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GEOMORPHOLOGICAL EVOLUTION OF SLOPES AND CLIMATE CHANGES IN NORTHERN ITALY DURING THE LATE QUATERNARY: SPATIAL AND TEMPORAL DISTRIBUTION OF LANDSLIDES AND LANDSCAPE SENSITIVITY IMPLICATIONS

Abstract: Soldati M., Borgatti L., Cavallin A., De Amicis M., Frigerio S., Giardino M., Mortara G., Pellegrini G.B., Ravazzi C., Surian N., Tellini C. & Zanchi A. In collaboration with: Alberto W., Albanese D., Chelli A., Corsini A., Marchetti M., Palomba M. & Panizza M., *Geomorphological evolution of slopes and climate changes in northern Italy during the Late Quaternary: spatial and temporal distribution of landslides and landscape sensitivity implications*. (IT ISSN 1724-4757, 2006).

This paper deals with the use of landslide records in the analysis of landscape sensitivity, with particular reference to climate change as a forcing process. The dating of past landslide events is useful to reconstruct the evolution of the slope-system at a broad temporal scale and to recognize the different formative events it has experienced. If the environmental context can be defined by means of a multidisciplinary approach which comprises geomorphological, sedimentological, palaeobotanical, dendrochronological and archaeological analysis, then a deep understanding of the relationship between the possible triggering factors and the responses of the landscape can be achieved. The goal is to recognize the temporal changes through environmental factors which condition landsliding events such as climate, seismic activity, vegetation and land use, trying to identify the relationship between landslide events and their initiating process, which is known to be complicated by the behaviour and the properties of the hillslope system, in other words its sensitivity.

The conceptual and methodological aspects of the topic are discussed, aiming primarily at the reconstruction of the temporal occurrence of landslides and at the assessment of possible clustering of climate-induced landslides, as a consequence of the slope-system sensitivity to climate changes. Case studies in the Alps and in the northern Apennines are described and the research perspectives are outlined.

Key Words: Landslide events, Climate changes, Slope sensitivity, Alps, Northern Apennines, Italy.

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Questo lavoro descrive l'utilizzo di archivi di eventi di frana nell'analisi della sensibilità del paesaggio, con particolare riferimento alle variazioni climatiche quale fattore condizionante. La datazione di eventi di frana preistorici è utile ai fini della ricostruzione dell'evoluzione del sistema versante ad una scala temporale ampia e del riconoscimento dei differenti eventi formativi da cui il versante è stato interessato. Quando le condizioni ambientali possono essere descritte attraverso un approccio multidisciplinare che comprende analisi geomorfologiche, sedimentologiche, paleobotaniche, dendrocronologiche e archeologiche, è possibile ottenere una conoscenza approfondita delle relazioni tra i potenziali fattori innescanti e la risposta del paesaggio. L'obiettivo è di descrivere le variazioni nel tempo dei fattori ambientali che condizionano la franosità, come il clima, la sismicità, la vegetazione e l'uso

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del suolo nel tentativo di identificare le relazioni tra eventi di frana e fattori innescanti, che come noto sono complicate dal comportamento e dalle caratteristiche del sistema versante, in altre parole dalla sua sensibilità.

Gli aspetti concettuali e metodologici della tematica sono discussi, con la finalità principale di ottenere una ricostruzione della ricorrenza temporale di fenomeni franosi e di riconoscere eventuali concentrazioni di eventi indotti da variazioni climatiche, come conseguenza principale della sensibilità del sistema versante alle variazioni climatiche.

Sono descritti casi di studio nelle Alpi e nell'Appennino settentrionale, oltre ai possibili sviluppi futuri della ricerca.

TERMINI CHIAVE: Eventi di frana, Variazioni climatiche, Sensibilità del paesaggio, Alpi, Appennino settentrionale, Italia.

INTRODUCTION

The concept of landscape sensitivity (Brunsden & Thornes, 1979) deals with the relationships between the environmental forces that drive landscape change and the organisms, soils and landforms which comprise landscapes. In particular, the concept concerns the likelihood that a change in the controls of the system or in the forces applied to it will produce a recognisable and complex response (Brunsden, 2001). The analysis of landscape sensitivity has to be performed in a four-dimensional framework, including space and time (Thomas, 2001).

Considering landsliding one of the main geomorphological processes that contribute to the evolution of a landscape, it is assumed that the stability of the landscape itself is a function of the spatial and temporal distribution of the resisting and driving forces, and to the effect of barriers to change (Brunsden, 2001). Therefore, the sensitivity of the terrain is strictly related with the system stability and is a function of the frequency and the magnitude of formative events. In particular, in the case of landsliding, the formative events generally show an episodic behaviour (Crozier, 1999) that can be inherent to the forcing process (i.e. rainfall, earthquake) or can be related to the system inertia to the forcing process (Terzaghi, 1950).

This episodical behaviour of landsliding processes is recorded by the event stratigraphy. On this basis, in an area with sufficiently constant and well-known geological and geomorphological features, the research can focus on the temporal evolution of the hillslopes, and on the triggering factors of the clusters of events. It follows that, if the sensitivity of landscape to climate change as a forcing process has to be assessed, landslides could be considered as one of the indicators of instability in the system. In fact, by means of dating past landslides, the landslide event stratigraphy achieved can be correlated with the climatic reconstructions obtained through other proxy records.

An Italian research project[1] has been dealing with the study of the relationships between climate and slope evolution, with particular attention to mass movement processes. More precisely, the aim is to assess the relationships between periods of enhanced landslide activity and palaeoclimate from the Lateglacial to the present, with reference to the southern Alps and northern Apennines, by adopting slope instability processes as geomorphological indicators of the slope-system sensitivity to climatic changes.

The research carried out considers, on the one hand, the dating of slope movements obtained by means of different methods and on different temporal scales and, on the other hand, the reconstruction of climatic changes, based on the fluctuations of climatic parameters or proxies. The analysis of the possible temporal correlations between landslide events and climate allows comparative chronological schemes to be constructed for different regions and considerations on the cause-effect relations between the various processes to be deduced.

The investigations have been carried out in test areas located in the western and central Alps, in the Dolomites, in the Belluno Prealps and in the Emilian Apennines, which have distinct characteristics, especially in terms of richness of available information, so to be considered as natural laboratories for the study of slope dynamics.

The research has shown the potential of this approach to reach some conclusions on landscape sensitivity implications with respect to slope instability phenomena and climate changes, and to understand the present and future geomorphological evolution in mountain areas and therefore to assess landslide hazards in the frame of global changes.

CONDITIONING AND TRIGGERING FACTORS OF LANDSLIDES AT A BROAD TEMPORAL SCALE

Geomorphology may contribute to the reconstruction of slope sensitivity under the forcing of climate changes by analysing present landforms and their evolution in space and time. Geomorphological indicators of climatic changes (Goudie, 1992) should be defined with great care since the evolution of landforms is controlled by several factors, besides climate. For example, a landslide process may be triggered by an earthquake, by river erosion, by meteorological events of a certain intensity and/or duration. Moreover, the response of a slope is influenced by the distribution of vegetation thickness of the weathered layer, steepness, aspect, altitude range and land use. Finally, it should be pointed out that some types of landslides are more sensitive than others to meteorological events and climatic changes. For example, in order to trigger debris flows or soil slips, heavy meteo-climatic conditions are necessary, which are different from those triggering rock slides and rock avalanches.

Also the frequency of landslide activity varies in space and time and depends on the terrain susceptibility and the intensity of triggering factors (Crozier & Glade, 1999). Furthermore, the assessment of a site's sensitivity to slope movements is of paramount importance (Crozier, 1997). In fact, the Factor of Safety prior to the event depends on the intrinsic slope conditions rather than climatic conditions in a strict sense. A change in the Factor of Safety with time is a natural phenomenon (Terzaghi, 1950): on

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[1] *MIUR - COFIN 2002 Project «Geomorphological evolution of slopes and climate changes: landslide analysis and palaeoclimatic reconstructions», funded by the Italian Ministry of Education, University and Research (National Scientific Coordinator Prof. M. Soldati). Research Units: Università di Milano-Bicocca, Modena e Reggio Emilia, Padova, Parma and Torino, with the collaboration of several public institutions.*

some slopes it tends progressively to decrease due to the response to different potential causes of slope instability both external, such as climatic and seismic ones, and internal, such as geological, structural and hydrogeological causes. It is also clear the same slope, upon failure, may move back to stability.

Therefore, a single climate fluctuation can indeed set off different consequences, not only on different regions but also on a limited area. In fact, single slopes may have had a certain evolution, also as a consequence of non-climatic causes.

On this basis, it is clear that the dating of past landslide events is useful to reconstruct the evolution of the slope system at a broad temporal scale and to recognize the different formative events it has experienced. When a significant database of landslide events is created, then some conclusions on the temporal changes in the environmental factors which condition and trigger landsliding such as climate, seismic activity, vegetation and land use, can be drawn.

Some ideas on Late Quaternary climatic fluctuations and their influence on landslide activity are first discussed, then geological and structural conditioning factors in the study areas are described.

LATE QUATERNARY CLIMATIC FLUCTUATIONS AND THEIR INFLUENCE ON LANDSLIDE ACTIVITY

The reconstruction of climatic fluctuations in the Quaternary is based on multidisciplinary criteria and has undergone a considerable development in the past few years, after the drilling of boreholes in the ice caps of Greenland and Antarctica and after the in-depth studies of numerous marine, continental, and lacustrine sequences.

As far as the reconstruction of climate evolution during the Holocene is concerned, thanks to pollen databases, a detailed temperature reconstruction with time resolution up to 100 years at the regional scale of the Alps is available (e.g., Davis & *alii*, 2003). This reconstruction reveals slight temperature variations during the last 8000 years, confirmed also by local reconstructions from chironomids (e.g., Heiri & Millet, 2005), tree rings (e.g., Nicolussi & Patzelt, 2000) and oxygen isotopes measured on ostracod valves (e.g., Von Grafenstein & *alii*, 1999). While Holocene temperature variability shows only weak fluctuations, there is documentation of significant glacier pulses (Ivy-Ochs & *alii*, 2005), as well as major changes in the hydrological regime of lakes (Magny, 2004) together with changes in intensity and frequency of major floods of alpine rivers (Arnaud & *alii*, 2002). It can be concluded that Alpine Holocene climate variability mainly consisted of changes in rainfall regime, in terms of intensity and duration. It is well known that mass movement activity is triggered by rainfall regime changes, and this provides a key to interpret the periods of enhanced landsliding compared to Late Glacial and Holocene palaeoclimatic records. However, a special care is required in the consideration of the regional setting, north or southward exposure, humid or arid, high levels in annual temperature changes and other factors lead to differently scaled or delayed signals in the climate history.

Since local-scale climate reconstructions are not available for the study sites, errors can be made in the correlation between landslide events and boundary climatic conditions by applying schemes obtained in areas located at different latitudes and different geographic setting. Furthermore, local response to global climatic changes depends on the sensitivity of the site considered and, in any case, each climatic event tends to be diachronic in space and time (Walker & *alii*, 1999).

