Geomorphology 120 (2010) 56–64

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

# Landslides as a geomorphological proxy for climate change: A record from the Dolomites (northern Italy)

Lisa Borgatti [a,*], Mauro Soldati [b]

[a] Dipartimento di Ingegneria delle Strutture, dei Trasporti, delle Acque, del Rilevamento, del Territorio - DISTART ALMA MATER STUDIORUM - Università di Bologna Viale Risorgimento, 2, 40136 Bologna, Italy

[b] Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia. Largo S. Eufemia, 19, 41121 Modena, Italy

ARTICLE INFO

*Article history:*
Accepted 7 August 2009
Available online 22 September 2009

*Keywords:*
Landslide events
Climate changes
Holocene
Dolomites
Italy

ABSTRACT

This study investigates the relationships between climate changes and hillslope evolution in the Dolomites (eastern Alps, Italy), during the Late Quaternary, with particular attention paid to landslide processes. The basic premise is that modifications in landslide frequency may be interpreted as changes in the hydrological conditions of slopes, which are in turn controlled by climate.

After the statistical analysis of a data set composed of 73 conventional radiocarbon ages, obtained from 24 landslides, four periods of enhanced landsliding have been identified: 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; and IV. from 4000 to 2100 cal BP, between Subboreal and Subatlantic.

These periods have been compared with different Lateglacial and Holocene paleoclimatic records, to check the correspondence between periods of enhanced landslide activity and cold and humid spells recognized at different spatial scales. As the records show, in the study areas, slope instability processes can be considered geomorphological indicators of climatic changes and to a certain extent reliable proxies of environmental evolution.



## 1. Introduction

The contribution of Geomorphology to paleoclimatic reconstructions is certainly significant. Since morphogenetic processes which take place on the Earth's surface are influenced by climate, landforms as well as superficial deposits potentially provide a record of the evolution of a landscape in a particular climatic framework. Previous investigations have clearly shown that from the Lateglacial 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 ancient landslide events has in fact been reported from different European regions such as Great Britain, Spain, Italy and Eastern Europe (Frenzel et al., 1993; González Díez et al., 1996; Panizza et al., 1996; Starkel, 1997; Alexandrowicz, 1997; Schoeneich et al., 1997; Ibsen and Brunsden, 1997; Lateltin et al., 1997; Matthews et al., 1997; Dikau and Schrott, 1999; Margielewski, 2001; Bertolini and Tellini, 2001; Schmidt and Dikau, 2004; Soldati et al., 2004; Bigot-Cormier et al., 2005). Case studies from Africa (Thomas, 1999; Busche, 2001), from northern and southern America (Bovis and Jones, 1992; Trauth et al., 2000; Smith, 2001; Trauth et al., 2003; Holm et al., 2004) and from Asia (Sidle et al., 2004) have also been recently published. Recent studies have been focused on the correlation between slope movements, climatic changes and land-use in prehistoric and historic times (Dapples et al., 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 et al. (2001).

The results presented here concern the study of the relationships between climate and slope evolution from the Lateglacial to the present and are an extension of the former study of Soldati et al. (2004). The research has been carried out in study sites located in the Dolomites (Alps, northern Italy), to test the premise that modifications in landslide frequency may be interpreted as changes in the hydrological conditions of slopes, which are directly controlled by climate. The correlation between temporal concentrations of landslide events and climatic events recognized at different spatial scales has been assessed, to identify to what extent slope instability processes can be considered geomorphological indicators of climatic changes.

## 2. Study area

Cortina d'Ampezzo (46°32′14.58″N, 12° 8′20.12″E) and Corvara in Badia (46°33′3.94″N, 11°51′35.10″E) are located in the eastern Italian Alps in the Dolomites (Fig. 1). The mountain groups, that rise 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

* Corresponding author. Tel.: +39 051 2093103; fax: +39 051 6448073.
*E-mail address:* lisa.borgatti@unibo.it (L. Borgatti).

