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PALEOCLIMATIC SIGNIFICANCE OF HOLOCENE SLOPE INSTABILITY IN THE DOLOMITES (ITALY) (***)

ABSTRACT: SOLDATI M. & BORGATTI L., *Paleoclimatic significance of Holocene slope instability in the Dolomites (Italy)*. (IT ISSN 0391-9838, 2009).

This paper deals with the use of records of past landslide events in the study of climate changes. The dating of past landslide events is a useful tool to reconstruct the evolution of the slope-system at a broad temporal scale and to recognize the different formative events it has undergone. When the environmental context can be traced by means of a multidisciplinary approach which comprises geomorphological, sedimentological, paleobotanical, dendrochronological and archaeological analyses, then a deep understanding of the relationship between the possible triggering factors and the slope response can be achieved. The goal is to recognize changes of environmental factors which condition landsliding processes such as climate, seismic activity, vegetation and land use, trying to identify the relationship between landslide events and their triggering process, which is known to be complicated by the behaviour and the properties of the hillslope system. With reference to the results of some case studies in the Dolomites, the conceptual and methodological aspects of the topic are here discussed.

KEY WORDS: Landslide events, Climate changes, Dolomites, Italy.

INTRODUCTION

Since morphogenetic processes occurring on the Earth's surface are driven also by climate, landforms as well, as superficial deposits, may provide a potential record of landscape evolution in a particular climatic framework. Previous investigations have clearly shown that, from the Late Glacial to the present, climate has influenced slope evolution, either directly or indirectly, and that slope processes may be considered geomorphological indicators of climate changes (e.g., Goudie, 1992). Temporal clustering of past landslide events has in fact been reported from different European regions such as Great Britain, Spain, Italy and Eastern Europe (Starkel, 1997; Alexandrowicz, 1997; Frenzel & *alii*, 1993; González Díez & *alii*, 1996; Panizza & *alii*, 1996; Schoeneich & *alii*, 1997; Ibsen & Brunsden, 1997; Lateltin & *alii*, 1997; Dikau & Schrott, 1999; Margielewski, 2001; Matthews & *alii*, 1997; Bertolini & Tellini, 2001; Schmidt & Dikau, 2004; Soldati & *alii*, 2004; Bigot-Cormier & *alii*, 2005; Pellegrini & *alii*, 2006; Soldati & *alii*, 2006). Case studies from Africa (Busche, 2001; Thomas, 1999), from northern and southern America (Bovis & Jones, 1992; Trauth & *alii*, 2000, 2003; Smith, 2001; Holm & *alii*, 2004) and from Asia (Sidle & *alii*, 2004) have also been recently presented. Recent studies have been focused on the correlation between slope movements, climatic changes and land-use in prehistoric and historic times (Dapples & *alii*, 2002; Glade, 2003), and on precipitation regime and seismicity (Corominas, 2001) as triggering causes of temporal and spatial concentrations of landslide events. Comprehensive reviews on the topic are provided by Berrisford and Matthews (1997) and Borgatti & *alii* (2001).

The results presented here concern the study of the relationships between climate and slope evolution from the Lateglacial to the present in study sites located in the Dolomites (Alps, northern Italy). This study is part of the Italian research project MIUR - COFIN 2002 «Geomorphological evolution of slopes and climate changes: landslide analysis and paleoclimatic reconstructions», funded by the Italian Ministry of Education, University and Research (National Scientific Coordinator: M. Soldati; Research Units: Università di Milano-Bicocca, Modena e Reggio Emilia, Padova, Parma and Torino, with the collaboration of several public institutions). The research has taken into account, 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 different paleoclimatic parameters or proxies. The analysis of the possible temporal correlations between landslide events and climate changes allows the cause-effect relationships between the various processes to be deduced. A common ap-

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proach has been applied to different study areas in the southern Alps and in the northern Apennines (fig. 1) with the following objectives (see also Soldati & *alii*, 2006):

– define the state of the art at an international level;
– create an archive of dated landslides from the Lateglacial to date, using Geographical Information Systems, identifying those phenomena which are believed to be significant indicators of climatic changes;
– provide the selected landslide events with a chronological frame, by applying radiometric, incremental methods etc.;
– reconstruct paleo-environmental conditions at the local scale in the study areas, by means of pollen analyses;
– evaluate the role of climatic and non-climatic (paleoseismicity and human impact in prehistoric times) causes in relation to the type of landslides;
– compare landslide records with paleo-environmental proxies, obtained at different time and spatial scales, in order to assess the relationship between slope instability processes and climate changes.

