentioned and will be dealt with in the following chapters), the Passo Incisa fault is considered active, with a transcurrent dextral movement during the Plio-Quaternary (Panizza & *alii*, 1978; Carton & *alii*, 1980; Zanferrari & *alii*, 1982; Slejko & *alii*, 1989; Castaldini & Panizza, 1991).

On the whole, the geomorphology of the Corvara in Badia area is strictly related to the slopes' geological structure and reflects the different climatic conditions of the Quaternary (Corsini & *alii*, 1997). From the morphostructural viewpoint, the selective erosion processes which led to the exhumation of previously buried geological structures, have played a major role starting from the Miocene-Pliocene, when the main valleys of the area started to develop (according to Nangeroni, 1938), with the modelling of the Passo Gardena and Pralongià. At present the slopes are practically vertical at the margin of the area's dolomite reliefs, highly inclined in correspondence with the Lower-Middle Triassic outcrops of limestones and pyroclastic arenites and mildly inclined and undulated in correspondence with the north-western slope of the Col Alto-Pralongià relief, where the Late Triassic sedimentary rocks crop out.

As regards the landforms and deposits linked to the Würm Pleniglacial and Lateglacial periods, worthy of note are the Pleniglacial moraines near Pralongià and Passo Gardena, as well as the cirques, suspended valleys, glacial deposits and moraine ridges which witness the presence and progressive disappearance of valley glaciers which had developed during the Lateglacial and Holocene. In Pralongià shale clasts are found (trapped inside Pleniglacial deposits or inside landslide bodies); these confirm the Austrian provenance of the Last Glacial Maximum glaciers, which stretched south as far as the 2300 m a.s.l. altitude, as already hypothesised by Penck & Brückner (1909), B. Castiglioni (1936), Sacco (1939) and G.B. Castiglioni (1964).

On the other hand, the talus and alluvial fans bordering the base of the Sella and Puez-Gardenaccia Dolomite slopes (fig. 2) are the result of periglacial and gravitation processes.

Particularly relevant are also the landforms and deposits due to slope movements. Landslides of various types and dimensions affect practically every sector of this area (fig. 2); some of these, in particular those which involve argillaceous materials, are at present active. The situations favouring landslide processes are extremely varied, mainly depending on the different rock types involved and the stratigraphic and tectonic relations between the outcrop-