0169-555X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2009.09.015

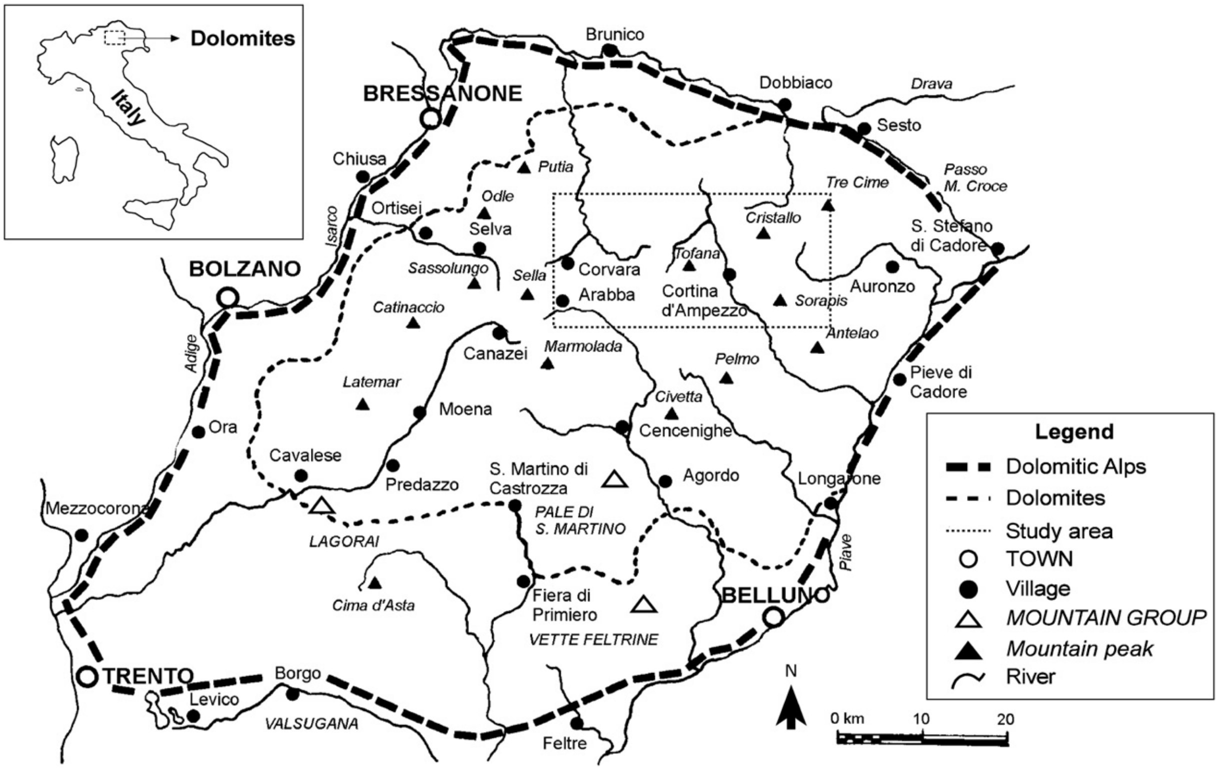


**Fig. 1.** Geographic setting of the Cortina d'Ampezzo and Alta Badia areas (Dolomites, Italy) (modified from Bertoglio and De Simoni, 1979).

with clayshales outcropping in the slopes underlying the dolomite peaks (Soldati et al., 2004).

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 (Doglioni and Bosellini 1987; Castellarin et al., 1992). In Alta Badia, evidence of neotectonic movements was also found (Castaldini and Panizza, 1991; Corsini and Panizza, 2003). Due to 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 (Corsini et al., 2005) and are mainly due to intense and/or prolonged rainfall and snowmelt.

Specific investigations into the temporal occurrence of landslides have been carried out in the Dolomites since the 1990s. These study areas, located in well-known geological and geomorphological contexts, have been chosen because the set of dated phenomena is composed of similar landslide types, affecting comparable lithologies. A wide number of landslides have been dated, either directly or indirectly (Panizza, 1990; Panizza et al., 1996; Corsini et al., 2000; Corsini et al., 2001). The chronology shows temporal clustering of dated mass movements, which allows climatic inference to be made using sets of contemporary landslides. Most of the data have been presented in Soldati et al. (2004), where the geological and geomorphological setting, and the context in which the dated material was found, are thoroughly described.

## 3. Landslides dating

### 3.1. Dating methods

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 et al., 1997; Corsini et al., 1998). The stratigraphy of the landslide bodies has been reconstructed from subsurface investigations and many organic samples have been obtained (Soldati, 1999; Corsini et al., 1999, 2001, 2005). Wood, peat and organic sediment samples linked to past landslide events have been collected by means of continuous coring, in natural or artificial scarps inside landslide accumulation zones. Direct or indirect dating of landslides has been carried out using stratigraphic methods and radiocarbon analyses by the conventional or AMS methods. In this study, eleven new datings have been added to the record by Soldati et al. (2004) (Table 1). The conventional radiocarbon ages have been calibrated using Calib. (Stuiver et al., 2004) and the intcal04 calibration data set (Reimer et al., 2004), with a 2 sigma error. In addition, the calibration software has allowed a statistical analysis to be carried out, that combines the age probability distributions of more than two close radiocarbon ages. The resulting curve is the best fit combination of the different curves and expresses the 2 sigma age interval for the combined event. Applying this procedure, a distinction between radiocarbon dates that could be referred to the same statistical landslide event (as defined by Schoeneich, personal communication) and real clustering of different events have been made.

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 single study sites and for both together. In this procedure, besides the direct datings of landslide events, also the ages obtained from lake sediments have been considered; in fact, they have been recognized as a the sedimentary expression of abrupt mass wasting phenomena occurred in the catchment (Borgatti et al., 2007).