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 (Soldati & *alii*, 2006) and to better understand the present and future geomorphological evolution in mountain areas in the frame of global changes. Infact, looking at the temporal distribution of the possible triggering factors, the role of climate seems of key importance. In particular, the alternation between dry and humid phases has proved to condition slope instability, both directly, as in the case of rainfall regime, or indirectly, as in the case of deglaciation or tree line oscillation.

STUDY AREA

Cortina d'Ampezzo and Corvara in Badia are located in the eastern Italian Alps in the Dolomites. The mountain groups, rising from 1400 m a.s.l. in the valley bottom up to 3000 m a.s.l., are made up of dolomite rocks, with, in most cases, marls or limestones alternating with clayshales outcropping in the slopes underlying the dolomite peaks. Structural features, including folds of regional or local extent, low-angle overthrusts and normal, reverse or strike-slip faults are related to the Tertiary Alpine compression

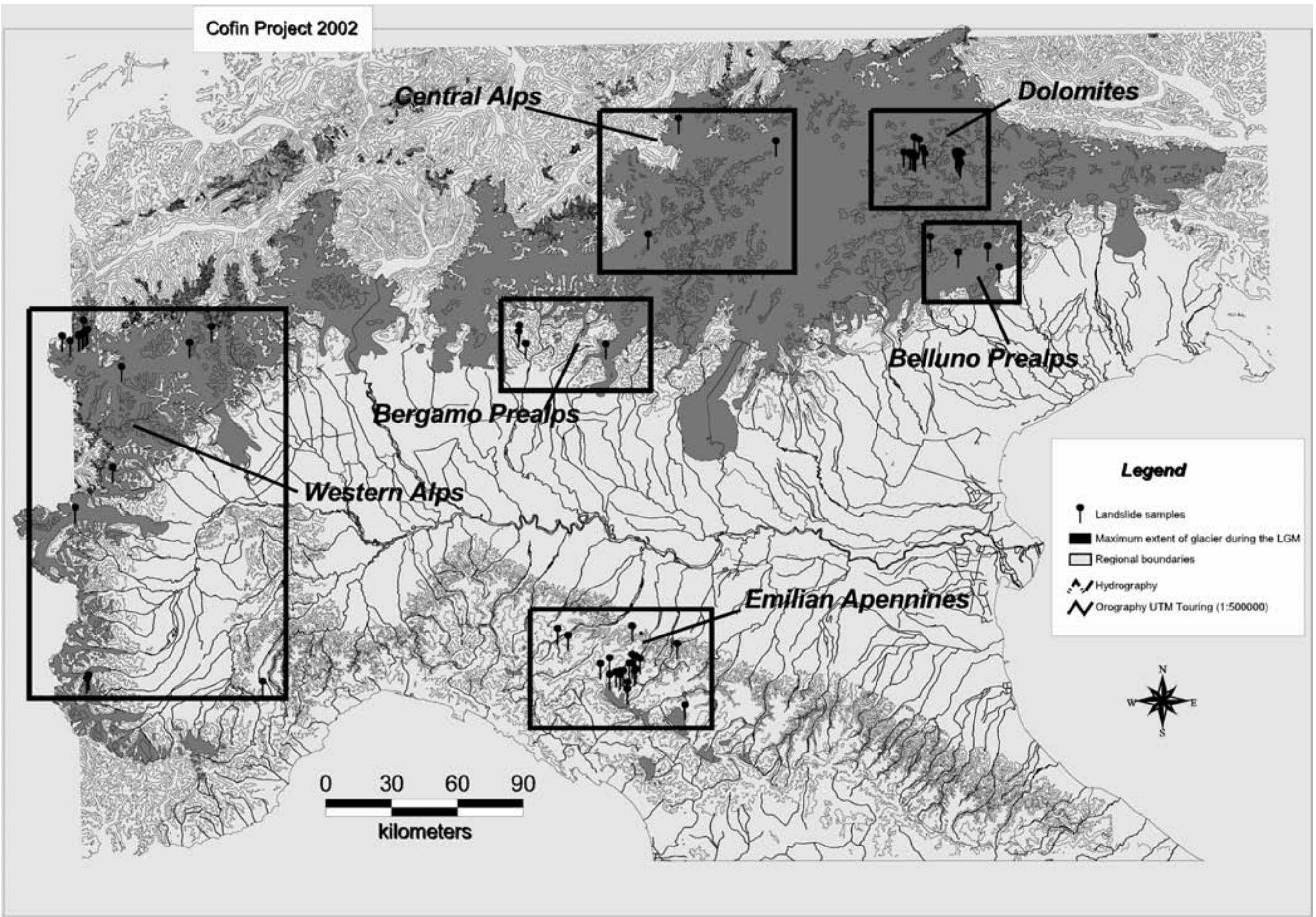

FIG. 1 - Location of MIUR-COFIN 2002 study areas (see also Soldati & *alii*, 2006) and geographic distribution of the dated landslides. The maximum extent of glacier during the LGM is adopted from Orombelli & *alii* (2004).