In conclusion, local climate variability and the occurrence of exceptional meteorological events cause a sort of «background noise», which cannot be completely eliminated. This limitation can be overcome by obtaining local-scale palaeoenvironmental reconstructions, which can be correlated with the regional and global reconstructions respectively (e.g., Borgatti & *alii*, in press).

RESEARCH OBJECTIVES AND METHODS

The research has been addressed to the following objectives:

- define the state of the art at an international level;
- create an archive of dated landslides in the southern Alps Late Glacial and in the northern Apennines (fig. 1) since the using Geographical Information Systems;
- identify and study landslide phenomena which are believed to be significant indicators of climatic variations;
- provide the selected landslide events with a chronological frame, by applying radiometric dating, incremental methods etc.;
- reconstruct palaeoclimatic and palaeo-environmental conditions at the local scale in the study areas, by means of pollen analyses;
- evaluate the importance of climatic control in relation to the type of landslides considered and the influence of climatic crisis on the occurrence of landslides;
- evaluate the influence of non-climatic causes, with particular attention to palaeo-seismicity and human impact in prehistoric times;
- define geotechnical models of the slopes affected by landslides, so as to define their evolution with respect to different hydrogeologic and environmental boundary conditions;
- compare landslide events chronologies in the study areas with other palaeo-environmental proxies, obtained at different time and spatial scales, in order to assess the relationship between slope instability processes and climate changes.

From the methodological viewpoint, two aspects deserve special attention and will be taken into account in detail in the following sections. In order to analyse the temporal distribution of past landslide events from the Lateglacial, the application of different dating techniques to landslide deposits is a key issue. The second aspect is

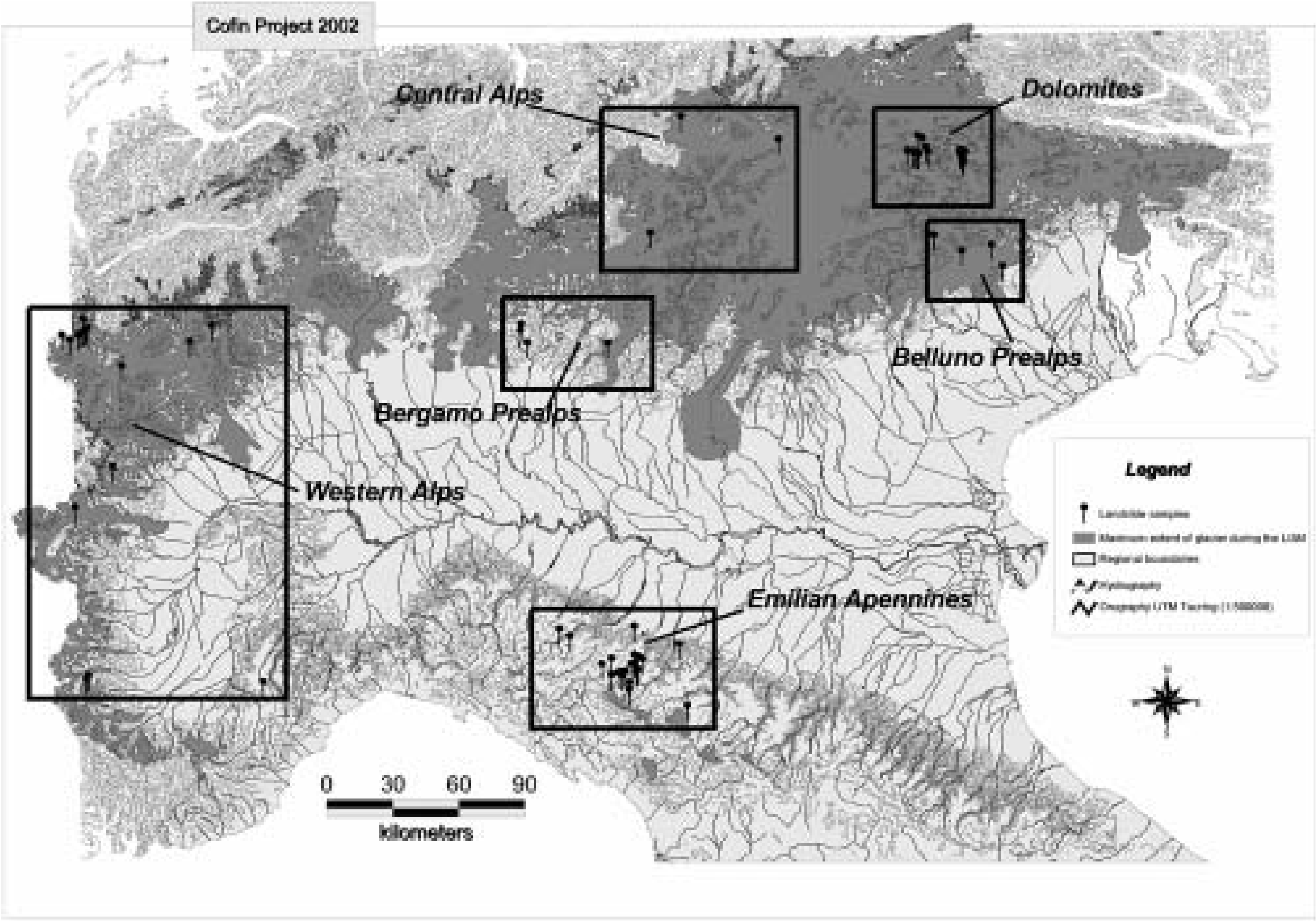


FIG. 1 - Geographical distribution of the study sites and of the dated landslides. The maximum extent of glacier during the LGM is adopted from Orombelli & *alii* (2004).

related to the implementation of a specific database that, besides the storage of datings allows spatial analysis to be carried out. The structure of the database is shown below, with particular reference to the typology of data.

Dating methods - state of the art and applications within the project

The following methods have been used to date the mass movements: isotopic and radiogenic (radiocarbon, thermoluminescence, TL and optically stimulated luminescence, OSL), sidereal (dendrochronology) and biological (lichenometry and palynology) (tab. 1). A reference work explaining the fundamentals of the different techniques applied to the dating of landslide landforms and deposits is Lang & *alii* (1999).

Radiocarbon dating (both decay counting and AMS) is the most valuable method. It is suitable to provide age constrains for the Holocene and some Late Glacial mass movements, as far as organic matter derived from terrestri-

TABLE 1 - Some characteristics of the dating methods, some of which have been used in this study; the ranges of applicability are according to Noller & *alii* (2000)

Dating technique	**Type of result**	**Material**	**Range of applicability**	**Application in this study**
Radiocarbon	Numerical-age	Wood, organic soil, etc.	From 300 to 55,000 years BP	yes
TL and OSL	Numerical-age	Fine sediments (sand and silt)	Last 500,000 years (or more in some cases)	yes
Dendrochronology	Numerical-age	Wood	Last 7000 years (or more in some cases)	yes
Lichenometry	Relative and calibrated-ages	Lichens	Last 1000 years (up to last 10,000 years in arctic/alpine environments)	no
Palynology	Relative-age	Pollens	—	yes

al plants is available. Many typologies of terrestrial plant debris were used. Tab. 2 summarizes the types of material that have been dated within the project and the interpretation of numerical radiocarbon ages in the determination of landslide age. When dealing with the dating of mass movements, the relationship between the dated object and the phases of activity of a mass movement should be considered, besides accuracy and temporal resolution affecting the age determination. In most cases the dated material lies in the accumulation zone of the landslide (below the landslide mass, mixed within the landslide mass or on the landslide surface), but it can also be located in the scar area or outside of the landslide (e.g., within a lake that formed upstream of the landslide body). In some cases the death of the organism submitted to dating was caused by the mass movement itself, thus the obtained age may offer a direct dating of the event. In other cases it provides a minimum or a maximum age constraint. For instance, direct ages of slope events were obtained dating wood material mixed within the landslide mass (e.g., several flows in the Apennines and Dolomites). Minimum ages were achieved from dammed lake deposits.

One of the main problems affecting the application of radiocarbon dating is the availability of suitable organic material. This is the case of the landslides occurred in the first part of the Late Glacial (e.g., landslides older than 12,000-14,000 years BP, conventional age) since limited vegetation cover and no trees were present at that time in most of the studied areas of the Alps.

As far as historical landslides are concerned, the accuracy of the method is relatively low compared to the frequency of climatic changes (Pellegrini & *alii*, 2004).

Other methods, like TL and OSL, can be a good option when radiocarbon cannot be used, such as in case of deposits lacking of organic matter. Some of the results obtained during the project have not been completely satisfactory. For instance, some OSL ages were too old compared to the chrono-stratigraphic evidences derived from the geological and geomorphological evolution of the region (see Pellegrini & *alii*, 2006). Some depositional processes, such as very high deposition rates and the subsequent inadequate exposure of sediments to sunlight, could be other factors for such inadequate results.

TABLE 2 - Materials dated with radiocarbon dating technique within the project

Materials	**Landslide dating**	
	direct	**indirect**
Wood		
wood, small fragments	x	
trunk wood, small fragments	x	
trunk wood, sampled at the centre	x	
trunk wood, sampled externally	x	
trunk bark	x	
root wood	x	
conifer cones	x	
woody branchlet(s)	x	
charred wood	x	
Peat		
bulk peat		x
moss peat		x
Soil and sediments		
humic soil organic matter		x
plant fragments dispersed in the sediment		x
limnic organic mud		x

Dendrochronology has been used to date some Holocene mass movements, in some cases in connection with radiocarbon dating. This method requires that a reference curve is available for the species to be dated, and this is not always the case, especially for very old trees or for particular species. When a reference curve, that is a master chronology, and a large number of tree rings are available, the dendrochronological approach may yield very accurate ages (see e.g. Schoeneich & *alii*, 1997).

Lichenometry can be a useful tool for dating mass movements but there are also some limitations in the applicability of the method. The most important is the variability in the rate of lichen growth, which can cause a degree of uncertainty in the results (see McCarroll, 1994).

Palynology may be used as a correlation method provided that the palyno-stratigraphy of the area under study is well known. The method is valuable to obtain relative ages, yielding valuable information, for example in case of events of lateglacial or older age (see Pellegrini & *alii*, 2006).

In the frame of the project, 76 landslides have been dated, including 40 events dated by single samples and 36 ones with multiple sampling, for a total of 160 collected samples. As far as the dating techniques applied during the research project are concerned, 140 radiocarbon, 14 lichenometry, 10 dendrochronology and 2 thermoluminescence dating records have been collected, for a total of 166 age determinations. Difference between the 160 collected samples and 166 dating records is due to 6 multiple radiocarbon-dendrochronology dating.

All the datings obtained in the study sites have been stored in a specifically-designed database. However, due to the limitations of some of the dating techniques and the scattered data acquired with lichenometry, radionuclides, dendrochronology and palynology, in the analysis and synthesis phases only radiocarbon datings have been used (tab. 3).