### 3.2. Dating constraints

Several issues have been taken into account in data interpretation stage, in order to establish a valuable database from the chronostratigraphic point of view. First of all, the analysis of the stratigraphic and geomorphological context is of paramount importance, in order to reduce the sampling bias. Datable materials may be found buried

**Table 1**
Radiocarbon dating in the area of Cortina d'Ampezzo and Corvara in Badia; data calibrated with Calib 5.0.2, data set by Reimer et al. (2004).

| Landslide | Landslide type | Sample code | Sample type | Site of collection | Depth (m) | Conventional Radiocarbon Age (years BP) | Calibrated Radiocarbon Age (years BP) |
|---|---|---|---|---|---|---|---|
| *a - Landslides dated in Cortina d'Ampezzo (see Soldati et al., 2004, for landslides location map)* | | | | | | | |
| Col Drusciè | Translational rock slide | - | Tree trunk | Excavation | 14.50 | 9000±150 | 9632–10,509 |
| Cadin_2 | Earth flow | B-179855 | Tree trunk | Excavation | 3.50 | 12.120±60 | 13,820–14,116 |
| Cadin_1 | Earth flow | GX-16117 | Tree trunk | Excavation | 3.50 | 12.150±435 | 13,193–15,350 |
| Chiave | Earth flow | B-74802 | Tree trunk | Excavation | 3.50 | 4520±60 | 4972–5437 |
| Lacedel_1 | Earth flow | GX-17696 | Wood | Borehole | 42.30 | 10.035±110 | 11,245–11,977 |
| Lacedel_2 | Earth flow | GX-17697 | Wood | Borehole | 22.20 | 9270±105 | 10,234–10,705 |
| Pierosà | Translational rock slide | B-63341 | Wood | Excavation | 4.50 | 10.850±80 | 12,736–12,949 |
| Cortina | Earth flow | B-83624 | Peat | Borehole | 23.00 | 8710±70 | 9535–10,112 |
| Cortina_2 | Earth flow | B-63338 | Wood | Excavation | 5.00 | 4350±60 | 4827–5270 |
| CortinaAlverà_1 | Earth flow | B-63340 | Wood | Excavation | 3.50 | 2810±60 | 2771–3078 |
| CortinaAlverà_2 | Earth flow | B-83623 | Wood | Excavation | 2.00 | 2560±80 | 2362–2784 |
| CortinaAlverà_3 | Earth flow | R-1753 | Tree trunk | Excavation | 7.50 | 1460±30 | 1303–1396 |
| CortinaStaulin_1 | Earth flow | *GX-17699* | Wood | Borehole | 24.00 | 3315±140 | 3218–3904 |
| CortinaStaulin_2 | Earth flow | GX-17698 | Wood | Borehole | 3.00 | 2465±125 | 2161–2835 |
| Chiamulera | Earth flow | B-63339 | Tree trunk | Excavation | 4.50 | 4700±60 | 5315–5583 |
| Pezziè_1 | Earth flow | B-186012 | Tree trunk | Excavation | 1.5 | 7940±60 | 8610–8992 |
| Pezziè_2 | Earth flow | B-83622 | Wood | Excavation | 6.00 | 6570±70 | 7327–7580 |
| Pezziè_3 | Earth flow | B-83621 | Wood | Excavation | 2.50 | 6190±50 | 6956–7245 |
| Pezziè_4 | Earth flow | B-74803 | Tree trunk | Excavation | 3.50 | 5730±70 | 6323–6713 |
| La Riva_1 | Earth flow | GX-17689 | Wood | Excavation | 5.00 | 8280±100 | 9025–9472 |
| La Riva_2 | Earth flow | B-63342 | Wood | Excavation | 3.50 | 4220±60 | 4539–4871 |
| Zuel_1 | Translational rock slide | GX-17687 | Wood | Excavation | 3.50 | 9440±105 | 10,408–11,125 |
| Zuel_2 | Translational rock slide | GX-17688 | Wood | Excavation | 3.50 | 9215±105 | 10,202–10,658 |
| Campo/Zuel | Sedimentation in dam lake | GX-17690 | Wood | Excavation | 4.50 | 7180±200 | 7629–8384 |
| *b - Landslides dated in Corvara in Badia (see Soldati et al., 2004, for landslides location map)* | | | | | | | |
| Corvara_1 | Rotational rock slide–earth flow | B-112032 | Wood | Borehole (C1) | 25.70 | 8820±50 | 9686–10,156 |
| Corvara_2 | Rotational rock slide–earth flow | B-112033 | Wood | Borehole (C1) | 26.40 | 8560±90 | 9319–9883 |
| Corvara_4 | Rotational rock slide–earth flow | B-112031 | Organic sediment | Borehole (C3) | 22.70 | 7920±70 | 8596–8990 |
| Corvara_3 | Rotational rock slide–earth flow | B-154704 | Wood | Borehole (C6) | 69.70 | 8020±60 | 8647–9028 |
| Corvara_5 | Earth flow | B-179847 | Wood | Borehole (CPZ4) | 50.40 | 6140±60 | 6808–7238 |
| Corvara_6 | Earth flow | Ki-9233 | Wood | Borehole (C6) | 47.50 | 5543±72 | 6208–6480 |
| Corvara_7 | Earth flow | B-179848 | Wood | Borehole (CPZ4) | 52.00 | 5510±80 | 6029–6486 |