(Doglioni & Bosellini 1987; Castellarin & *alii*, 1992). In Alta Badia, evidence of neotectonic movements was also found (Castaldini & Panizza, 1991; Corsini & Panizza, 2003). Due to past tectonic stresses, the rock masses are highly fractured and consequently prone to slope instability. Landslide processes are widespread: the dolomite cliffs are involved in lateral spreads, rock falls and topples, while rotational and translational slides and flows affect the slopes where clay-rich rocks outcrop. In some cases, landslide deposits can be more than 100 m thick and extend for several square kilometres. At present, the deepest sliding surfaces are dormant, while recurrent reactivations tend to be more superficial and are mainly due to intense and/or prolonged rainfall and snowmelt (Corsini & *alii*, 2005).

LANDSLIDES DATING

In the study areas, detailed geological and geomorphological field surveys have been carried out to identify the type and activity of slope instability processes (Panizza, 1990; Pasuto & *alii*, 1997; Corsini & *alii*, 1998). The stratigraphy of the landslide bodies has been reconstructed from subsurface investigations (Corsini & *alii*, 1999; Corsini & *alii*, 2000; Corsini & *alii*, 2001; Soldati & *alii*, 2004). Wood, peat and organic sediment samples somehow linked to past landslide events have been collected by means of continuous coring, in natural or artificial scarps mainly in landslide accumulation areas. Direct or indirect dating of landslides has been carried out using stratigraphic methods and radiocarbon analyses by the conventional or AMS methods (for a total of 73 ages). The conventional radiocarbon ages have been calibrated using Calib (Stuiver & *alii*, 2004) and the IntCal04 calibration data set (Reimer & *alii*, 2004), with a 2 sigma error. Then, in order to analyse the temporal occurrence of landslide events, the distributions of probability for each dating have been summed, producing plots for the each site and for both together. In this procedure, besides the direct dating of landslide events, also the ages obtained from lake sediments have been considered; in fact, these ages have been recognized as a the sedimentary expression of abrupt mass wasting phenomena occurred in the Corvara catchment (Borgatti & *alii*, 2007).

LANDSLIDE ACTIVITY RECORDS IN THE DOLOMITES

By analysing the statistical distribution of calibrated radiocarbon ages, the first outcome is a clear difference between the two datasets (Borgatti & Soldati, in print). In the area of Cortina the ages are older, with the oldest samples to be referred to more than 14 ka cal BP. This difference may be related to the timing of deglaciation and of subsequent reforestation at different altitudes (Cortina d'Ampezzo 1224 m a.s.l., Corvara 1568 m a.s.l.) and to the morphological setting, with respect to valley width and exposure. Indeed, no tree vegetation occurred in the Dolomites until 14.5 ka cal BP, that means also low chance to find organic matter buried by a mass movement before that time. Moreover, only few deep drillings or exposed sections reach the basal sliding surface and, therefore, many initial failures may be still not dated. On the other hand, the lack of very old landslides could have also a climatic significance, related with progressive and delayed permafrost melting processes at higher altitudes.

In the area of Corvara the ages distribution shows a persistent landslide activity during the entire time span of the Holocene, whereas in Cortina the ages tend to be more scattered. This could be linked to the number of dated samples, i.e., 24 samples in Cortina, 49 in Corvara. Anyway, some clusters are recognisable in both records (around 5 ka cal BP and from 2 to 3 ka cal BP), while others are not analogous, such as the 11,000-9500 temporal cluster in Cortina, which is not so marked in Corvara.

If the distribution of probability is considered for both study sites together (fig. 2), the picture is different and the clustering around certain ages is more evident. By analysing the complete data set, four periods of enhanced landsliding can be outlined: I. from 10,700 to 8400 cal BP, between Younger Dryas and the Preboreal; II. from 8200 to 6900 cal BP, during the older Atlantic; III. from 5800 to 4500 cal BP, between Atlantic and Subboreal; IV. from 4000 to 2100 cal BP, between Subboreal and Subatlantic (Borgatti & Soldati, in print).