Spatial and relational database

One of the most important phases of the research was the computerization of all available and updated datasets, loaded and recorded by each contractor of the project. The goal of the activity was the need to develop a structured and standardized database. A preliminary impression of relationships has been made: specific tables of sample parameters, landslide features and dating techniques have been defined, following normalization and standardization rules. Different information has been considered: technical results derived from surveys of each unit have

TABLE 3 - Landslides dated with radiocarbon dating technique within the project

Landslide	Municipality	Region	Samples
Corvara	Corvara in Badia	Trentino Alto Adige	15
M. Cervellino	Berceto	Emilia-Romagna	8
Col Maladat	Corvara in Badia	Trentino Alto Adige	7
Col Alto	Corvara in Badia	Trentino Alto Adige	5
Pezziè	Cortina d'Ampezzo	Veneto	4
Colfosco	Corvara in Badia	Trentino Alto Adige	4
Corvara	Corvara in Badia	Trentino Alto Adige	4
Sackung-Vedeseta	Vedeseta	Lombardia	4
Tosca	Varsi	Emilia-Romagna	4
Alverà	Cortina d'Ampezzo	Veneto	3
Zuel	Cortina d'Ampezzo	Veneto	3
Frebouge	Courmayeur	Valle D'Aosta	3
Freney	Courmayeur	Valle D'Aosta	3
Arlara	Corvara in Badia	Trentino Alto Adige	3
DF Col Maladat	Corvara in Badia	Trentino Alto Adige	3
Greif	Corvara in Badia	Trentino Alto Adige	3
La Lama di Corniglio	Corniglio	Emilia-Romagna	3
Marra Centrale	Corniglio	Emilia-Romagna	3
Tre Rii	Corniglio	Emilia-Romagna	3
Carobbio	Tizzano Val Parma	Emilia-Romagna	3
Cadin	Cortina d'Ampezzo	Veneto	2
Cortina	Cortina d'Ampezzo	Veneto	2
La Riva	Cortina d'Ampezzo	Veneto	2
Lacedel	Cortina d'Ampezzo	Veneto	2
Staulin	Cortina d'Ampezzo	Veneto	2
Larzey	Courmayeur	Valle D'Aosta	2
Lavachey	Courmayeur	Valle D'Aosta	2
Triolet	Courmayeur	Valle D'Aosta	2
San Cassiano	Badia	Trentino Alto Adige	2
Sackung-Venosta	Naturno	Trentino Alto Adige	2
Gran Vallon	Cesana	Piemonte	2
Serre la Voute	Salbertrand	Piemonte	2
Riopoggione	Bardi	Emilia-Romagna	2
Miano	Corniglio	Emilia-Romagna	2
Le Ripe di Martino	Tizzano Val Parma	Emilia-Romagna	2
Secchio	Villa Minozzo	Emilia-Romagna	2
		Total:	**120**

been combined with previous datasets collected in the study areas. A web-based dynamic tool was developed to organize landslide studies and dating results. Through this tool, every research unit was able to load the database with its own samples and use the geographical dataset of all project contractors, to complete its own statistical and geomorphological analysis.

A web-based interface (dynamic ASP page) was created to compile and upload the database. Through this device, every user is able to load data, exploiting the browser capability. In a particular server environment, a specific website http://geoserver.disat.unimib.it/cofinfrane/) managed customized forms and specific database connections. Client-server architecture (fig. 2) allowed the definition of some constraints and guidelines, to prevent a user from uploading incompatible information. Messages of uploading confirmation, coordinates transformer, links and other useful tools have been implemented in the website to support updated activity. This step prevented the database from redundancy of information and it has clearly made up for time, due to the automation of uploading data in specific fields. Landslide datasets and samples dating of the project became available for download for each research unit; as a consequence, the complete database has been used to apply custom analysis, thematic maps and elaboration through GIS.

Database has been built with specific tables for every type of dating methods, for dated samples parameters and for geomorphological features of every single landslide. To support the uploading step and to create some pull-down menu, some secondary tables have been added; in this way users have been able to choose among limited choices in customized forms. This capability has allowed the standardization of data entry; it has also prevented mistakes to occur during the uploading phase. The relationships of the structure have been defined on primary keys (e.g., field «*ID_CAMPIONE*» for tables of dating types and dating parameters; field «*NUMERICO*» for landslide features tables), according to some key principles previously fixed (fig. 3). A one-to-many relation has been set up among landslide and samples, because it was possible to record one single landslide event by more samples or multiple reactivations of the same landslide with different samples. The same typology of relationship has been kept for the dating method dataset: one sample could be linked to more dating techniques.

RESULTS

The results of the investigations are presented, with reference to the study areas of the western and the central Alps, of the Dolomites, of the Belluno Prealps and of the Emilian Apennines (fig. 1).

Western Alps

Data on magnitude and frequency of events have been obtained and interpreted in the general framework of the Plio-Quaternary migration of the major alpine drainage divide and considering the local history of slopes dynamics, related either to shallow landslides or to deep-seated gravitational slope deformations (DGSD). The geostructural and tectonic control on landslides have been also investigated.

From a preliminary selection of 59 landslides, 33 datings resulted, including 7 multi-sample cases. Data showed some multi-event landslides, such as the Gran Vallon debris flows (3010±60 yr BP; 2850±60 yr BP) and the Serre la Voute DGSD (9525±85 yr BP; 8380±95 yr BP). In the second case, besides landslide activity connected to deglaciation, historical data also showed recent reactivations connected to heavy hydrometeorological events (e.g., AD 1728; AD 1957).

A regional map and a geodatabase have been developed for a landslide dam inventory. Sites for field investigations have been chosen where landslide dams developed, in order to obtain environmental and climatic data

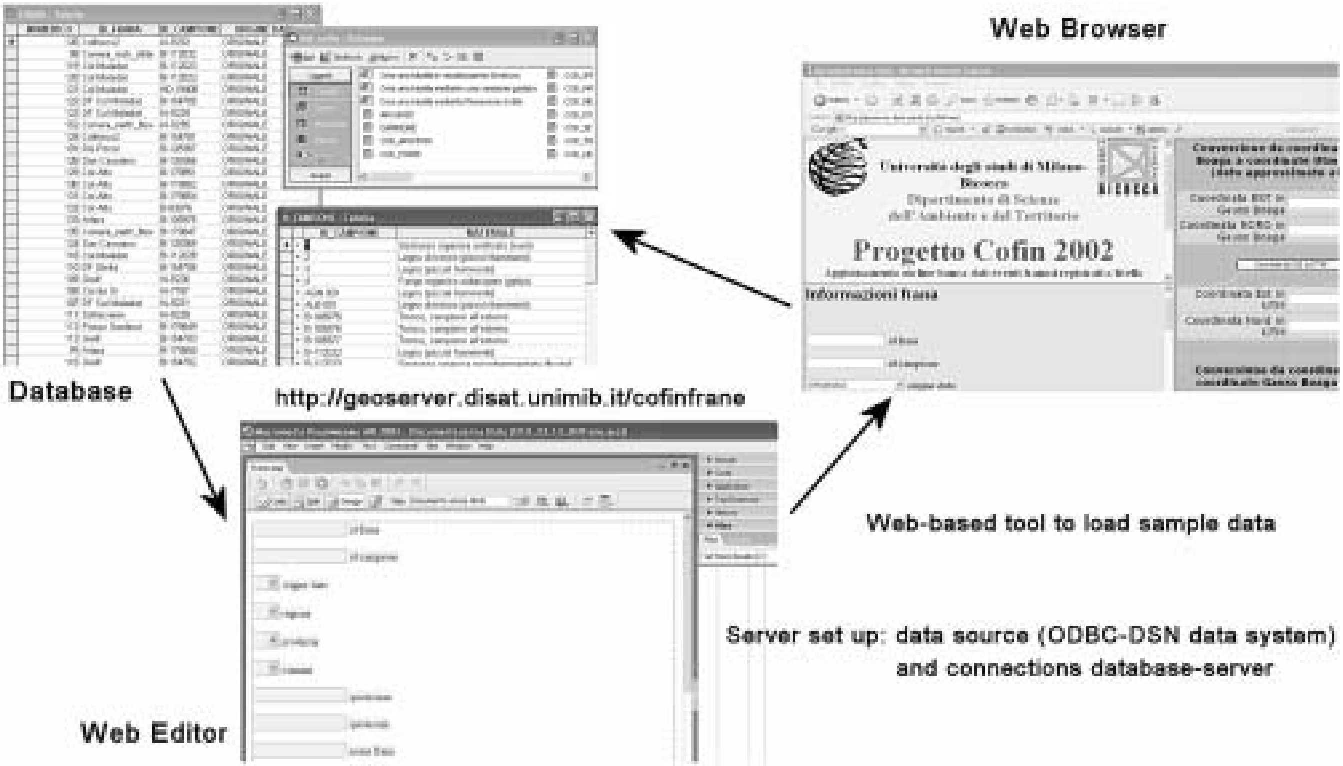


FIG. 2 - Server-client architecture used in the uploading of the data into the data base.

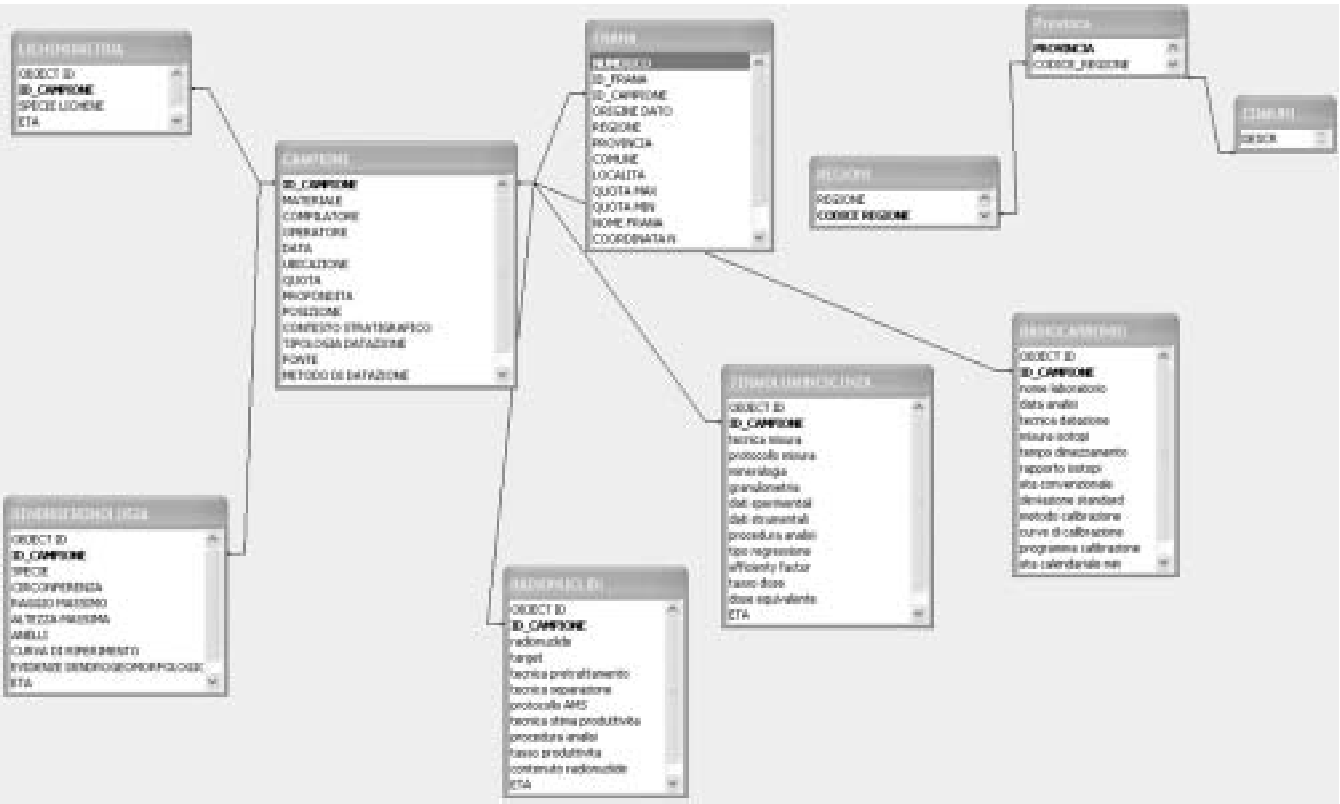


FIG. 3 - Database structure, showing the relationships between the different tables related to landslide (geographical location, altitude etc.), dated sample (date of collection, material, stratigraphic context details etc.) and dating techniques (details on the analysis).

from lacustrine deposits. By using remote-sensing technologies some maps have also been produced, showing local slope behaviours, in response to the different rheologies of various bedrock-type, and areal distribution of landslides and DGSDs controlled by the regional setting of tectonic discontinuities.