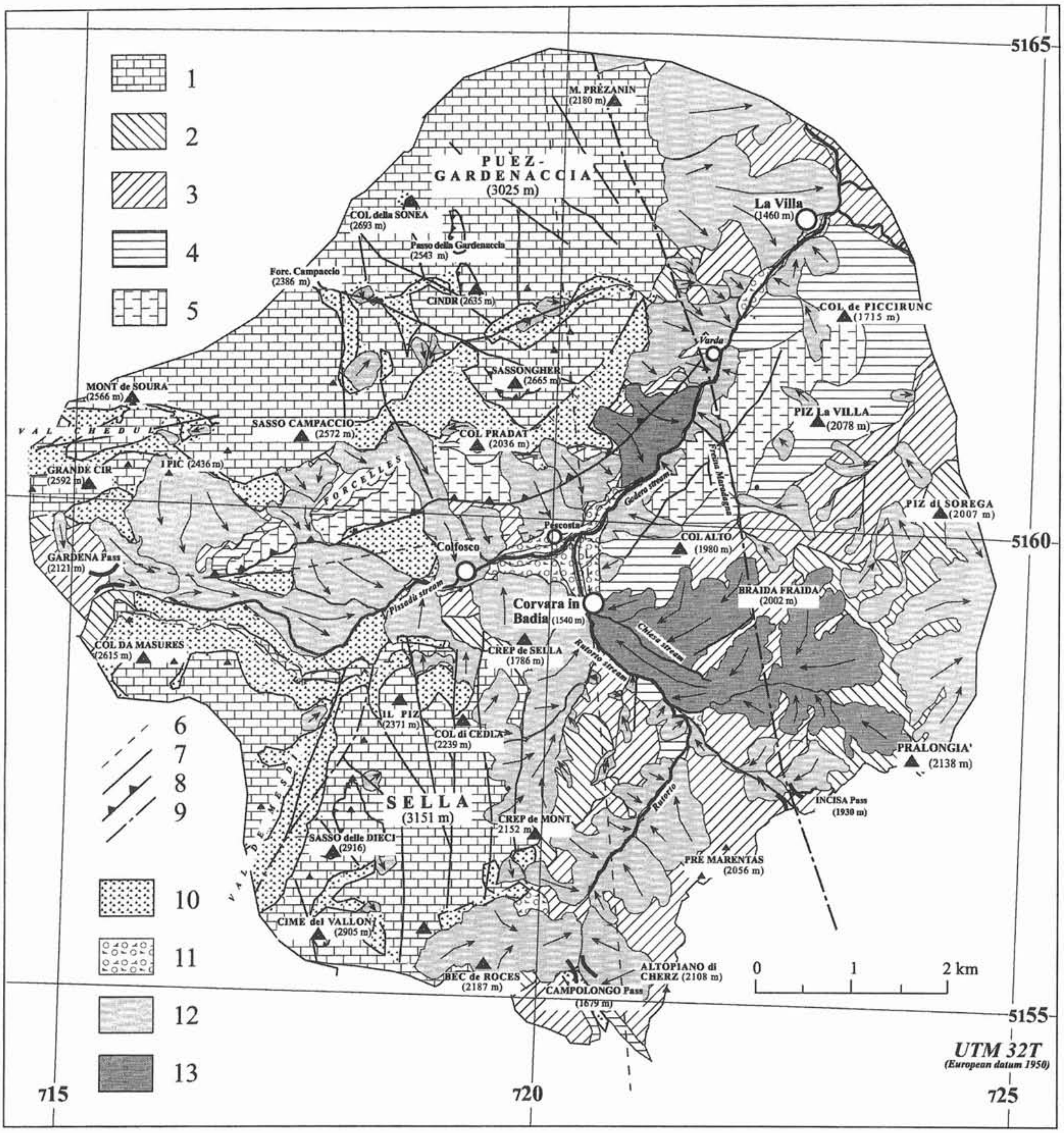

FIG. 2 - Geological schematic map of the Corvara in Badia area. Legend: 1 - dolomites and marls (Middle and Upper Triassic); 2 - alternances of calcarenites, marls and claystones (Middle and Upper Triassic); 3 - alternances of sandstones and siltstones (Middle Triassic); 4 - volcanoclastic arenites and conglomerates (Middle Triassic); 5 - limestones, sandstones and marls (Upper Permian - Lower Triassic); 6 - paleotectonic line (Upper Permian-Lower Triassic); 7 - meso-neoalpine fault (Tertiary); 8 - meso-neoalpine overthrust (Tertiary); 9 - neotectonic fault (Plio-Quaternary); 10 - scree slopes, scree fans (Lateglacial-Holocene); 11 - alluvial or lacustrine deposits (Lateglacial-Holocene); 12 - landslides (Lateglacial-Holocene); 13 - landslides investigated in detail in this paper.

ping formations. The development of numerous slope movements in correspondence with the margins of the Sella and Puez-Gardenaccia groups appears to be linked to the overlapping of jointed competent rocks, such as dolostones, on materials showing a substantially ductile behaviour, such as the S. Cassiano and La Valle formations. In this case, various types of movement combine and take place on different stretches of the same slope, affecting materials with different mechanical characteristics, thus giving origin to vast landslides with a complex and composite movement style. Other complex landslides are started owing to situations of structural weakness, or for the presence of pelitic rock types which give rise to rotational slides accompanied by earth flows. In particular, in order to reconstruct the Holocene gravitational slope dynamics, great importance is assumed by: i) rotational slides / earth flows, which involve alternating sequences of Upper-Middle Triassic pyroclastic arenites, siltites, calcarenites, marls and pelites along the north-western slope of the Col Alto-Pralongià ridge; ii) rotational slides affecting Upper Permian-Lower Triassic limestones, sandstones and marls cropping out along the eastern slope of the Puez-Gardenaccia Group. In the past, one of these mass movements barred for a long time the Gadera stream near the Col Maladat, about 1 km north of Corvara in Badia, thus causing the sedimentation of considerable layers of alluvial and lacustrine deposits, which are now terraced in correspondence with the flat area on which the village itself is located.

GEOMORPHOLOGICAL EFFECTS AND CHRONOLOGY OF SOME LANDSLIDES

In this chapter the typology, extent and chronology of the landslide processes and their associated deposits surrounding Corvara in Badia are described. In particular, the landslides affecting Col Alto - Pralongià and the lacustrine deposits near Corvara in Badia (fig. 3) are analysed. For this purpose stratigraphic data were used acquired by means of six continuous-coring boreholes (made in collaboration with the Bolzano Autonomous Province: B1÷B4 and S5÷S6 in fig. 3) and three opencast building excavations (Sections A÷C in fig. 3). Moreover, the presence of wood and peat remnants found at various levels within the landslide and lacustrine deposits, has allowed an important series of chronological data to be obtained by means of radiometric dating (tabs. 1 and 2).

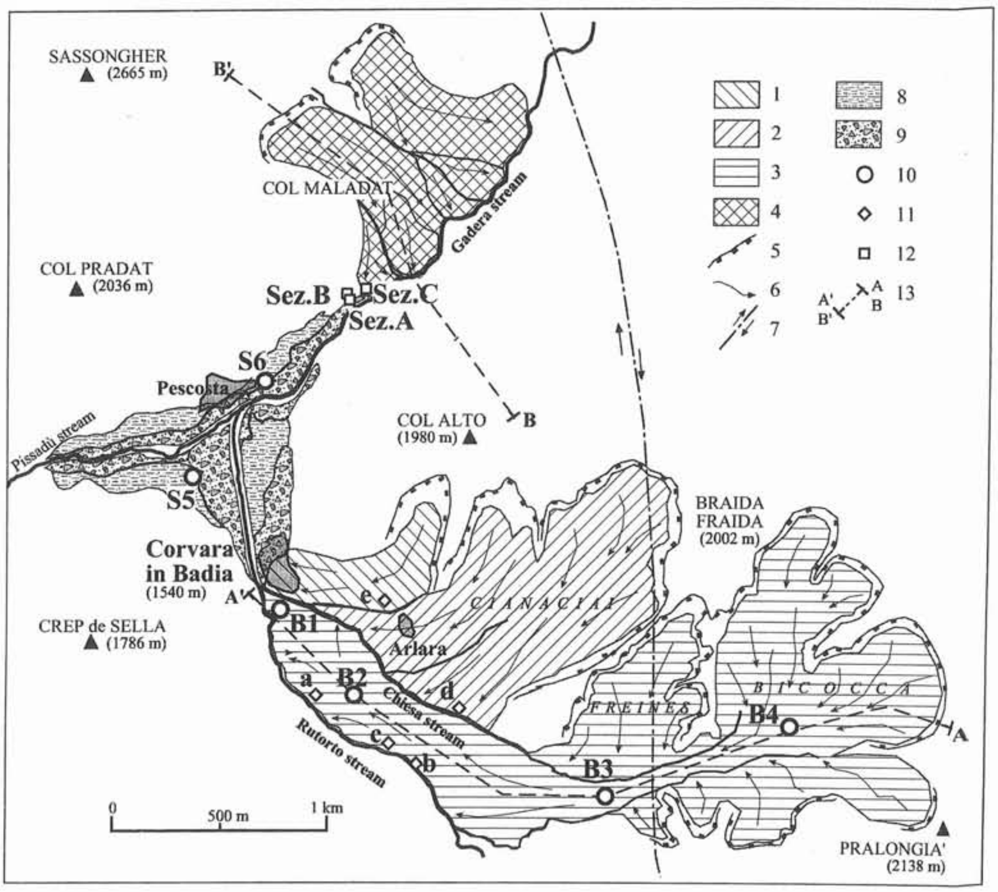

FIG. 3 - Geomorphological sketch of the landslides and lacustrine-alluvial deposits studied. Legend: 1 - Col Alto landslide; 2 - Arlara landslide; 3 - Corvara landslide; 4 - Col Maladat landslides; 5 - landslide scarp; 6 - direction of slope movement; 7 - strike-slip fault; 8 - lacustrine deposit; 9 - alluvial deposit; 10 - continuous-coring borehole; 11 - tree remnant sampled; 12 - exposed section analysed; 13 - trace of cross sections shown in figs. 5 and 6.