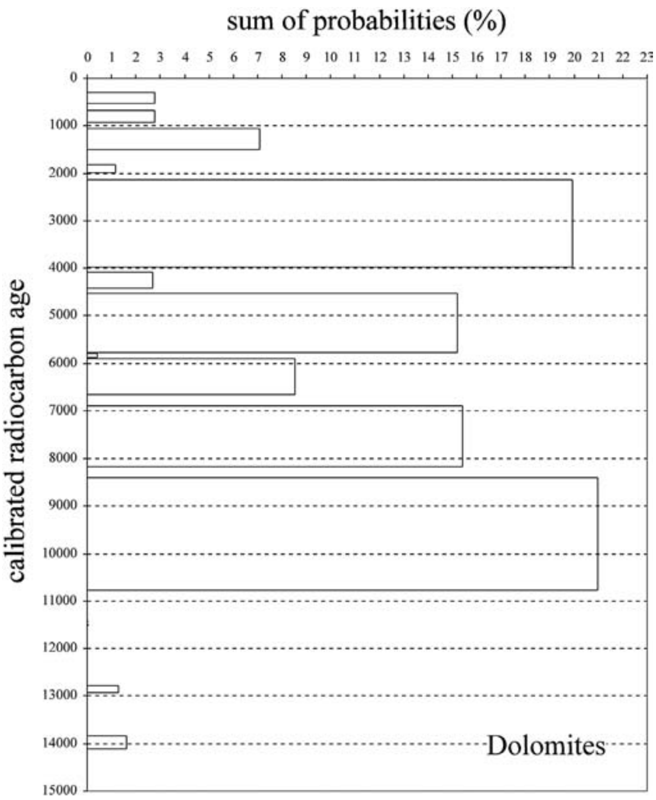

FIG. 2 - Temporal distribution of dated slope instability events in the Dolomites (modified from Borgatti & Soldati, in print).

CLIMATE AS A CAUSAL FACTOR FOR LANDSLIDING AT A BROAD TEMPORAL SCALE

Field observations of present-day activity and historical records show that first-time failures of large landslides follow a complex hydrological and mechanical behaviour (Corominas, 2001). In fact, first-time failures are the result of long-term evolutionary processes of the slope rather than the near-immediate response to a specific trigger. On the other hand, the influence of moisture balance is evident in the case of reactivations of dormant landslides, the acceleration of active movements and in the triggering of shallow slope failures. Therefore, considering the significance of rainfall regime and the resultant hydrologic response of the slopes in triggering mass movements (if it is possible to exclude the direct influence of seismicity and human activity) the periods of enhanced landsliding have been compared to different Late Glacial and Holocene paleoclimatic records, in order to verify the climatic control on the clustering of landslide events (fig. 3).

The proxy records come from different realms, either continental or marine. 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. The landslide records from the Dolomites show the periods of enhanced landsliding documented in this study and periods of reduced landslide activity as described in Borgatti & *alii* (2007). Despite the intrinsic difficulties in correlating these records, mainly due to different spatial scales (local, regional and global), dissimilar time-resolutions and several dating constraints, some remarkable indications are apparent. The periods of enhanced slope instability found in the Dolomites display quite a good correlation especially with the indicators of cold and humid climate, suggesting 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. The phases of minimum landslide frequency identified from Borgatti & *alii* (2007) alternating with the enhanced landsliding periods fall within phases of reduced glacier extent, with warmer summers and/or reduced rainfall.