The analysis of the relationships between slope dynamics and climatic changes has allowed the orders of spatio-temporal evolution of the alpine landscape to be identified. The first, connected to the present geomorphological evolution, is referred to single slope instability events of small to medium magnitude, that are sometimes clustered from spatial and temporal contexts. The second order of magnitude is related to the Late Glacial dynamics, with large instability phenomena that involve whole slopes and also interfere with the glacial landforms and deposits on the valley floors. The latter scale is the most ancient, recognizable only in the main drainage divides at the extent of the whole mountain chain.

The comparison between geomorphological and geological-structural elements has allowed some sectors where neotectonic activity and slope evolution interfere to be recognized. In particular, this is testified by the location and reactivations of DGSDs.

In conclusion, four phases of relative concentration of landslide events have been documented in the Western Alps: 9500-8300 BP (large instabilities on intermediate or lower altitude slopes of major valleys, related to glacier retreat), 6000-3990 BP (rock slides and complex landslides, through a long time interval characterized by neoglacial pulses and climatic instabilities), 3000-2000 BP (rock falls and flows at intermediate to upper altitude of major and tributary valleys, at the transition Subboreal-Subatlantic) and the Little Ice Age (rock avalanches and falls in the upper altitudes of the mountain relief, related to widespread slope instabilities probably induced by permafrost degradation and complex landslides connected to major hydrometeorological events, as documented by historical data).

Central Alps and Orobic Prealps

The analysis of the relationships between palaeoclimatic evolution and slope movements in the Central Alps and Orobic Prealps has been carried out through the integration of geological and geomorphological surveys, trench digging, palaeoclimatic analyses and computer elaborations using GIS and 3D modelling (Crosta & Zanchi, 2000; Agliardi & *alii*, 2001; Zanchi & *alii*, 2002; Zanchi & *alii*, 2004).

In these areas, the study of DGSDS allowed the relationships between their activity and climatic changes to be verified. DGSDs are complex phenomena, related to the interaction among different processes, including a quick deglaciation, the neotectonic evolution of the Alpine chain, seismic events and a passive structural control, due to inherited tectonic features. Aim of this research was to compare the evolution of DGSDs in the Central Alps, which was severely affected by the last glaciation with the Prealps, which were affected only by periglacial phenomena. Examples of DGSDs have been studied in the upper Venosta Valley (Mt. Watles). In this area, peat bog successions have been dated through radiocarbon methods and the lowermost layers were analysed for their palaeobotanic content. The radiocarbon chronology has been also supported by stratigraphic analysis. The results indicate that a DGSD developed in an area formerly occupied by glaciers reactivated around 10,000 yr BP after the retreat of Adige glacier (17-14 ka cal BP), due to slope debuttressing. On the other hand, the evolution of secondary trenches related to gravitational movements and infilled with peat bogs highlighted further phases of late Holocene deformation, dating back to 3500 cal BP. Actually, the latter evidence suggests that some sectors of the Watles DGSD were subjected to intense slope release for a long time during the Holocene, being stabilized only at about 3500 cal BP.

The origin of late Holocene peat bogs within counterscarps related to DGSD phenomena may also rely on anthropic activities. The case study of the Malga di Naturno DGSD, located uphill of Naturno (Val Venosta) in a huge sackung affecting the northern slope of Cima della Guardia Alta is emblematic. Here, the recent evolution of the peat bog accumulation is possibly related with an anthropic dam. The base of the infill has been dated back to the Bronze Age. The proposed interpretation is the following: ponds were formed to support seasonal Alpine livestock; after abandoning, peat accumulation started and continued till today.

In the Bergamo Prealps an ancient DGSD has been studied (Corno Zuccone, Val Taleggio, Zanchi & *alii*, 2002, 2005). The last phase of activity dates back to the late Holocene. Deposits filling a gravitational trench at Suaggio di Vedeseta (Val Taleggio), provided lithostratigraphic and palynological evidence of several phases of late Holocene activity, the latest phase being radiocarbon dated to the beginning of the Roman age. This event predates the first anthropic activities in this sector of the valley, which comes shortly later. The conclusion is that slope instability has not been triggered by any causes linked to changes either in the vegetation (e.g., denudation and high erosion rates), or in anthropic factors (wildfires and deforestation).

Dolomites

In the Dolomites, the first studies carried out locally on the relationships between landslide susceptibility and climate during the Holocene have produced interesting data and starting points for systematic and in-depth investigations. Direct datings of landslide deposits have been carried out on 24 landslides, for a total of 86 datings.

In particular, geomorphological studies, palynological, dendrochronological and archaeological analyses have been carried out, with the aim of defining landslide triggering causes and assessing the influence of climatic crises and anthropogenetic activities on mass wasting phenomena.

The first phase of marked slope instability occurred in the Preboreal and Boreal, consisting of large rock slides, affected the dolomitic slopes after the withdrawal of Late Glacial glaciers and complex movements (rotational slides and flows) involving the underlying pelitic formations, probably favoured by the abundance of water resulting from an increase of precipitation and permafrost meltdown. Other concentrations of events are reported during the Holocene, when rotational slides and/or flows mainly took place and correspond to cold and humid phases at regional and global scales.

The palaeoclimatic evolution in the study areas has been attained by means of palynological investigations on lacustrine deposits spanning throughout the middle Holocene, sampled in the study site of Alta Badia. Moreover, a dendrochronological master curve for the area of Alta Badia is also in progress, thanks to the cross-datings of several well preserved tree trunks buried in landslide deposits. Finally, the human influence since the Bronze age has been analysed together with archaeologists in the study site of S. Leonardo, even if no evidence of direct relationships between mass wasting phenomena and anthropic activity has been observed so far.

In conclusions, four phases of enhanced slope instability have been identified: between 10,500 and 9500 cal BP, during the Younger Dryas, Preboreal, between 8000 and 7000 cal BP, in the older Atlantic, between 6000 and 4500 cal BP, during Atlantic-Subboreal and between 3000 and 2000 cal BP, in Subboreal-Subatlantic.

Belluno Prealps

In the study area of the Belluno Prealps (Eastern Alps) research has been carried out 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 been also taken into account, since vegetation is a fundamental feature for reconstructing environmental variations. The results show that the geomorphological processes have been active during the phase of climatic change at the end of the Last Glacial Maximum, followed by the alpine deglaciation. The retreat of the Piave glacier was very rapid both in the Quero Canyon, in the Vallone Bellunese and in the Lapisina Valley, as documented by some radiometric datings and pollen analyses, and was complete since 15,000 cal BP. When the Piave glacier retreated, several landslides took place on the slopes of this alpine region and the stratigraphic relationships show that the landslide deposits are lying on bedrock or glacial tills, and are never covered by glacial deposits but by Late Glacial and Holocene alluvial deposits.

Where lacustrine deposits correlated with landslides occur, drillings have been carried out. Cores from drillings have been used to date landslides and for climate reconstruction through pollen analysis.

Emilian Apennines

In the western Emilian Apennines, the geomorphological evolution of slopes during the Late Quaternary has been reconstructed. Thirty six landslides have been dated by radiocarbon and 75 dates have been obtained. The radiocarbon datings allow the chronological distribution of the landslide events to be described. 18 of them are recorded in the Subatlantic period, 28 in the Subboreal period, 4 in the Late Atlantic and 2 in the Early Atlantic, 6 in the Boreal and one in the Preboreal. In the Late Glacial period four landslides recorded movements from the Younger Dryas to Allerød/Older Dryas periods (Orombelli & Ravazzi, 1996; Stuiver & Reimer, 1993). The oldest datings are Pleniglacial and referred to two landslides in Parma province (Carobbio and Berceto): the first show a conventional ^{14}C age of 25,129±160 yr BP, the second of 29,620±290 yr BP.

The analysis of the distribution of the landslide movements in the Western Emilian Apennines shows clusters in three periods. The first includes dates between about 9600 cal BP and 6350 cal BP. The most significant one includes events occurred between about 5400 cal yr BP and 1800 cal BP. The third cluster is in the last millennium and includes dates witnessing the influence of the Little Ice Age. It is worth noting that many chronological data derived from historical sources (Almagià, 1907; Dall'Oglio, 1975) confirm a large number of movements related to the climatic deterioration which began in the XVI century and culminated in the XIX century.

The trend of palaeo-rainfalls and the palaeo-temperatures, elaborated by Corsini & *alii* (2000) from Goudie (1992) and Orombelli & Ravazzi (1996) source data, shows the relationship between the increase of landslides activity and the increase of precipitation, and relative decrease in temperature.

Synthesis

On the basis of the data collected, it emerged that the clusters of landslide events can be considered relevant only if a significant number of landslides have been dated in the study sites during the considered time span. It is also clear that the spatial distribution of the data is conditioned by the location of the study sites and the subsequent lack of knowledge for wide areas, in particular as far as prehistoric landslides are concerned.

Moreover, a wide range of predisposing and triggering factors do exist, among which lithology, tectonics, geomorphology, groundwater, vegetation, land use and human activity. As seismicity, climate and human activity are the only factors that can produce concentrations of events in time and space, one viable procedure to establish the role of climate should be to exclude those events that can be directly related to other causes.

Further uncertainties, as verified in all the study sites, derive from the landsliding process itself. Very often landslides undergo subsequent reactivations and in these cases, the attribution of a single dating to a specific event is very difficult, and also leads to an underestimation of the actual landslide activity.

The application of different dating techniques, displaying dissimilar accuracy and precision characteristics, can in turn influence the interpretation of the results. This is the main reason that brought us to consider only radiocarbon dating in the interpretation phase.

The importance of the analysis of the stratigraphical context has also to be emphasized, with particular attention paid to the relationship between the dated object and the dated event.