| Corvara_8 | Earth flow | Ki-9230 | Wood | Borehole (C6) | 19.10 | 4616±64 | 5053–5576 |
| Corvara_9_1 | Earth flow | B-112029 | Wood | Borehole (C2) | 7.50 | 4260±70 | 4575–5033 |
| Corvara_9_2 | Earth flow | B-112030 | Wood | Borehole (C2) | 20.000 | 4260±70 | 4575–5033 |
| Corvara_10 | Earth flow | B-179846 | Wood | Borehole (CPZ3) | 38.00 | 4170±80 | 4445–4861 |
| Corvara_11 | Earth flow | Ki-9234 | Tree trunk | Erosion scarp | 8.00 | 3888±64 | 4099–4514 |
| Corvara_12 | Earth flow | B-105976 | Tree trunk | Erosion scarp | 6.00 | 3830±60 | 4013–4418 |
| Corvara_13 | Earth flow | B-105977 | Tree trunk | Erosion scarp | 4.50 | 2860±60 | 2808–3207 |
| Corvara_14 | Earth flow | B-93975 | Tree trunk | Erosion scarp | 5.00 | 2490±60 | 2363–2735 |
| Corvara_15 | Earth flow | B-112034 | Wood | Borehole (C4) | 37.40 | 2260±50 | 2152–2348 |
| Arlara_1 | Rotational rock slide–earth flow | B-179850 | Tree trunk | Erosion scarp | 1.5 | 7000±60 | 7697–7942 |
| Arlara_2 | Rotational rock slide–earth flow | B-105975 | Tree trunk | Erosion scarp | 3.5 | 6870±50 | 7610–7826 |
| Arlara_3 | Rotational rock slide–earth flow | B-186011 | Tree trunk | Erosion scarp | 1.5 | 5530±70 | 6192–6463 |
| Col Alto_1 | Mud flow | B-179853 | Organic sediment | Excavation | 1.8 | 6450±100 | 7171–7561 |
| Col Alto_2 | Mud flow | B-179851 | Organic sediment | Excavation | 1.1 | 5470±80 | 6004–6411 |
| Col Alto_3 | Mud flow | B-179852 | Wood | Excavation | 1.1 | 5230±50 | 5909–6179 |
| Col Alto_4 | Mud flow | B-179854 | Organic sediment | Excavation | 0.7 | 4980±60 | 5601–5892 |
| Col Alto_5 | Mud flow | B-93976 | Tree trunk | Excavation | 2.00 | 2350±60 | 2159–2700 |
| Rio Pocol | Earth flow | B-128367 | Tree trunk | Erosion scarp | 5.00 | 950±50 | 742–952 |
| Colfosco_1 | Rock fall/avalanche | B-112024 | Tree trunk | Excavation | 3.50 | 4420±70 | 4858–5287 |
| Colfosco_l1 | Sedimentation in dam lake | Ki-9232 | Organic sediment | Borehole (S4) | 15.10 | 7088±72 | 7738–8029 |
| Colfosco_l2 | Sedimentation in dam lake | B-154701 | Wood | Borehole (S3) | 12.80 | 6810±60 | 7570–7785 |
| San Cassiano_2 | Earth flow | B-128365 | Tree trunk | Excavation | 3.50 | 2260±60 | 2120–2358 |
| San Cassiano_1 | Earth flow | B-128366 | Organic sediment | Excavation | 7.40 | 2610±60 | 2490–2855 |
| San Leonardo | Earth flow | B-128368 | Wood | Borehole (SL2) | 11.00 | 4890±70 | 5470–5878 |
| Col Maladat_1 | Rotational rock slide | B-112026 | Wood | Borehole (B5) | 20.20 | 9080±70 | 9948–10,490 |
| Col Maladat_2 | Sedimentation in dam lake | B-112028 | Wood | Borehole (B6) | 20.24 | 8810±70 | 9610–10,161 |
| Col Maladat_3 | Sedimentation in dam lake | B-112025 | Wood | Excavation (C) | 5.64 | 7740±80 | 8383–8716 |
| Col Maladat_4 | Sedimentation in dam lake | B-112027 | Wood | Borehole (B6) | 4.40 | 6460±90 | 7177–7562 |
| Col Maladat_5 | Sedimentation in dam lake | B-112023 | Wood and peat | Excavation (B) | 4.20 | 3550±70 | 3272–3577 |
| Col Maladat_6 | Sedimentation in dam lake | B-112022 | Wood | Excavation (B) | 1.43 | 3210±60 | 3272–3577 |
| Col Maladat_7 | Sedimentation in dam lake | HD-19408 | Wood | Excavation (A) | 0.48 | 1249±22 | 1088–1269 |
| Col Maladat_df2 | Debris flow | B-154705 | Organic sediment | Excavation (D) | 3.50 | 1320±60 | 1084–1338 |
| Col Maladat_df3 | Debris flow | Ki-9229 | Chalk | Excavation (D) | 5.00 | 1281±64 | 1063–1302 |
| Col Maladat_df1 | Debris flow | Ki-9231 | Tree trunk | Excavation (D) | 6.00 | 2537±64 | 2365–2757 |
| Col da Oi | Earth flow | Ki-7757 | Tree trunk | Erosion scarp | 2.00 | 3050±50 | 3080–3376 |
| Greif_1 | Mud flow | Ki-9226 | Tree trunk | Excavation | 3.50 | 1490±64 | 1298–1519 |
| Greif_2 | Mud flow | B-154703 | Peat | Excavation | 3.30 | 810±60 | 662–905 |
| Greif_4 | Mud flow | B-154702 | Peat | Excavation | 2.80 | 340±60 | 297–505 |
| Greif_3 | Mud flow | Ki-9227 | Organic sediment | Excavation | 2.50 | 378±64 | 306–515 |