Complex landslides on the Col Alto-Pralongià slope

The upper Col Alto-Pralongià slope is affected by numerous complex mass wasting processes which, on the whole, may be considered as part of the same «landslide unit», as defined by Pasuto & *alii* (1997). The main gravitational movements are those from Col Alto, Arlara and Corvara (fig. 3). Their geomorphological, dynamic and chronological characteristics have been reconstructed thanks to a detailed field survey (Corsini & *alii*, 1998), supported by the analysis of cores retrieved from four boreholes on the Corvara landslide (B1÷B4 in fig. 2), and radiometric dating of tree trunk remnants found in the cores or in correspondence with river erosional cuts or excavations. The numerous ^{14}C data obtained on the landslides occurring along the Col Alto-Pralongià ridge (tab. 1) have allowed the reconstruction of the slope's geomorphological evolution during the Holocene. The ages quoted later in this text are the calendarial ages (cal. yr BP), obtained by calibrating the conventional ^{14}C ages by means of the *Radiocarbon calibration program* set up by Stuiver & Reimer (1993) on the basis of data by Stuiver & *alii* (1998). In any case, for comparison tabs. 1 and 2 show also the conventional radiometric dates (yr BP).

The *Col Alto landslide* is a rotational-translational slide which has affected the pyroclastic sandstones (Fernazza Formation) making up the western slope of the Col Alto ridge (fig. 3). The landslide accumulation, on which the oldest part of the Corvara in Badia village is located, stretches over an area of about 0.2 km^2, with a thickness of several dozens of metres, and is made up of metric boulders mixed with a silt-clay matrix. On the basis of geomorphological evidence, the accumulation may be considered dormant, even if recently it has been affected by more or less superficial reactivations, in concomitance with particularly intense precipitation, as in 1966. The type of bedrock involved in the movement and the typically concave morphology of the source area, point to a previous development following large-scale mass wasting processes. The 2708-2183 cal. yr BP age of this landslide was obtained from a tree branch with a 10 cm diameter (sample B-93976; tab. 1) brought to light (at 2.5 m from the ground level) in the intermediate portion of the accumulation zone thanks to excavations carried out for building purposes. These tree remnants have been ascribed to a Norway spruce (*Picea abies* Karsten) which probably grew on well developed forest soil (Dibona, personal communication). The destruction of the tree was probably caused by considerable rock slides in the source area, followed by earth slides which buried even older accumulation deposits of the landslide itself.

The *Arlara landslide* is a complex slope movement, definable as a rotational rock slide-earth flow (according to Cruden & Varnes, 1996), which has affected the arenaceous-pelitic rock types of the La Valle Formation between Col Alto and Braida Fraida (fig. 3). The landslide, which stretches on the whole for about 1 km^2, is bounded at the crown by a main scarp, in some places higher than 20 m. The source area is mainly characterised by the presence of a clayey material cover which has been involved in translational slides and earth flows, which at present are generally dormant. The main landslide accumulation zone is made up of a silty-clayey cover (some dozens of metres thick) surrounding a vast rock slab (on which the village of Arlara rises), which is likely to have been dismembered by deep-seated gravitational movements. By considering the geomorphological features of the slope, part of the materials originally accumulated by the landslide was probably removed by the Rutorto stream, flowing on the valley floor, whereas part of it could still be buried under the accumulation lobe of the Corvara landslide. The latter hypothesis is confirmed by the 10,000 year age obtained from wood remnants which were found at great depth in the cores of borehole B1 (fig. 3), drilled at the foot of the accumulation zone of the Corvara landslide (samples B-112032 and B-112033, fig. 4 and tab. 1). The burial of this organic material was probably linked to the development of the Arlara landslide, which in this area was later covered by the deposits of the Corvara landslide (see fig. 5). Furthermore, activity in the

TABLE 1 - Dating of landslide events which have affected the Col Alto-Pralongià slope

Landslide	Site (fig. 3)	Depth (m)	Material	Sample (lab. code)	Age ^{14}C (yr BP)	Calendar age 2σ (Cal. yr BP)	Landslide type
Corvara	B1	25.7	wood	B-112032	8820 ± 50	10,152 - 9632	Rotational slide - earth flow
Corvara	B1	26.4	wood	B-112033	8560 ± 90	9709 - 9334	Rotational slide - earth flow
Corvara	B3	22.7	wood	B-112031	7920 ± 70	9009 - 8543	Rotational slide - earth flow
Corvara	B2	7.5	wood	B-112029	4260 ± 70	5025 - 4575	Earth flow
Corvara	B2	20.0	wood	B-112030	4260 ± 70	5025 - 4575	Earth flow
Corvara	c	6.0	wood	B-105976	3830 ± 60	4417 - 3999	Earth flow
Corvara	b	4.5	wood	B-105977	2860 ± 60	3207 - 2792	Earth flow
Corvara	a	5.0	wood	B-93975	2490 ± 60	2750 - 2352	Earth flow
Corvara	B4	37.4	wood	B-112034	2260 ± 50	2351 - 2129	Rotational slide - earth flow
Arlara	d	3.5	wood	B-105975	6870 ± 50	7789 - 7592	Rotational slide - earth flow
Col Alto	e	2.5	wood	B-93976	2350 ± 60	2708 - 2183	Rotational slide - earth flow

accumulation zone of the Arlara landslide during the Preboreal-Boreal is also confirmed by the 7789-7592 cal. yr BP age obtained from sample «d» (B-105975, tab. 1), a tree trunk with over 50 cm in diameter, which was exposed (at a depth of 3.5 m from the surface) in the erosion scarp found along the right flank of the Chiesa stream. Owing to the geomorphological characteristics of the landslide, it seems that the tree was buried by earth slides linked to the onset of vast rotational slides affecting the bedrock in the source area.