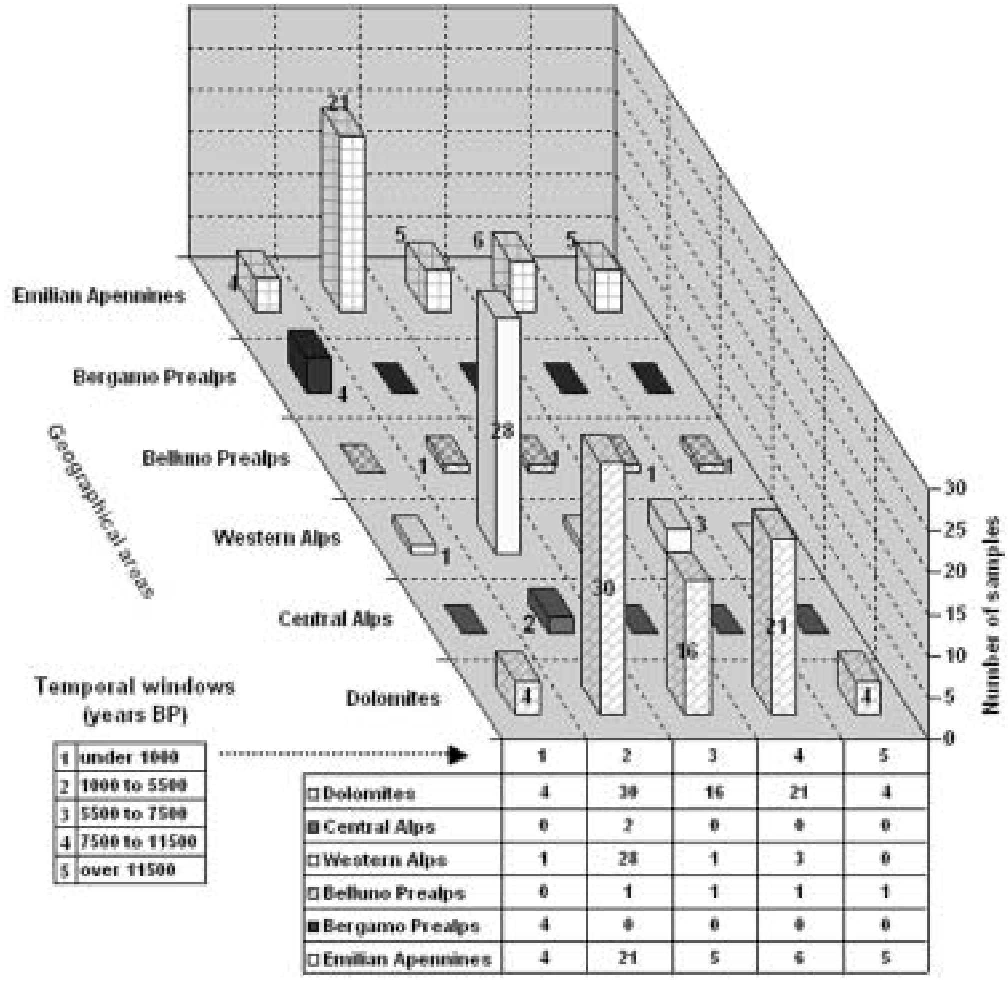
Notwithstanding all the uncertainties and the fact that further data are necessary, some findings have been made. The data obtained in the study sites have been synthesised in fig. 4, where the datings have been subdivided into five periods that can also be significant in terms of climate changes:

- before 11500 ky cal BP (Late Glacial);
- 11500-7500 ky cal BP (general warming trend);
- 7500-5500 ky cal BP (marked oscillations within the temperature optimum);
- 5500-1000 ky cal BP (rapid and marked climate variations);
- 1000 ky cal BP to date (historical data, including the LIA).

Up to 49% of the datings fall in a period characterised by rapid and marked climate variations, from the Subboreal to the Subatlantic. The second relative maximum follows the deglaciation, during a period of general warming trend in the lower Holocene (20%). The number of landslides dating back to the so-called climatic optimum is relatively low, around 15%. Only 9% of the datings refer to the Pleistocene. The absolute minimum referring to the number of recent landslides is due to bias in the dataset, as the number of historical landslides would be certainly greater than the pre-historical ones. Here only the landslides dated with radiocarbon datings are considered.

LANDSLIDE SPATIAL DISTRIBUTION

Since type, magnitude and frequency of landslides can also be related to several conditioning factors other than meteorological and climatic/palaeoclimatic ones, a general description of geomorphological, litho-structural and tectonic contexts of the sampled landslides is given below. This will be performed firstly by highlighting the relevant structural features of the major alpine domains (fig. 5), then by considering their different role in the geodynamic



1	under 1000
2	1000 to 5500
3	5500 to 7500
4	7500 to 11500
5	over 11500

	1	2	3	4	5
□ Dolomites	4	30	16	21	4
■ Central Alps	0	2	0	0	0
□ Western Alps	1	28	1	3	0
□ Belluno Prealps	0	1	1	1	1
■ Bergamo Prealps	4	0	0	0	0
□ Emilian Apennines	4	21	5	6	5

FIG. 4 - Dated landslides in the study areas during the following periods: before 11,500 (Late Glacial); 11,500-7500 (general warming trend); 7500-5500 (marked oscillations within the temperature optimum); 5500-1000 (rapid and marked climate variations); 1000 to date (historical data, comprising the LIA).

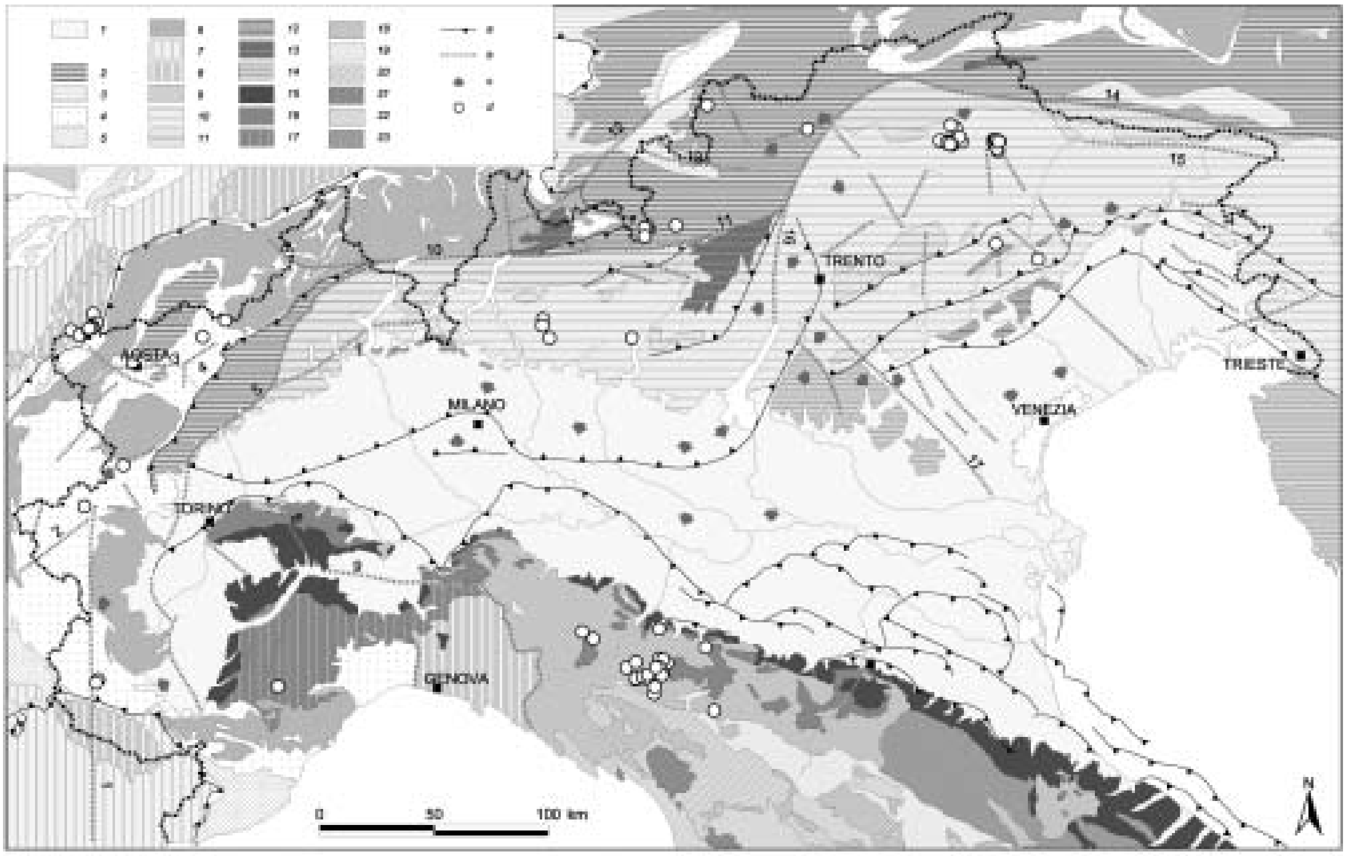


FIG. 5 - Structural map of the Alps and North-Apennines: 1. Quaternary; Alpine chain (Europe-verging orogenic system): 2. Austroalpine domain: pre-Alpine cristalline basement and Palaeozoic cover; 3. Austroalpine domain: Permian-Mesozoic-Tertiary cover; 4. Pennidic domain: Permian-Mesozoic-Tertiary cover (metamorphic); 5. Pennidic domain: «Helminthoid Flysch Units», with their basal complex (Cretaceous-Eocene); 6. Penninic domain: Pretriassic crystalline basement; 7. Helvetic domain: Permian-mesozoic cover; 8. Helvetic domain: pre-Alpine crystalline basement and Carboniferous cover; 9. Foredeep (Swiss molasse, Oligocene-Miocene); Africa-verging orogenic system: 10. Southern Alps and Dinarides, Permian-Mesozoic-Tertiary cover; 11. Southern Alps and Dinarides, pre-Alpine Cristalline basement and Paleozoic cover; 12. Foredeep (Oligocene-Miocene deposits); 13. Tertiary plutonics rocks; 14. Foreland (Mesozoic-Cainozoic cover); Apenninic chain (Africa-verging orogenic system): 15. Internal margin foredeep deposits, locally included in the chain (Messinian-Quaternary); 16. Epiligurian Sequences: episutural basins deposits unconformably covering the Ligurian units, (Middle Eocene-Tortonian); 17. Epiligurian Sequences («Oligo-Miocene» of the Langhe); 18. Ligurian and Subligurian Units: Nappes, locally ophiolitic-bearing, derived from the Thetys ocean realm and from the edge of the African margin (Jurassic - Lower Miocene); 19. Modino-Cervarola Unit: nappe enucleated West of of the Umbria-Marche domain (Upper Oligocene-Middle Miocene); 20. Tuscan Nappe, derived from the African continental margin (Upper Triassic-Lower Miocene); 21. Metamorphic Tuscan Units: nappes originated from shear zones within the African continental margin. Triassic-Oligocenic cover and Hercynian basement; 22. Intermontane extensional basin deposits (Messinian-Quaternary); 23. Umbria-Marche Domain: external thrusts units and fold of the Apenninic chain (Upper Triassic-Upper Miocene); a. Front of tectonic units derived from different paleogeographic units; b. Main neotectonic deformation zones; c. Tilting; d. Dated landslides. Modified Map and data collection from ENEL (1981), Bosi (1983), Polino & Sacchi (1995), Bistacchi & *alii* (2000), Polino (2002), Carraro & *alii* (2005).

evolution of the Alps (Compagnoni & *alii*, 1977; Castellarin & Vai, 1986; Hunziker & Martinotti, 1987; Dal Piaz & Polino, 1989).