**Table 1** (*continued*)

| Landslide | Landslide type | Sample code | Sample type | Site of collection | Depth (m) | Conventional Radiocarbon Age (years BP) | Calibrated Radiocarbon Age (years BP) |
|---|---|---|---|---|---|---|---|
| *b - Landslides dated in Corvara in Badia (see Soldati et al., 2004, for landslides location map)* | | | | | | | |
| Stella_df | Debris flow | B-154706 | Organic sediment | Excavation | 5.00 | 1950±60 | 1729–2040 |
| Sottocianin | Rotational rock slide–earth flow | Ki-9228 | Tree trunk | Excavation | 2.50 | 8143±72 | 8784–9397 |
| Passo Gardena | Translational rock slide | B-179849 | Organic sediment | Borehole (PG2B) | 38.5 | 6280±80 | 6994–7416 |

underneath the landslide deposit, within the landslide mass, at the surface, or associated with the movement, whether in an outcrop, in a section of the deposit or from boreholes. In all these cases, the direct dating of a landslide event and the indirect dating of correlated processes, from which minimum and maximum ages can be obtained, have to be distinguished. Schoeneich (1991) and Lang et al. (1999) have stressed the difficulty of assigning the correct ages to first slope failure and subsequent reactivations. Indeed, in the case of landslides which have undergone several reactivations, the sampling and dating procedure generally results in an underrating of the actual landslide activity. The typical situation found in the study areas is shown in Fig. 2. The samples are buried by subsequent reactivations of rock or earth slides or flows (Cruden and Varnes, 1996). Ideally, the sequence of all landslide events is represented in the stratigraphical record of landslide deposits. The oldest samples refer to the first movement, followed by progressively younger samples, going up in the sequence. However, in the real world, not all the events may have been recorded in the sediments: on the one hand, in the case of landslides, the sedimentation process is not continuous and, on the other hand, only landslide events that affected vegetation-covered areas can be dated with radiocarbon technique. Moreover, the geomorphological process and the mechanism of landsliding itself are the source of further constraints. The three-dimensional shape of the landslide body should be delineated, in order to distinguish the correct sequence of dated samples and related events. Furthermore, in the case of earth flows, some samples could have been reworked by subsequent events.

The inherent principles and limits of the dating method have then been considered. As far as the analytical bias is concerned, alteration effects, i.e. changes of the original $^{14}C/^{12}C$ ratio after death, due to processes other than radioactive decay (exchange of carbon with the environment through chemical and physical processes, and/or biological activity), contamination (e.g., addition of extraneous carbon during sample preparation) and “old wood” effect have been taken into account during sampling and preparation procedures. The hard-water effect, that is a recognized source of error in radiocarbon dating, but if the sample consists of tree wood, or the leaves, twigs or seeds of wholly terrestrial plants, then it can be assumed that no hard-water error is present.

In any case, pretreatment was used to eliminate secondary carbon components, reducing the sample to a single component. It is clear that pretreatment procedures don't ensure that the radiocarbon date will represent the event, that is otherwise determined by the sample integrity.

Finally, the structure of the database has also been considered, to check whether bias towards younger events exists. In fact, older events are less likely to be sampled, being more difficult to be reached as generally there is a lack of deep boreholes reaching the original sliding plan, and having a higher probability to be removed by erosional processes. Moreover, before the Bølling, due to the sparse vegetation, the chance of finding organic matter buried by a mass movement is low. As in the case of the Dolomites, this fact generally leads to a marked predominance of surface samples (Soldati et al., 2006). In any case, it is worthy to stress that even if this bias exists, the distribution of the ages is almost continuous throughout the Holocene, with several old event included in the database (Table 1).

## 4. Landslide activity records in the Dolomites

Starting from the synthesis of the set of data presented in Soldati et al. (2004) and from eleven new datings (see Table 1), the sequence of enhanced slope instability has been further developed, by analysing the statistical distribution of calibrated radiocarbon ages.

The first outcome is the clear difference between the elaborations of the data collected in the two study sites (Fig. 3).

In the area of Cortina the ages are clearly older, with the oldest samples to be referred to more than 14 ka cal BP. This difference is related to the timing of deglaciation and of the subsequent reforestation at different altitudes (Cortina d'Ampezzo 1224 m a.s.l., Corvara 1568 m a.s.l.) and to the morphological settings, with respect to valley width and exposition. In any case, the onset of deglaciation at the southern alpine border is dated to 20 ka cal BP (Bondesan, 1999; Orombelli et al., 2005), whereas the Lateglacial reforestation in the mountain belt of the Southern Alps is dated 14.5 ka cal BP (Avigliano et al., 2000; Pini, 2002).