The *Corvara landslide* is a complex slope movement (fig. 3), definable as a rotational rock slide-earth flow, which took place between Braida Fraida and Pralongià and affected both the La Valle and S. Cassiano formations (Corsini & *alii*, 1998). This landslide, which stretches over an area of about 2.5 km^2, is subdivided into three distinct sectors of depletion, track and accumulation. The source area, which is bounded at the crown by an over 25 m high scarp, is composed of three main sectors, separated by crests made up of rock masses which are either displaced or in their primary setting. The landslide head generally corresponds to sub-plain or reverse-slope surfaces, followed by well developed secondary scarps resulting from rotational slides which have affected the bedrock up to a depth of about 50 m. The source area is covered by clayey deposits some 40-50 m thick (B4 borehole in fig. 4). These clayey covers are subject to translational slides and flows which at present take place along multiple slip surfaces up to 30 m deep, as proved by inclinometric measurements carried out in instrumented boreholes. The track zone (some 300 m wide) is made up of a 40 m thick clayey cover showing a fair density increase from about 18 m in depth (B3 borehole in fig. 4). This cover is at present subject to a continuous translational movement on multiple slip surfaces up to 20 m deep. Moreover, the track zone is still fed by flows from the source area. The accumulation lobe spreads into the Rutorto valley at the altitude of 1720 m circa (at the 36th km of the no. 244 state

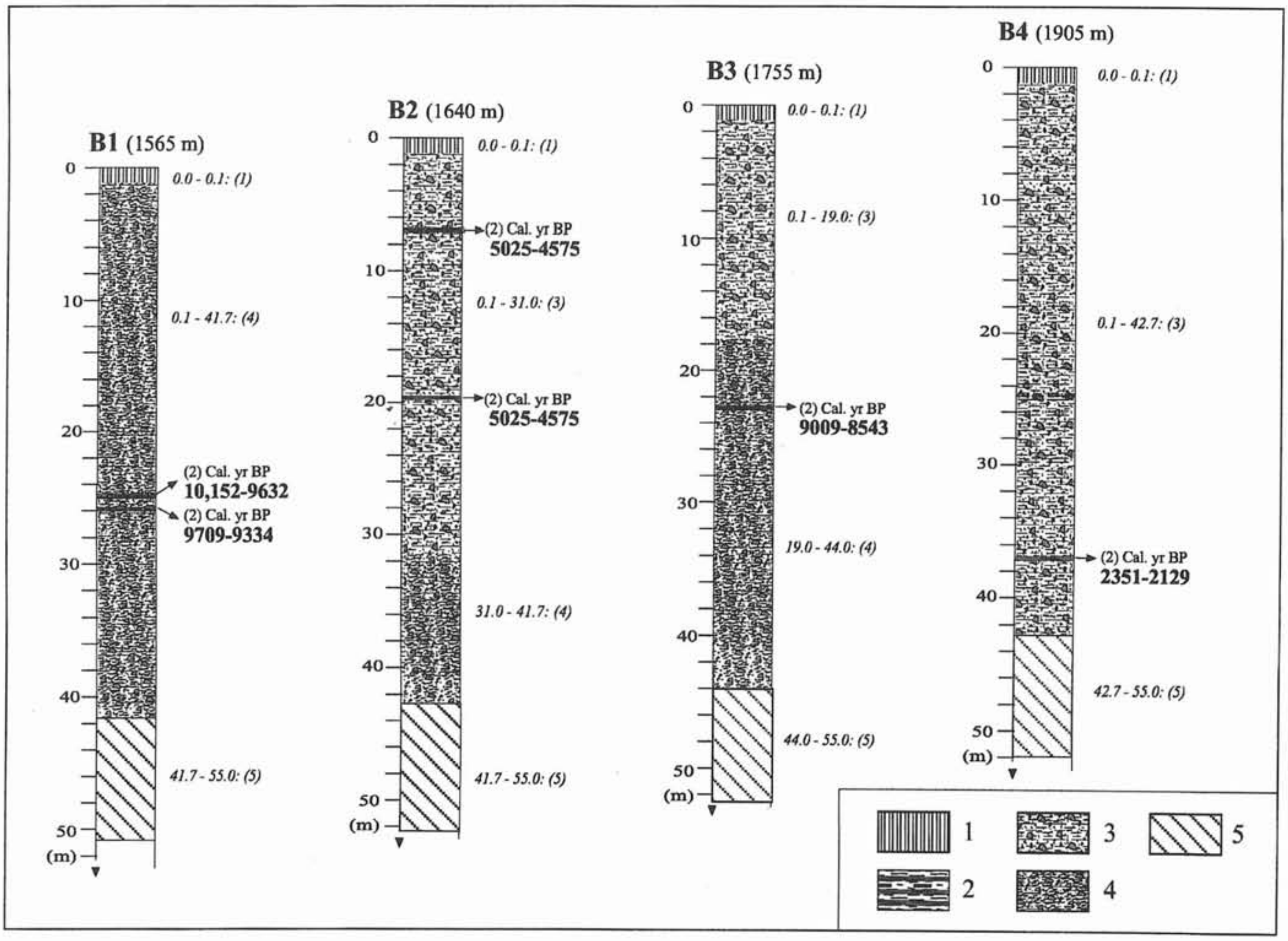

FIG. 4 - Stratigraphy and chronological data from boreholes drilled in the Corvara landslide. Legend: 1 - soil; 2 - wood or coal remnants; 3 - poorly compacted landslide deposit; 4 - highly compacted landslide deposit; 5 - weathered and fractured bedrock (La Valle Formation).

road) and stretches over a distance of 1.5 km, as far as the south outskirts of the village of Corvara (about 1540 m). This landslide portion, made up of silty-clayey material, gravel and large boulders attains a maximum thickness of about 45 m, as confirmed by boreholes B1 and B2 (fig. 4). In the case of B2, a considerable increase of material compaction is recorded from 30 m downward. Both the flanks of the accumulation lobe are characterised by often active secondary scarps, linked to slide processes triggered by the undermining caused by the Chiesa and Rutorto streams, besides the general downstream displacement of the accumulation lobe.