In order to assess the role of seismotectonics and other regional geomorphic processes in conditioning areas of slope instability during the temporal interval relevant to our landslides studies, the major neotectonic deformational zones have been related to the geo-structural map (fig. 5), and a simplified seismic map of the studied area (fig. 6) has been presented. The areal extent of major, recent to present, geomorphological environments has been described, in order to determine possible interactions with slope instability phenomena.

In the Western Alps, the majority of the studied landslides occur in the Penninic Domain, a complex tectonic system composed of a crystalline basement and meta-sedimentary cover both of continental and oceanic origins. Within this multilayer complex, a great number of large complex landslides and DGSDs originated on thin layered, favourable dipping and fractured calcschist, part of the «Piemonte Nappe System». This special role in landslide conditioning is consistent with evidence from regional studies and landslide inventories (Mortara & Sorzana, 1987; Puma & *alii* 1989), including the IFFI Project (Inventario dei Fenomeni Franosi in Italia by Italian Agency for Environmental Protection and Technical Services -

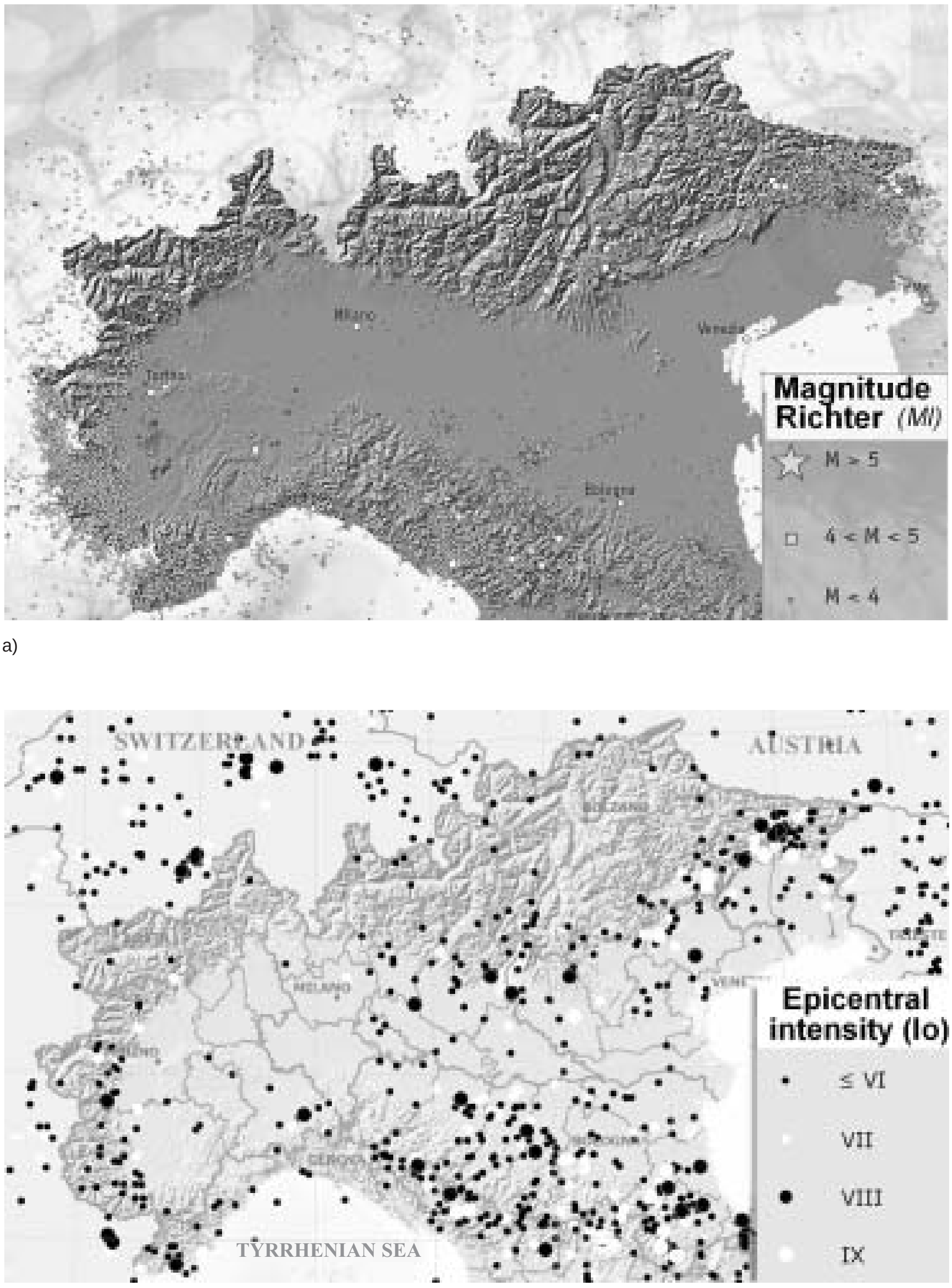


FIG. 6 a - Seismicity of northern Italy from 1981 to 2002. Earthquake locations from instrumental data, sorted by magnitude (from Castello & *alii*, 1995). b - Major earthquakes of northern Italy from 217 b.C. to 1992 AD. Epicentre locations from historical data, sorted by intensity (from CPTI, parametric catalogue of earthquakes in Italy; ING & *alii*, 1999). Base map: hillshade with administrative borders.

APAT). As confirmed by monitoring data in the Western Alps, long-term progressive, slow-velocity large slope deformations shaped major valley slopes of calcschist lithostructural units. Reports on present-day landslides (Bonnard & *alii*, 2004) also indicate the role of major hydrogeological events in the activation of unstable sectors of DGSDs, to give rise to rock falls and/or rock avalanches.

These latter are also more frequent among case studies of the Western Alps located on massive metamorphic rocks derived from continental crystalline basements both of the Internal Massives (Dora-Maira, Gran Paradiso, Monte Rosa) or of the External Massif (Mont Blanc). In these cases, the repeated migration of glacial and periglacial processes often undermines the stability of major rockwalls, whose slope's energy can determine huge gravitational effects down to the valley bottoms, as shown in the Val Veny and Val Ferret case studies (Chiarle, 2000; Deline, 2002).

Still in the Europe-verging orogenic chain, the studied landslides affect basement rocks of the upper Austroalpine units, including phyllites, micaschists, paragneiss and ortogneissic units with minor amounts of metabasic rocks. Their various movement type (planar and rotational slides, flows etc.) are related to different local litho-structural settings. Strong tectonic deformations related to the activity of the complex Insubric lineament are also responsible for large slope instabilities whose areal extent vary depending on the geometry of single fault segments. Along the E-W Tonale-Centovalli line, several morphotectonic features (parallel or incident to the E-W direction) affect valley slopes, mainly in the Valtellina sector. On the northwest of this sector similar features are connected to the Zebrù and Val Venosta tectonic lines, incident to the Insubric segments, namely the North Giudicarie, Val Pusteria and Gailtal lines.

The prolonged phases of intense shortening, uplifting, and exhumation of this area (Castellarin & *alii*, 2004) could be a dynamic conditioning on slope instability and landslide activation in a complex neotectonic setting; data for the Tauern window, north of the Val Pusteria-Gailtal lines, account for 30 km uplift over the last 20 million years (Christensen & *alii*, 1994).

As regards the Southern Alps, inherited litho-structural conditions constrained the present-day landslide distribution and typology. Intrusive rock masses (e.g. Adamello), crystalline basement units (Trento Plateau) and other rigid non-metamorphic rocks (Carnic belt) showed strong rheological contrasts with respect to other sedimentary and volcanic layers (e.g. Lombardian basin and surrounding platforms), both in terms of crustal deformations and in terms of responses to slope-related morphodynamic processes.

In the Dolomites, the recorded landslides offer an overview on the conditioning factors of the widespread slope instability processes. Stratigraphic and tectonic discontinuities affect general geomechanical properties of the outcropping rock masses. The mass movements taking place in correspondence with the margins of the dolomitic groups appear to be linked to the overlapping of competent but densely jointed hard rocks (such as dolostones; brittle mechanical behaviour), on weak materials showing substantially ductile behaviour (such as marls, clayshales or flysch). In this case, various types of movement combine and take place on different parts of the same slope, large landslides with a complex and composite movement style). Structural weakness situations, or the presence of pelitic rock types can also give rise to rotational slides accompanied by earth flows.

Furthermore, the incidence of tectonics is also significant on slope instabilities in particular geomorphological contexts. In fact, the major rock walls in the Dolomites were affected by intense jointing mainly in correspondence with the principal faults, eventually reactivated during the Pliocene and the Quaternary (e.g., Val de Mesdì fault, active between 5.2-0.7 million years BP, Castaldini & Panizza, 1991, and Col Alto - Pralongià - Passo Incisa strike-slip fault, Corsini & Panizza, 2003).

The active seismo-tectonic of the Eastern part of the Southern Alps represents a major dynamic factor in conditioning slope instabilities. Neotectonic evolution of the Montello structural belts is consistent with the morphodynamic evolution of the area. Direct effects of macroseismic activity on slope instabilities are historically documented in terms of widespread rock fall phenomena and shallow landslides around the epicentre zones.

The activation of DGSD in the Orobic Prealps (central Southern Alps) is still poorly constrained in time, due to the lack of suitable sites. Most of the analyzed phenomena (e.g., Crosta & Zanchi, 2000) suggest a long-living activity, possibly pre-dating the last-glacial maximum (Albenza, Cornagera, Canti and Corno Zuccone sackungs). The main evidence is related to the occurrence of deeply eroded and weathered slide deposits pre-dating and accompanying the evolution of the main DGSD phenomena. The studied DGSDS of this area develop in a complex structural setting related to the occurrence of Upper Triassic weak rocks (shales and marlstones of the Argillite di Riva di Solto Fm.), underlying thick massive carbonate layers. Triggering factors mainly depend on local structural conditions and can be related to deep valley incisions following the Middle Pleistocene and to a peculiar structural setting related to down-slope dipping beds and occurrence of high-angle strike-slip and normal faults favouring rock mass sliding. Although no record is available, seismic shaking along the frontal part of the Southern Alps in the Bergamo area cannot be excluded. Recent reactivations have been dated to the Roman age in the Taleggio valley (Corno Zuccone).

In the study sites located in the Northern Apennine, the geological structure derives from tectonic piling of stratigraphic successions related to different palaeo-geographic domains (internal oceanic Ligurian Domain; transitional Subligurian units; external units of the Tuscan-Umbrian-Romagna fold-and-thrust belt, related to the continental margin of Adria microplate; Elter, 1973; Zanzucchi, 1980; Boccaletti & *alii*, 1981; Bettelli & De Nardo, 2001).