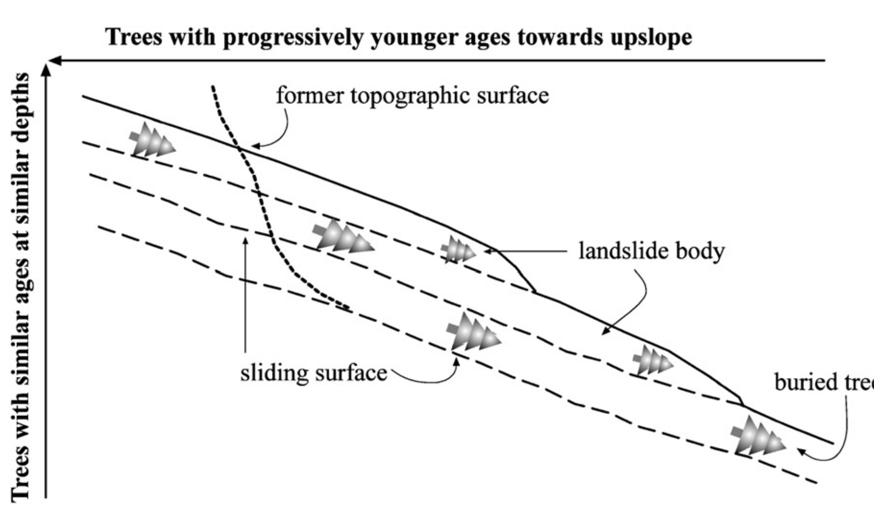


**Fig. 2.** Sketch of an ideal cross section of a landslide body, showing the typical stratigraphical situation found in the study areas. Tree trunk and wood remnants are usually buried and/or transported during subsequent reactivations of the landslide (modified from Schoeneich, 1991).

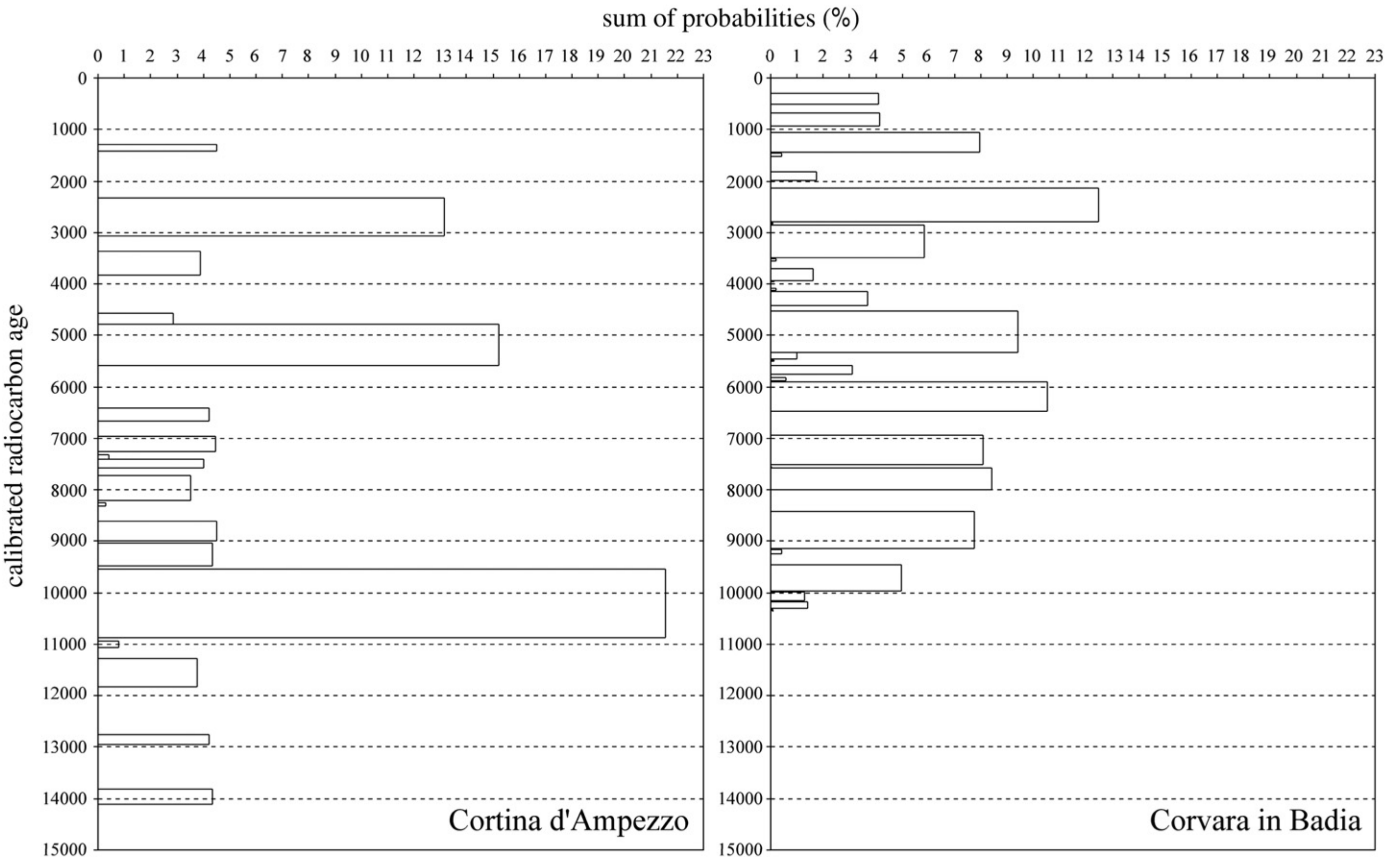


**Fig. 3.** Radiocarbon ages calibration of organic samples found buried in the landslide bodies. The statistical distributions have been summed.