The most ancient ages (about 10,000 years BP) of the Corvara landslide were detected from wood remnants found at great depth in the cores of two of the boreholes drilled on the landslide body (B1 and B3; fig. 3). As previously stated, it is probable that the data obtained from the samples collected in B1 are linked to the onset of the Arlara landslide. On the other hand, the date of 9009-9334 cal. yr BP provided by the sample collected in B3 (B-112031; fig. 4 and tab. 1), in the present landslide's track zone, witnesses an early activity phase of the Corvara landslide which, by affecting the Freines area, took place by means of vast bedrock rotational slides and subsequent earth slides.

Moreover, the dates of about 4500-5000 years ago, obtained in the Corvara landslide's zone of accumulation by means of two samples collected in B2 (B-112029, B-112030; fig. 4 and tab. 1) and tree trunk «c» (B-105976; fig. 3 and tab. 1), which was retrieved from a scarp of the Rutorto stream, could be related to slides/earth flows which reactivated the landslide body accumulated in the previous activity phase. The date of 3251-2129 cal. yr BP provided by the sample collected in B4 (B-112034, fig. 4 and tab. 1) in the source area, at a depth of 37 m, witnesses a second phase of significant retrogression of the Corvara landslide's crown caused by both rotational slides and slides/earth flows. Therefore, the dates of about 2500-3000 years ago obtained from samples «a» and «b» (B-93975, B-105977, fig. 3 and tab. 1) witness a reactivation of the accumulation zone due to the widening of the source area. In particular, samples «a» and «b» are from tree trunks with diameters of about 50 cm, cropping out of the landslide body in correspondence with the Rutorto scarp. As for the tree species, specific analyses on a portion of trunk from which sample «a» was obtained (in a sub-horizontal position and perpendicular to the scarp) point to a Norway spruce (*Picea abies* Karsten) growing on a poorly developed preforestal soil (Dibona, personal communication), which could easily correspond to the landslide body itself.

On the basis of the data collected, it is possible to reconstruct the chronology of Holocene landslide events on the Col Alto-Pralongià slope and define, at the same time, the age and area of provenance of the various overlapping landslide bodies which make up the Corvara landslide (fig. 5) (Corsini, 2000).

In particular, the most ancient displacements of the Arlara and Corvara landslides, which took place between 10,000 and 8000 years ago, moved from the Cianaciai and Freines areas in corrispondence to a fault, quoted as neotectonic by Panizza & *alii*, 1978 (fig. 3). The influence of this tectonic element on the onset of slope movements is due to the jointed state of the rock masses which favoured water infiltration up to a considerable depth and the consequent triggering of rotational slides in the bedrock.

On the contrary, the subsequent landslide events responsible for the formation of the present Corvara landslide body, which go back to about 4000 years ago, should be related to the progressive dismantling of the area of Freines and the first involvement of the Bicocca area owing to scarp retrogression. The age of about 2800 years, obtained from a sample found at the bottom of

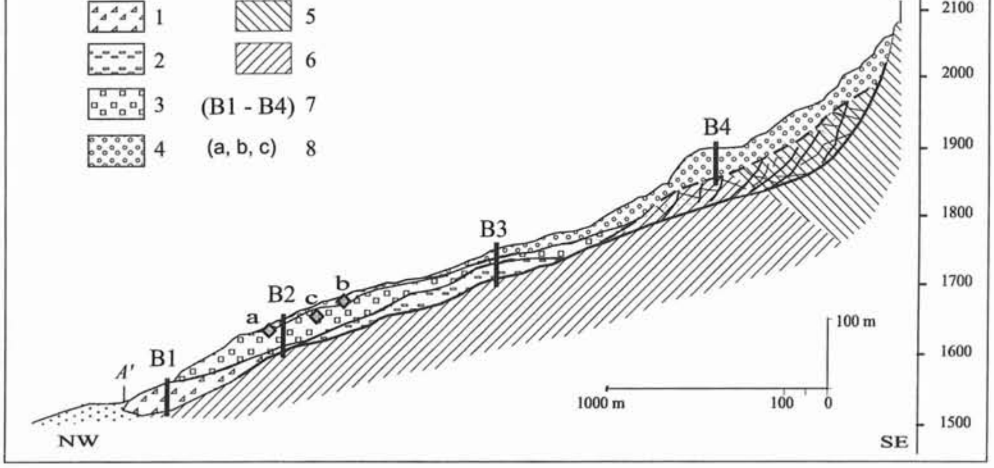

FIG. 5 - Interpreted chronological cross section of the Corvara landslide. Legend: 1 - events ca. 10.000 cal. yr BP (provenance Cianaciai: Arlara landslide; see fig. 3); 2 - events ca. 9000 cal. yr BP (provenence Freines; see fig. 3); 3 - events ca. 5000-4000 cal. yr BP (provenance Freines and Bicocca; see fig. 3); 4 - events ca. 3000-2000 cal. yr BP (provenance Bicocca; see fig. 3); 5 - La Valle Formation; 6 - S. Cassiano Formation; 7 - boreholes (see fig. 3); 8 - tree trunks collected in the Rutorto river scarp (see fig. 3).

borehole B4, in the source area of the Corvara landslide, shows that the Bicocca area was affected by the landslide only in relatively recent phases. Furthermore, the dates of about 2500-3000 years obtained from samples «a» and «b» in the zone of accumulation of the Corvara landslide, pinpoint that the activity in the source area had significant repercussions also on the accumulation zone, causing such soil disarrangement that the survival of the forest cover was inevitably doomed. Finally, it should be noticed that some 2500 years ago considerable slope displacements affected also the Col Alto landslide.