Most of the studied landslides affect the Ligurian allochtonous successions constituting the top structural units of the Northern Apennine orogenic wedge. These are highly deformed and fractured flysch units overthrusted on chaotic (block-in matrix) basal complexes and on scaly clays rock masses belonging to the Subligurian units.

Some of the dated landslides occur at the margins of the Epiligurian sequences deposited by angular unconformity on the already deformed Ligurian formations during the tectonic translation on the passive Adria margin. The Epiligurian sequences outcrop mainly in isolated flat-lying or gently folded patches characterized by high-angle normal faults and strike-slip faults. Here, large landslides (deepseated rotational and translational slides associated to shallow earth-slides;) affect fine to coarse-grained turbidites and marls. The relationships with seismo-tectonic activity have been proved in two cases (Rossena and Corniglio; Brunamonte, 1999; Larini & *alii*, 2001).

PHASES OF ENHANCED LANDSLIDING WITH RESPECT TO CLIMATE CHANGES

The regional analysis of the phases of enhanced landsliding with respect to climate changes has been performed through a multidisciplinary approach, directed to the appraisal of the palaeo-environmental conditions at the time of the landslides. The aim is to distinguish between the climatic and non-climatic factors which conditioned the slope-system in the short-, medium- and long-term periods. Thus, besides the development of landslide events records, other environmental proxies have to be considered in order to identify the possible interactions between natural systems, in this case the slope-system, climate and humans.

A wide range of proxy records coming from different realms, either continental or marine, have been taken into account (fig. 7). Some of the records carry clear signals of cold and humid phases, whereas others are more related to warmer periods, primarily as a consequence of the nature of the proxy.

On the one hand periods of cold and humid climate in the Central and Eastern Swiss Alps and Plateau have been considered (Maisch & *alii*, 2000) after Burga (1988), Maisch (1992), Burga & Perret (1998), Haas & *alii* (1998), Tinner & Ammann (2001). On the other hand, warm periods, recorded by the Unteraar glacier retreat in the Central Swiss Alps, as reported by Hormes & *alii* (2001), are taken into account together with fluctuations of the glaciers in the Swiss Alps, with reference to the glacier fronts stages of 1850, 1920 and 2000, after Gamper & Suter (1982), as reported in Maisch & *alii* (2000). Other proxies are distinct phases of soil formation and solifluction in the Swiss Alps (Gamper, 1993) and the oscillation of the treeline in the Central Alps (Burga & Perret, 1998). It is worth notice that in some periods the records display opposite trends that are mainly due to different time resolutions and local variability.

The record of mid-European lake levels (Magny, 1999, 2004), obtained from the systematic study of littoral sediment sequences in the lakes of the Jura, the French Pre-Alps and the Swiss Plateau, have shown the sensitivity of the regional lake levels to Holocene climatic oscillations and allowed the setting up of a comprehensive regional pattern of palaeohydrological variations during the Holocene.

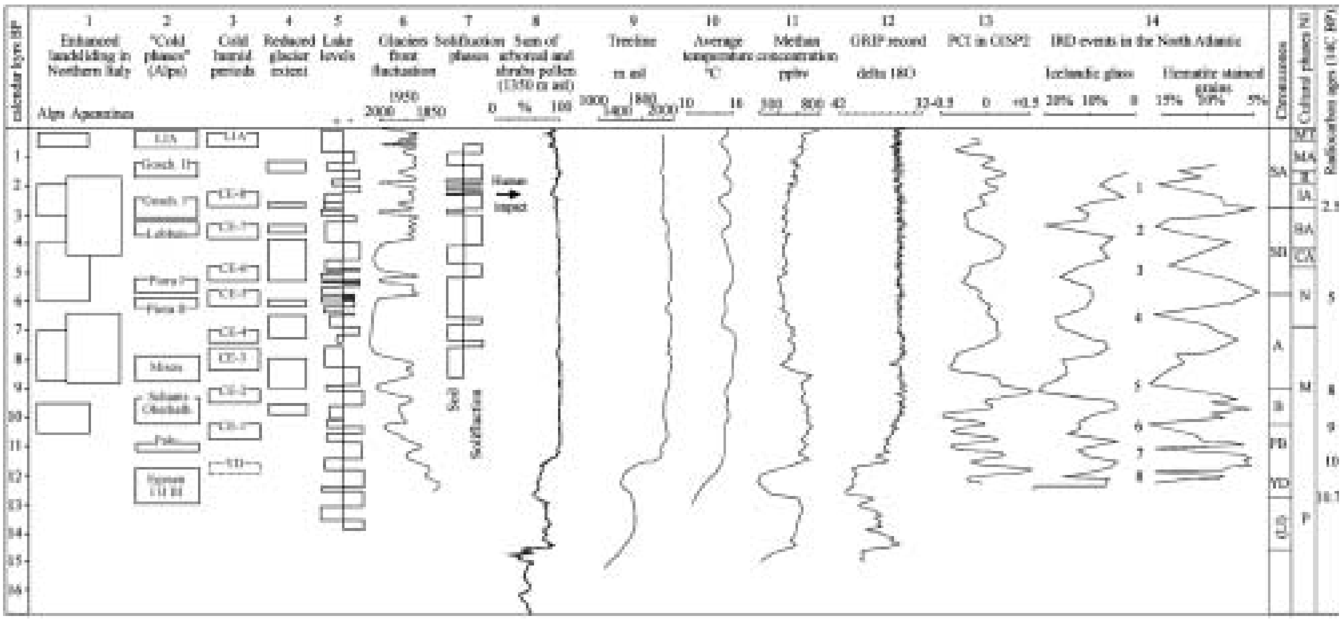


FIG. 7 - Synoptic sketch landslide activity phases compared with Late Glacial and Holocene palaeoclimatic records from the Alps (modified from Borgatti & *alii*, In press). 1. Phases of enhanced slope instability in the Alps and in the Apennines; 2. Periods of cold climate in the Central and Eastern Swiss Alps, compiled by Maisch & *alii* (2000) after Burga (1980), Maisch (1992), Burga & Perret (1998); 3. Cold and humid periods in the Alps and on the Swiss Plateau (Haas & *alii*, 1998; Tinner & Ammann, 2001); 4. Phases of reduced glacier extent, recorded by the retreats of the Unteraar and other Swiss glaciers (Hormes & *alii*, 2001); 5. Mid-European lake levels (Magny, 1999) as palaeohydrological indicators; 6. Glacier front fluctuations in the Swiss Alps, with reference to the glacier fronts stages of 1850, 1920 and 2000, after Gamper & Suter (1982), as reported in Maisch & *alii* (2000); 7. Distinct phases of soil formation and solifluction in the Swiss Alps (Gamper, 1993); 8. Treeline in the mountain belt of the Alps: sum of arboreal and shrub pollen (local plants excluded from percentage calculation) from Pian di Gembro, Rhetian Alps, 1350 m a.s.l. (Pini, 2002; courtesy R. Pini); 9. Oscillation of the treeline in the Central Alps (Burga & Perret, 1998); 10. Northern Hemisphere mean temperature oscillation as reported in Schoenwiese (1995); 11. Atmospheric methane concentration in the Northern Hemisphere, that is an indicator of the alternation between dry and humid phases (Blunier & *alii*, 1993; Wanner & *alii*, 2000); 12. Delta ^{18}O in GRIP ice cores, central Greenland (Johnsen & *alii*, 1997); 13. GISP2 Polar Circulation Index record (Mayewski & *alii*, 1994); 14. The North Atlantic Ice Rafting Debris Event record (Bond & *alii*, 1993, 1997, 2001). LI: Late Glacial Interstadial, not a chronozone and therefore shown in brackets; YD: Younger Dryas; PB: Preboreal; B: Boreal; A: Atlantic; SB: Subboreal; SA: Subatlantic. Cultural periods in NI (Northern Italy): P: Palaeolithic; M: Mesolithic; N: Neolithic; CA: Copper Age; BA: Bronze Age; IA: Iron Age; R: Roman Period; MA: Middle Ages; MT: Modern Times.

The regional lake-level record can also be directly compared with other records from the North Atlantic, as evidence of possible general atmospheric circulation patterns coupled with Holocene climate oscillations (Magny, 1999).

Following this basic idea, a number of important Northern Hemisphere records are also reported. The Northern Hemisphere mean temperature oscillation as reported in Schoenwiese (1995) and atmospheric methane concentration in the Northern Hemisphere, that is an indicator of the alternation between dry and humid phases (Blunier & *alii*, 1993; Wanner & *alii*, 2000) are shown in fig. 7, as well as delta ^{18}O in GRIP ice cores, in central Greenland (Johnsen & *alii*, 1997).

A comparison with the GISP2 Polar Circulation Index record (Mayewski & *alii*, 1994) and the North Atlantic Ice Rafting Debris Event record (Bond & *alii*, 1993, 1997, 2001) has also been attempted. As stated elsewhere, the correlation between lake-levels and Atlantic records suggests tele-connections in a complex cryosphere-ocean-atmosphere system, underlined in particular by cold-humid phases.

Despite the intrinsic difficulties in the correlation among these records, which are mainly due to different spatial scales (local, regional and global), to different time-resolutions and dating constraints, some remarkable evidence has been found.

The periods of enhanced slope instability found in the study areas display a quite good correlation especially with the indicators of cold and humid climate. This fact suggests that these phases could have been climatically-driven, and, in particular, that a positive moisture balance could have played a major role in conditioning landslide activity at the hundred to thousand years time-scale. It is clear that a positive moisture balance could have been determined by different environmental conditions. An increase in intensity and/or duration of rainfall could have played a major role at every time scale, together with evapotranspiration variability driven also by temperature regime changes. Nevertheless, other processes such as permafrost melting could have been significant in specific time windows, when the environmental conditions were significantly different than during the rest of the Holocene.

The results obtained so far tend to indicate that landslide events clustering have a climatic significance. Nevertheless, the number of datings, and especially the number of thoroughly dated landslides are still not adequate to draw general conclusions. Moreover, many interpretation problems are still unresolved.

The first question refers to the absence of datings before ca 14,000 cal BP. This could be related to the absence of datable organic matter, or be referred to a lower landslide activity.

Before the Bølling, due to the sparse vegetation, the chance of finding organic matter buried by a mass movement is low. Generally, there is also a lack of deep boreholes reaching the original sliding plane. The consequence is that many initial failures may remain undated. Actually, many landslides that occurred during the end of the Last Glacial Maximum and early Late Glacial are dated on the basis of stratigraphical evidence (e.g., Pellegrini & *alii*, 2006).

If the lack of old slides had a climatic significance, the reason could be found in the presence of permafrost having a stabilization effect on slopes even at lower altitudes.

The subsequent melting of permafrost could have then triggered many initial failures, as shown in fig. 8 where the age/altitude relationship of some landslides in the study sites is displayed. A progressive elevation of the crown altitude with time can be noticed, possibly reflecting the elevation of the permafrost boundary. This outcome is not so clear in the Belluno Prealps and the Apennines. In particular, in the latter case the extension of the permafrost belt and the effects of melting could have been less effective.