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. Again, only few deep drillings or exposed sections reach the basal sliding surface. 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 age distribution shows a persistent landslide activity during the entire time span of the Holocene, whereas in Cortina the ages are 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. 4), the picture is different and the clustering around certain ages becomes clearer. 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; and IV. from 4000 to 2100 cal BP, between Subboreal and Subatlantic.

Many initial failures of large landslides occurred between 11,000 and 10,000 cal BP, i.e. during the Lateglacial-Holocene transition (Soldati et al., 2004). The higher number of dated events in this time span may not indicate an increase in landslides frequency, being a consequence of the amplified chance of finding buried plants debris. Otherwise, assuming a climatic significance for this cluster, it could be related with slope release following the definitive permafrost melting and the subsequent increase of water availability at high altitudes.

Period II could be related to the effects of the 8200 ka event (Bond et al., 1997), as in the case of many other records from different proxies that carry the signal of this global climatic event. The enhanced activity in the Upper Holocene is related to more cold and humid periods throughout the Subboreal and Subatlantic. In particular, starting from the Subatlantic, some Authors found that the increase of slope instability phenomena is related to human impact, mainly because of deforestation (Dapples et al., 2002). These studies show that anthropogenic factors must be considered at least since the Bronze Age, possibly as amplificators of climatic factors.

## 5. Discussion: climate as a causal factor for landsliding at a broad temporal scale

Field observation 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.

Previous research has clearly demonstrated the linkages between climate change and landslide activity (Buma and Dehn, 1998; Dehn et al., 2000). In particular, changes in the hydrological balance, resulting from the temporal distribution of temperature and rainfall, and the resulting evapotranspiration, directly influence the hydrological regime of slopes, which in turn governs the type, the rate and the temporal and spatial evolution of mass movements. Consequently, in the analysis of the relationships between landslides and climate, it

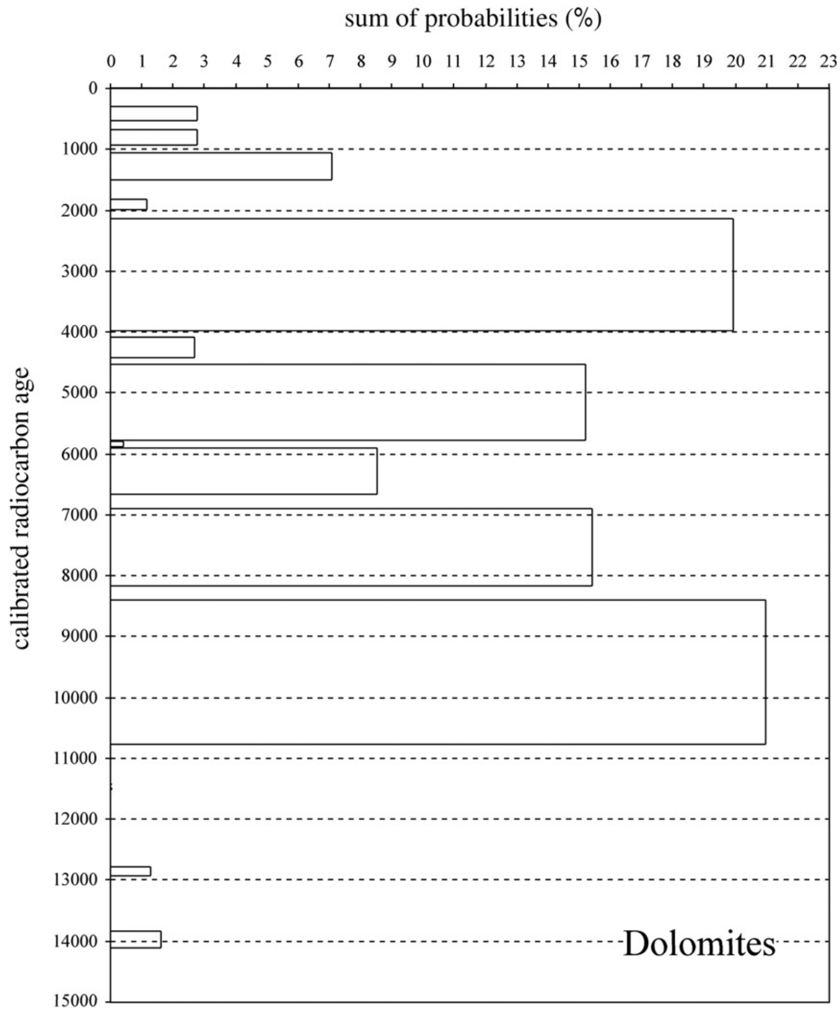


**Fig. 4.** Temporal distribution of dated slope instability events in the Dolomites.

is necessary to focus on temperature changes as well as on the timing, frequency and magnitude of rainfall.