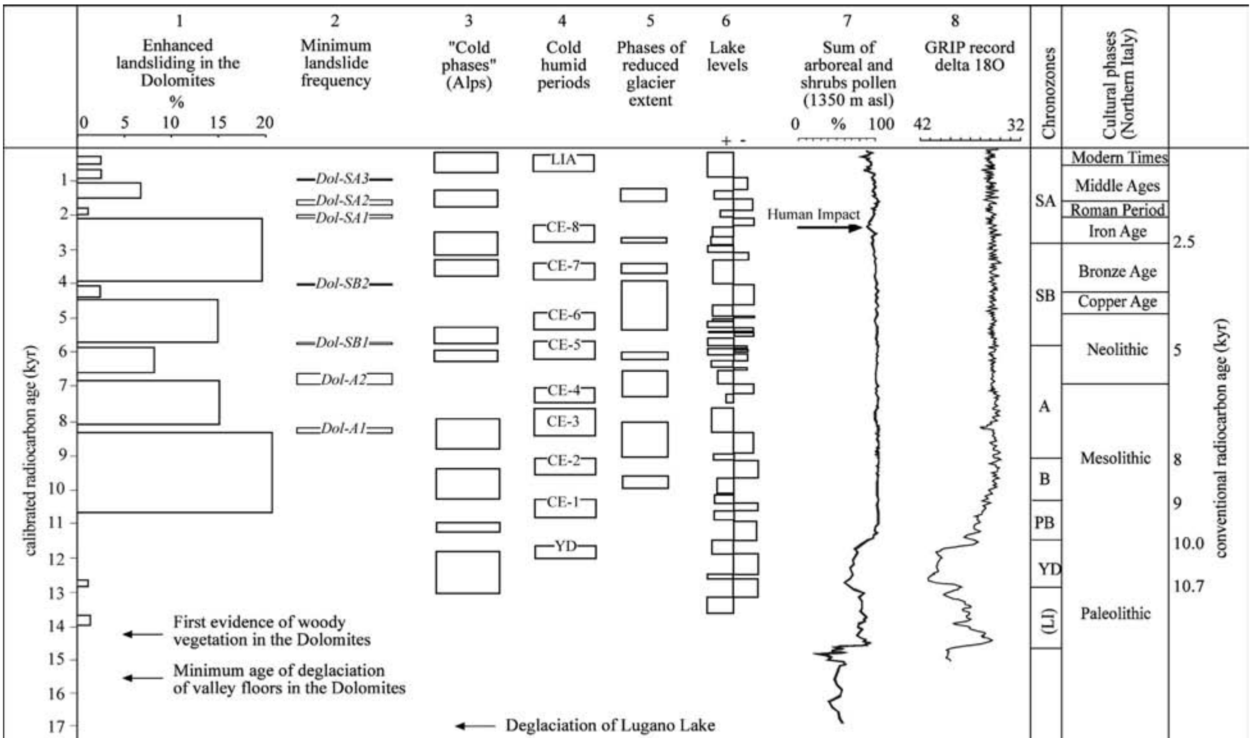

FIG. 3 - Comparison of different Late Glacial and Holocene paleoclimatic record at different spatial scales (modified after Borgatti & *alii*, 2007). Legend: 1. Enhanced slope instability events in the Dolomites (Borgatti & Soldati, in print); 2. Phases of minimum landslide frequency in the Dolomites (Borgatti & *alii*, 2007); 3 and 4. Cold and humid periods in the Alps and on the Swiss Plateau (Haas & *alii*, 1998; Tinner & Amman, 2001; Tinner & Kalterieder, 2005); 5. Phases of reduced glacier extent, recorded by the retreats of the Unteraar and other Swiss glaciers (Hormes & *alii*, 2001); 6. Mid-European lake levels (Magny, 1999) as paleohydrological indicators; 7. Tree line 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). 8. Delta ^{18}O in GRIP ice cores, central Greenland (Johnsen & *alii*, 1997). Cultural periods in Northern Italy (Cardarelli, 1993). The age of deglaciation onset of Italian piedmont amphitheatres is from Monegato & *alii* (2005). LI: Lateglacial Interstadial, not a chronozone and therefore shown in brackets; YD: Younger Dryas; PB: Preboreal; B: Boreal; A: Atlantic; SB: Subboreal; SA: Subatlantic.

Mass wasting processes are primarily controlled by the geological and structural predisposing factors, which may differ from region to region, but this record shows that the apparent modulations are induced by centennial to millennial-scale climate changes. In addition, in formerly glaciated mountain belts, the long-term effects of the deglaciation and permafrost melting may result in effects that may be opposite to the contemporary climate tendencies, as in the case of the clustering around the onset of the Holocene. Finally, during the upper Holocene, the long-term tendency towards slope stability after the last deglaciation could then be counterbalanced by the effects of human activity, starting from 4 ka cal BP.

LANDSLIDES IN A CHANGING ENVIRONMENT: CONCLUSIONS AND PERSPECTIVES

Landslides provide a record of climate variability at a range of temporal and spatial scales. Besides the intrinsic complexity of the landsliding phenomenon, many factors may produce changes in the frequency and magnitude of both first-time slope failures and reactivations. A variety of triggers may account for first-time failures of large landslides, while reactivations may be generally due to prolonged periods of positive moisture balance, extending over years to decades.

In this study, the effects of different environmental changes (temperature increase, rainfall regime and vegetation disappearance), seismicity and human impact have been taken into account. The results show that a match exists between some clusters of landslide events and regional and global paleoclimatic frameworks. This suggests that, in particular contexts, landslide can be considered as geomorphological indicators of climatic changes. Nevertheless, at present, landslide records undergo several biases and there are still gaps to be fulfilled in order to consider them as consistent paleoclimatic proxies.

From the geomorphological point of view, an integration of these data into a complete paleoclimatic record can help in distinguishing the actual triggers of known phases of slope instability. At the same time, for the paleoclimate community, landslide records could be a sort of independent data source, that can be added to a multidisciplinary and comprehensive data archive, towards a common framework.

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