Col Maladat landslides and associated lacustrine deposits

In the plain of Corvara in Badia two main orders of alluvial terraces are found; they are located at a higher altitude with respect to the Rutorto and Pissadù watercourses. A detailed study of this area, supported by the stratigraphic data obtained from two continuous-coring boreholes carried out on the terraces (S5 and S6 in fig. 3) and by the analysis of excavation fronts some hundred metres north of Corvara in Badia (Section A to Section C, in fig. 3), has revealed that the origin of the deposits making up these terraces is ascribable to both alluvial and lacustrine sedimentation. The analysis of the geomorphological characteristics of the slopes located downstream of Corvara in Badia has allowed the origin of the valley barrage to be ascribed to rotational slides affecting the eastern slope of Puez-Gardenaccia, near Col Maladat (fig. 3). This valley barrage was responsible for the onset of lacustrine environment conditions in the plain of Corvara in Badia. The slide gave origin to a zone of accumulation made up of various-sized limestone and dolostone boulders and marls, which barred the valley floor, now cut through by the Gadera stream.

In particular, from the continuous-coring boreholes carried out upstream of the barrage in the plain of Corvara in Badia (S5 and S6, in fig. 3), conspicuous layers of lacustrine clay interbedded with organogenous horizons have been identified (especially in S6). Lacustrine sedimentation is followed by alluvial deposition (especially in S5) and, to greater depths, by gravel deposits of probable torrent origin and fluvioglacial deposits (fig. 6). Moreover, in the excavation fronts analysed (Section A to Section C, in fig. 3), gravel and sand deposits related to alluvial deposition, thin bedded lacustrine silt-clay deposits, palustrine peat deposits and coarse-grained breccias mobilised by debris flow have been recognised; they make up the top four metres of the deposits exposed in Section C (fig. 6).

Radiocarbon dating of some of the most significant samples of organic material (tab. 2) and the correlation between the different types of sediments from boreholes and sections has allowed the Holocene environmental evolution of the Corvara in Badia plain to be reconstructed. Two main phases seem to have occurred in the past, during which lacustrine and alluvial sedimentation linked to landslide damming prevailed. These phases were intervalled by a period of erosion, which led to the cutting of the barrage and the formation of first order terraces in the plain of Corvara in Badia.

In particular, the most ancient damming phase (between about 10,500 and 7200 yr BP, see fig. 6) caused the formation of a lake which occupied all the Corvara in Badia plain, with the deposition of fine materials between the altitudes of 1500 and 1522 m. The particle-size and morphological characteristics of the Col Maladat landslide, responsible for the damming, as well as the results obtained by Pirocchi (1991) and Casagli & Ermini (1999) on other landslide damming lakes in the Alps and Apennines, show that the depletion of the most ancient lake is to be ascribed to the progressive erosion of the barrage sill. On the other hand, the most recent damming phase (between about 4000 and 3200 yr BP, fig. 6) is related to a smaller impoundment which led to the deposition of fine material between the altitudes of 1499 and 1503 m in the areas close to the barrage (this phase was identified only in Sections A and B). In these areas, the cutting of the second-phase lacustrine deposits by the Gadera stream began some 3000 yr BP. In the upstream areas, which in this second phase were not affected by lacustrine conditions (e.g., in correspondence with borehole S5), a phase of alluvial deposition started, lasting in some places until the mid-20th

TABLE 2 - Dating of the lacustrine deposits of Corvara in Badia

Site (fig. 3)	Depth (m)	Material	Sample (lab. code)	Age ^{14}C (yr BP)	Calendar age 2σ (Cal. yr BP)	Geomorphological event type
S5	20.20	peat	B-112026	9080 ± 70	10,401 - 10,154	Deposition in dam lake (start of 1st phase) (first failure of Col Maladat landslide)
S6	20.24	peat	B-112028	8810 ± 70	10,173 - 9557	Deposition in dam lake (1st phase)
S6	5.47	peat	B-112027	6460 ± 90	7563 - 7213	Deposition in dam lake (1st phase)
Sez. C	4.40	wood	B-112025	7740 ± 80	8696 - 8386	Deposition in dam lake (1st phase)
Sez. B	4.20	peat	B-112023	3550 ± 70	4075 - 3640	Deposition in dam lake (start of 2nd phase) (Col Maladat landslide reactivation as debris flow)
Sez. B	1.44	wood	B-112022	3210 ± 60	3626 - 3272	Deposition in dam lake (end of 2nd phase)
Sez. A	0.48	soil	HD-19408	1249 ± 22	1263 - 1090	Recent soil