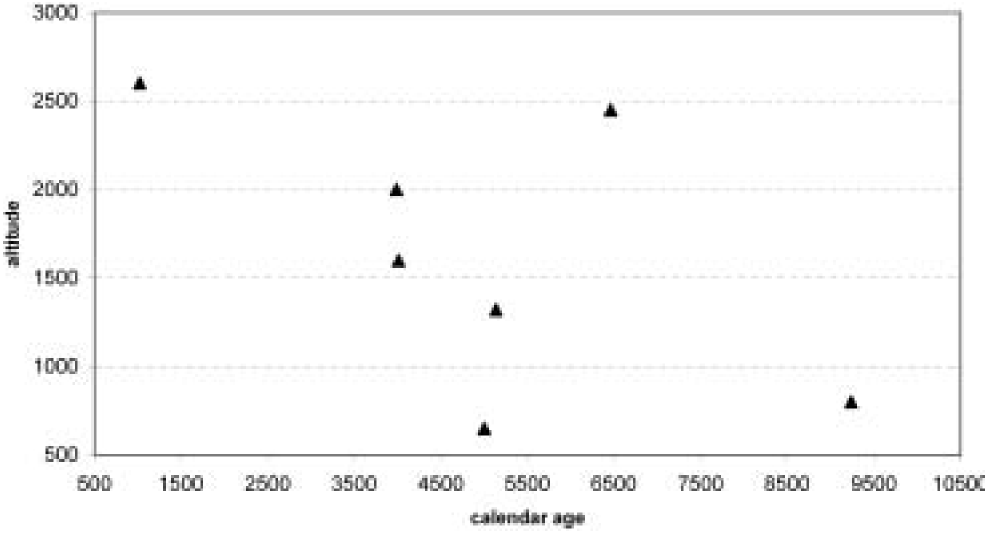


FIG. 8 - Altitude of the crown of the landslide with respect to the age in the Western Alps.

The second point is the significance of the cluster during the Pleistocene-Holocene boundary. It could indicate an increase of organic matter and the consequent higher chances of dating or an increased landslide activity. This cluster may be due to a bias in the dataset that is the increased probability of obtaining datable organic matter buried by landslides. In this case the cluster would not indicate an increase of landslides frequency.

The cluster of datings could have a climatic significance, being related to the slope release following deglaciation and/or the permafrost melting.

In any case, the rapid warming after the end of the Younger Dryas would have increased water availability at higher altitudes. In addition to this indirect effect, a change in the precipitation regime could have also triggered a greater amount of landslides.

One further issue is the small number of datings during the Holocene climate optimum. In this case, one reason could be a bias in the dataset that is a lack of deep samples, whilst reduced landslide activity seems to be the most reliable hypothesis.

As in the case of the Dolomites (fig. 9), generally there is a marked predominance of surface samples. It is clear that a larger number of deep samples could provide more middle Holocene ages. At the same time, there is a clear cluster of datings at the beginning of the Holocene that is in contrast with this idea. Actually, when cores can be dated throughout, no Middle Holocene ages have been found, as in the case of several earth slides and earth flows in the Apennines (Tellini & Chelli, 2003). If the absence of dated events had a climatic significance, it would then indicate a relatively drier climate, as also supported by several proxy data (see fig. 7).

Finally, the enhanced activity in the Upper Holocene could have also been affected by the structure of the dataset, the increase of landslides in recent periods being due to the dominance of surface samples. On the contrary, the climatic significance of this phase would be related in particular to more cold and humid periods throughout the Subboreal and Subatlantic. An important point on this aspect is the type of dated landslides, which is different from the Early Holocene. For example, Soldati & *alii* (2004) indicate that in this period many earth flows were triggered, possibly because of a changing in the rainfall regime.

Starting from the Subatlantic, some Authors found that the increase of slope instability phenomena is related to human impact, mainly because of deforestation (Dapples & *alii*, 2002). These studies show that anthropogenic factors must be considered at least since the Bronze Age, possibly as amplificators of climatic factors.

CONCLUSIONS

Among the factors that act on slope stability, climate changes, vegetation cover and anthropic activity have been analysed in detail. The periods of enhanced landslide activity correspond with cold and humid climate conditions at regional and global scales, with periods of scarce presence of vegetation, sometimes also due to human activity. The influence of climate is clear in periods characterised by cold and humid conditions, that have destabilizing effects on slopes, since a positive moisture balance can be considered as one of the most important triggering factors of landslides in the majority of geological and environmental contexts.

Since type, magnitude and frequency of landslides can also be related to several conditioning factors other than meteorological and climatic/palaeoclimatic ones, a general

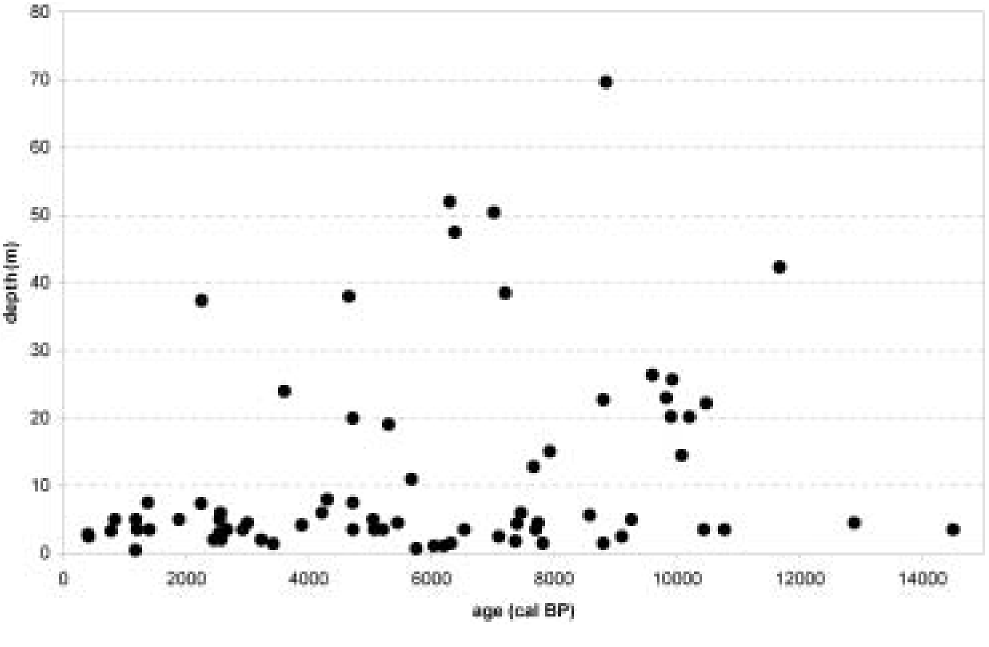


FIG. 9 - Age-depth model of the radiocarbon-dated samples in the area of the Dolomites.

description of geomorphological, litho-structural and tectonic contexts of the sampled landslides has been proposed. Possible static and dynamic factors affecting the spatial distribution of landslides have been analyzed. During the temporal interval of interest for our landslides studies, no relevant changes in the spatial distribution of major outcropping lithological units and structural domains have been reported in the literature. Therefore, this control on slope instability phenomena has to be considered as «static». As regards «dynamic» factors affecting the spatial distribution of landslides, special attention has been given to seismotectonic activity: only some neotectonic deformational zones of the studied area and the major seismic districts of Northern Apennines and Venetian Prealps showed cases of interactions with slope instability phenomena.

Besides the direct effects of climate, also some indirect effects have to be considered, among which are deglaciation and vegetation dynamics. In the latter case, climate changes do affect the distribution of the vegetational belts, either with the latitude, or with the altitude. These effects are remarkable in the distribution of extreme vegetational belts, as at the treeline, and play also a significant role in the evolution of geomorphological processes. In this sense, in the alpine areas, some of the formative events can be related also to vegetation dynamics. The mean annual temperature changes that have been registered during the Holocene, between 1° C and 2° C, induced treeline oscillations in the order of one hundred metres. The consequences of these variations could have been particularly severe at higher altitudes, as at valley bottoms, the instability of slopes and the sediment delivery to the streams have been continuously controlled by vegetation.

After the colonization of arboreal species in the alpine regions following the retreat of the glaciers, vegetation could have had a stabilisation effect between 11,000 e 6000 cal BP. This period is in general characterized by dry conditions, referred to as the climatic optimum, that in any case has been distinguished by several phases of climate worsening. After 6000 cal BP, because the general deterioration of the climate conditions, together with the ever increasing human impact on landscape, with particular reference to deforestation, the stabilising effect of vegetation tends to decrease gradually. The last 5000 years witnessed a combination of negative effects, either climatic, or vegetational or anthropic.

Looking at the temporal distribution of the possible triggering factors, the role of climate seems therefore of key importance. In particular, the alternation between dry and humid phases conditions slope instability, both directly, as in the case of rainfall regime, or indirectly, as in the case of deglaciation or tree line oscillation.

On the basis of the data gathered so far in the study areas, besides the litho-structural and tectonic «static» and «dynamic» factors that affect the spatial distribution of landslides and the importance of vegetation and human impact in the general context of slope instability, climate changes have clearly played a key role in the control and in the triggering of landslide processes. In fact, widening the temporal window, the relationships between landslides and climate arise, as the local effects and the secondary triggering factors are filtered, allowing definition of the fundamental link governing the system.

The results obtained so far show that the different types of mass movements display different behaviour with respect to climate at a broad temporal scale.

In general, rock slides are not directly related to climate, but the influence of glacial debuttressing and permafrost melting could have been of great importance, in particular at the beginning of the Holocene. At the same time, earth slides and earth flows display a clearer climate-dependent behaviour.

The relationship between landslides and climate is certainly complex, therefore consistent and reliable interpretations can be gained from detailed studies and extensive databases. One of the major constraints is the more or less constant activity of some phenomena or the moderate accelerations, that are obviously not datable. The first consequence is underestimation of the landslide activity. Moreover, non-climatic factors, such as human impact, interfer with climate, at least since the Middle Holocene.

Bearing in mind the limitations discussed above, the results illustrate that on the one hand during the Upper Pleistocene most of the landslides occurred in the Prealps, the first area witnessing the deglaciation, and that on the other hand a fourfold division of the Holocene can be observed:

- the beginning of the Holocene (e.g., the Preboreal), characterised by first-time failures of large landslides. The boundary conditions might be related to glacial debuttressing and the thawing of permafrost at high altitudes;
- the hypsithermal climate optimum, with few dated landslide events, probably as a consequence of a drier climate;
- the second part of the Holocene (e.g., Subatlantic and Subboreal), with an increased landslide activity, related to reactivations of earth slides and flows, possibly indicating an increase in intense rainfall events as well as an increase in total precipitation;
- the Little Ice Age, with rock avalanches, falls in the upper altitudes of the mountain relief, related to widespread slope instabilities probably induced by permafrost degradation and complex landslides, associated with major hydrometeorological events, as documented by historical data.

The correlation of landslide activity records with the environmental context obtained from other proxies and confirmed by a multidisciplinary approach can confirm the assumption that the process of landsliding is an expression of landscape sensitivity to climate changes. In any case, the analysis of the geomorphological evolution of a slope by means of dating and in the context of the climatic and environmental evolution, offers an in-depth view of its sensitivity with regards to the relationships between the causes and the system response.

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