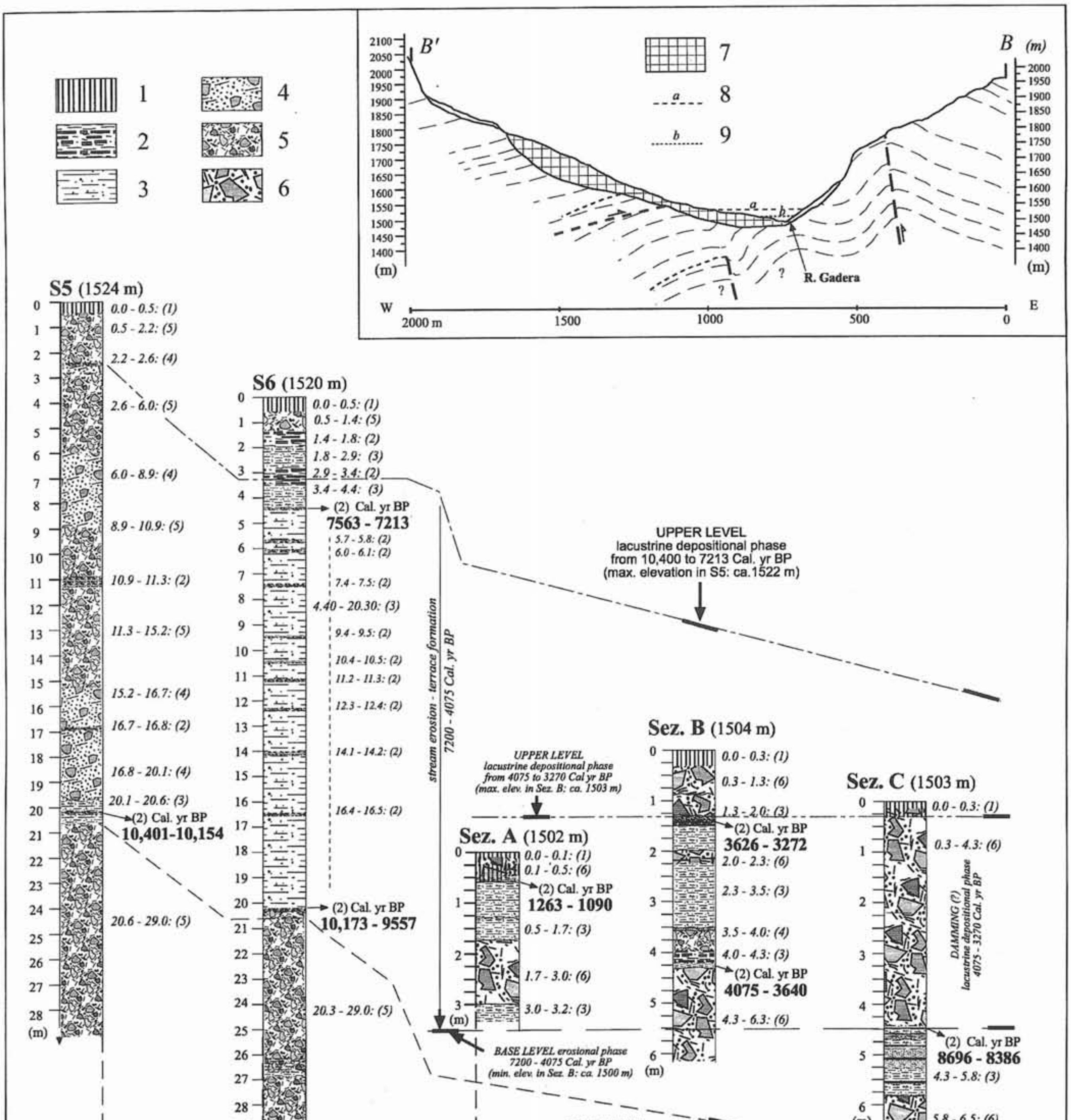

FIG. 6 - Stratigraphy, chronology and correlation of terraced deposits at Corvara in Badia and cross section of the Col Maladat landslide. Legend: 1 - soil; 2 - peat and coal remnants; 3 - lacustrine clay and silt; 4 - lacustrine silt with alluvial inflows; 5 - alluvial and fluvioglacial gravel and sand; 6 - debris flow angular blocks and gravel; 7 - Col Maladat landslide; 8 - valley damming elevation 10,400-7213 cal. yr BP; 9) valley damming elevation 4075-3270 cal. yr BP.

century (as shown by 1955 aerial photographs). The formation of the second order terraces found in the Corvara plain is in fact a consequence of the hydraulic works implemented after the 1966 intense precipitation.

The ^{14}C data relative to the lacustrine deposits of the Corvara in Badia plain show that the onset of the Col Maladat rotational slide, about which no direct data exist, presumably took place some 10,000 years ago (data obtained from B-112026 and B-112028 samples, collected from S5 and S6 boreholes respectively, in correspondence with the appearance of fine lacustrine-type sediments; tab. 2). This event barred the valley with a sill exceeding the altitude of 1520 m (which is the maximum altitude at which lacustrine deposits were found in S5 and S6; fig. 6). A subsequent reactivation, which took place about 3800 years ago (B-112023 sample, collected at Section B; tab. 2), caused the formation of a barrage with a sill exceeding 1503 m a.s.l., which is the maximum altitude at which lacustrine deposits were found in Sections A and B (fig. 6). From the analysis of the landslide's morphological features, it results that this reactivation took place by means of debris slides and flows. The debris flow blocks that were found in Section C (in which deposits ascribable to this second lacustrine phase were not found, fig. 6) could in fact belong to the landslide deposits responsible for the second damming phase.

RELATIONSHIPS BETWEEN GEOMORPHOLOGICAL EVOLUTION AND PALEOCLIMATE

The area of Corvara in Badia was affected by typically glacial environmental conditions until 18,000-20,000 yr BP, when the pleniglacial cover, which attained elevations near to 2300 m, started to undergo a rapid decline. Later, during the Lateglacial period, the area was affected by valley-type glaciers but, at the same time, there was a quick transition towards periglacial environmental conditions, as shown by data resulting from studies on the temporal recurrence of landslides in the adjacent Cortina d'Ampezzo area (Panizza, 1973; Panizza & *alii*, 1996; Panizza & *alii*, 1997; Pasuto & *alii*, 1997; Soldati, 1999) and from the paleoclimatic reconstructions by Orombelli & Ravazzi (1996). The latter have been taken as a reference for the present discussion on the relationship between geomorphological evolution and paleoclimate. The change of the environmental conditions which accompanied the beginning of the Lateglacial led to a morphogenesis linked mainly to frost-shattering processes and slope movements which gave origin to both talus and debris fans and massive rock falls from the dolomite cliffs. The geomorphological characteristics of some complex landslides of the Alta Val Badia - which are not described in this article - seem to suggest that during the Lateglacial some slopes were subject to deep-seated gravitational deformations linked to the neotectonic fault affecting the eastern sector of the Puez Gardenaccia and the Col Alto - Pralongià ridge which was previously discussed (Panizza & *alii*, 1978; Corsini, 2000).

With the beginning of the Holocene, some 10,000 ^{14}C yr BP (Mangerud, 1982), a considerable increase in temperature caused the progressive disappearance of permafrost on the lower slopes, which are generally characterised by arenaceous-marly bedrock with a dominant pelitic component, and the onset of forest vegetation, which at the end of the Preboreal, attained altitudes near to 2000 m[1]. Indeed, it was just during the Preboreal and Boreal that the complex slope deformations previously described were triggered, i.e. the rotational-translational slides and earth flows of the Col Alto-Pralongià slope, and the Col Maladat rotational slide which gave origin to a long lasting valley barrage.

Later, during the Atlantic period, which was characterised by «optimal» climatic conditions, the already existing landslides underwent a phase of relative dormancy. In this period, the morphogenesis of the area was probably conditioned by prevailing frost-shattering processes (which increased the thickness of debris and alluvial fans) and by the action of surface water. In the area of Corvara in Badia, where a lacustrine impoundment was present, sedimentation processes were rather intense. The data concerning this area (fig. 6) show that in about 2500 years over 20 m of clay, gravel and peat were deposited, corresponding to a sedimentation rate of nearly 1 cm/yr. The abundant input of sediments into the lacustrine impoundment may also be justified by considering the erosional action of the Rutorto stream on the Arlara and Corvara landslide bodies.

The climatic worsening which took place in the Subboreal period and during the first Subatlantic phase coincided with the reactivation, widening and retrogression of most complex landslides occurring along the Col Alto-Pralongià slope. The increase of precipitation during this period probably had consequences also on the erosional power of the watercourses. Between 6500 and 3500 years ago, following the erosion of the barrage of the Col Maladat landslide, the Rio Gadera cut through the materials deposited near Corvara in Badia for a thickness of about 20 m. This took place during the previous lacustrine phase, thus causing the formation of the marked terracing still visible on the site. The gravitational activity due to landsliding processes continued with the further increase of precipitation, which occurred about 2500 yr BP, and with a strong repercussion on the landslides of Col Maladat (which once again dammed the Gadera valley), Corvara and Col Alto.

During the Subatlantic, the environmental conditions were on the whole very similar to the present ones and deep-seated landslides remained probably dormant.

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[1] According to Burga (1988), during this period in the Swiss Alps the tree line rose from 1300 m to nearly 2000 m a.s.l.

FINAL REMARKS

The geomorphological and stratigraphic study of the landslide deposits observable on the Col Alto-Pralongià slope and of the lacustrine sediments found near the Corvara in Badia plain, together with radiometric dating on organic remnants enclosed in these deposits, have allowed a detailed reconstruction, also from the chronological viewpoint, of the geomorphological evolution of some slope's portions surrounding the village of Corvara in Badia, identifying the phases of intense gravitational activity.

The data collected demonstrate the existence of a certain chronological correspondence between onset of movement and phases of development of the Arlara and Corvara landslides, on the Col Alto-Pralongià slope, and of the Col Maladat landslides, which are held responsible for the formation of a large dam lake in correspondence with the Corvara in Badia plain.

Furthermore, there is likely to be a correlation between the dated landslides and the climatic vicissitudes which have affected the Alps since the beginning of the last deglaciation. The triggering of slope movements chronologically corresponds to the considerable increase of temperature of the Early Holocene, which caused the withdrawal of glacial tongues and the melting of permafrost. On the other hand, further stages of landslides' intense activity correspond to the humid periods of the second half of the Holocene.

The data achieved in this research, although they are not sufficient for defining a direct and reciprocal relationship between a slope's weathering processes and climatic changes, have nevertheless confirmed some hypotheses already emerging from previous investigations carried out in adjacent areas (see Soldati, 1999; Corsini & *alii*, 2000).

Although a certain uncertainty remains about the causes which triggered the landslides investigated (the initial movement might be linked also to neotectonic causes), it seems logical to hypothesise that during the deglaciation period the progressive disappearence of permafrost allowed water infiltration through the rocks' joints and other discontinuities. Therefore, the increase in temperature may be considered, in any case, a determining cause for the ancient displacements that affected the Arlara, Corvara and Col Maladat landslides.

The landslide events studied and, in particular, their phases of activation alternating with periods of dormancy, seem to be significant geomorphological indicators of climatic changes, although it is not possible to identify a direct cause-effect relationship between landslides and climate changes. In particular, there are some limits for their use as indicators; indeed, the landslides investigated developed in correspondence with tectonic features (considered as neotectonic by Panizza & *alii*, 1978) which might have caused or simply favoured the onset of displacements. Moreover, the lithological characteristics and geological structure of the study area are, on one hand, a limiting factor for the use of these landslides as indicators and, on the other hand, a determining one. Slide and flow landslides, which are produced on pelitic rocks with poor geomechanical characteristics are generally highly influenced by climate conditions. At the same time, though, these rock types are responsible for a limited persistence of the accumulation forms on slopes; slide and flow-type landslides are in fact quickly obliterated and their persistence in time is directly proportional to the material volumes involved. It can therefore be inferred that, in order to evaluate medium and long-cycle climatic changes, small-sized slides and flows are generally not utilisable, whereas landslides involving large volumes of material, such as those investigated in the study area, are extremely useful.

Furthermore, slide and flow landslides allow appreciable climate changes to be identified when they occur after a sufficiently long period of dormancy, that is after the colonisation of the landslide body by arboreous vegetation. However, when one of these events takes place, the mass wasting process continues mostly indipendently of climate conditions, until the whole slope has come to a new equilibrium (*relaxation time* according to Allen, 1974, and Brunsden, 1980).

On the basis of the data available, it is therefore possible to hypothesise a close relationship between deglaciation and onset of the vast slope movements present in the study area (Arlara, Corvara and Col Maladat landslides), in agreement with the data from other European areas. At the same time, the support of other data would be necessary for maintaining the assumption of a massive resumption of erosional slope activity during the humid phases of the Subboreal period.

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