It can be assumed that the relationship between climate, in particular positive moisture balance and landslide activity exists at every time scale. At a broad temporal scale, the relationship between landslide activity and triggering mechanisms can be established from the temporal clustering of dated landslides, starting from the assumption that a concentration of dated landslides around a specific age may have a similar cause.

As regards the factors predisposing and triggering landslide events, seismicity, climate and human activities are the only factors able to produce temporal and spatial concentrations of single landslides events. Also fluvial undercutting related to stages of landscape evolution can produce concentration of events, but this requires the same terrains to be involved and the same landscape history. Both rainfall and earthquakes can mobilise debris flows, rock falls, rotational and translational slides, and unless additional information can be retrieved, no distinctive morphological feature can discriminate isolated landslides triggered by rainfall from ones having other causes. The first two triggers cause widespread landsliding, while human activity usually causes local instability phenomena. Therefore, a correct procedure for establishing a scheme of temporal recurrence of landslides carrying a climatic signal, could be given by a critical analysis of the instability events, in order to exclude those landslides ascribable to non-climatic causes. This goal can be achieved through a multidisciplinary approach directed to the appraisal of the paleoenvironmental conditions at the time of the landslides, in order to discriminate between the climatic and non-climatic factors which conditioned the slope-system in the short-, medium- and long-term period. As a direct consequence, besides the development of a landslide events record, other proxy records have to be considered in order to disentangle the possible interactions between natural systems, in this case the slope-system, climate and humans.

The active seismo-tectonics of the eastern part of the Southern Alps represents a major dynamic factor in conditioning slope instabilities. 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 and 0.7 million years BP, Castaldini and Panizza (1991), and Col Alto–Pralongià–Passo Incisa strike-slip fault, Corsini and Panizza, 2003). Direct effects of macro-seismic activity on slope instabilities are historically documented in terms of widespread rock fall phenomena and shallow landslides around the epicentral zones. In the study areas, the only confirmed case of correlation is the Cinque Torri earth flow, which occurred in concomitance with the 15th September 1976 quake of the in the Friuli-Venezia Giulia Region (Zardini, 1979). It is likely therefore that, while that the spatial location of slope instability processes is guided by structural features, climatic conditions are the main cause of widespread landsliding.

Particular attention has also been paid to possible human influence on temporal and spatial concentrations of landslide events. The intense exploitation of forests, agricultural and farming resources, high-altitude pastures and mining activities are the causes of mass wasting processes which have been clearly identified in various archaeological contexts. In the study site of Corvara in Badia, a multidisciplinary study has been carried out on an Early Holocene lacustrine sequence (Borgatti et al., 2007), also to look for the interactions between human activity and mass wasting phenomena. It has been made evident that time span of lake sedimentation (9900 to 6500 cal BP) predates the main phases of human impact in the eastern Alps, as no anthropic pollens have been identified. In any case, although precise data are still lacking, deforestation and abandonment and introduction of particular crops probably occurred during the Bronze Age, with villages located in internal valleys like Alta Badia, exploiting slopes adjacent to the valley floors and also high-altitude sites during the summer (Tecchiati, 1998).

As far as the reconstruction of climate evolution during the Holocene is concerned, thanks to pollen databases a detailed temperature reconstruction on a time resolution up to 100 years at the regional scale of the Alps is available (e.g., Davis et al., 2003). This reconstruction reveals slight temperature variations during the last 8000 years, confirmed also by local reconstructions from chironomids (e.g., Heiri and Millet, 2005), tree rings (e.g., Nicolussi and Patzelt, 2000) and oxygen isotopes measured on ostracod valves (e.g., Von Grafenstein et al., 1999). This weak temperature variability contrasts with evidence of clear glacier fluctuations (Ivy-Ochs et al., 2006), as well as variability in hydrological regime registered as lake-level fluctuations (Magny, 2004) together with changes in intensity and frequency of major floods of alpine rivers (Arnaud et al., 2002). It can be concluded that Holocene climate variability was driven by changes in precipitation regimes, in term of intensity and duration.

Therefore, considering the significance of rainfall regime and the resultant hydrologic response of the slopes in triggering mass movements, after excluding the direct influence of seismicity and human activity, the periods of enhanced landsliding have been compared to different Lateglacial and Holocene paleoclimatic records, in order to verify the climatic control on the clustering of landslide events.

Besides landslide records from the Dolomites, some proxy records coming from different realms, either continental or marine, have been taken into account, with reference to Fig. 5. 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 records from the Dolomites show the periods of enhanced landsliding documented in this study and the periods of reduced landslide activity as described in Borgatti et al. (2007). A lake sediment record dating back to the early Holocene in the area of Corvara in Badia (see Borgatti et al., 2007) also supports this figure. The chronology of the lacustrine succession was obtained on the basis of three datings: (i) near the base (20.24 m depth), (ii) in the middle part (14.10 m depth) and (iii) in the uppermost succession (4.40 m depth). The calculation of the sedimentation rate for in the first part

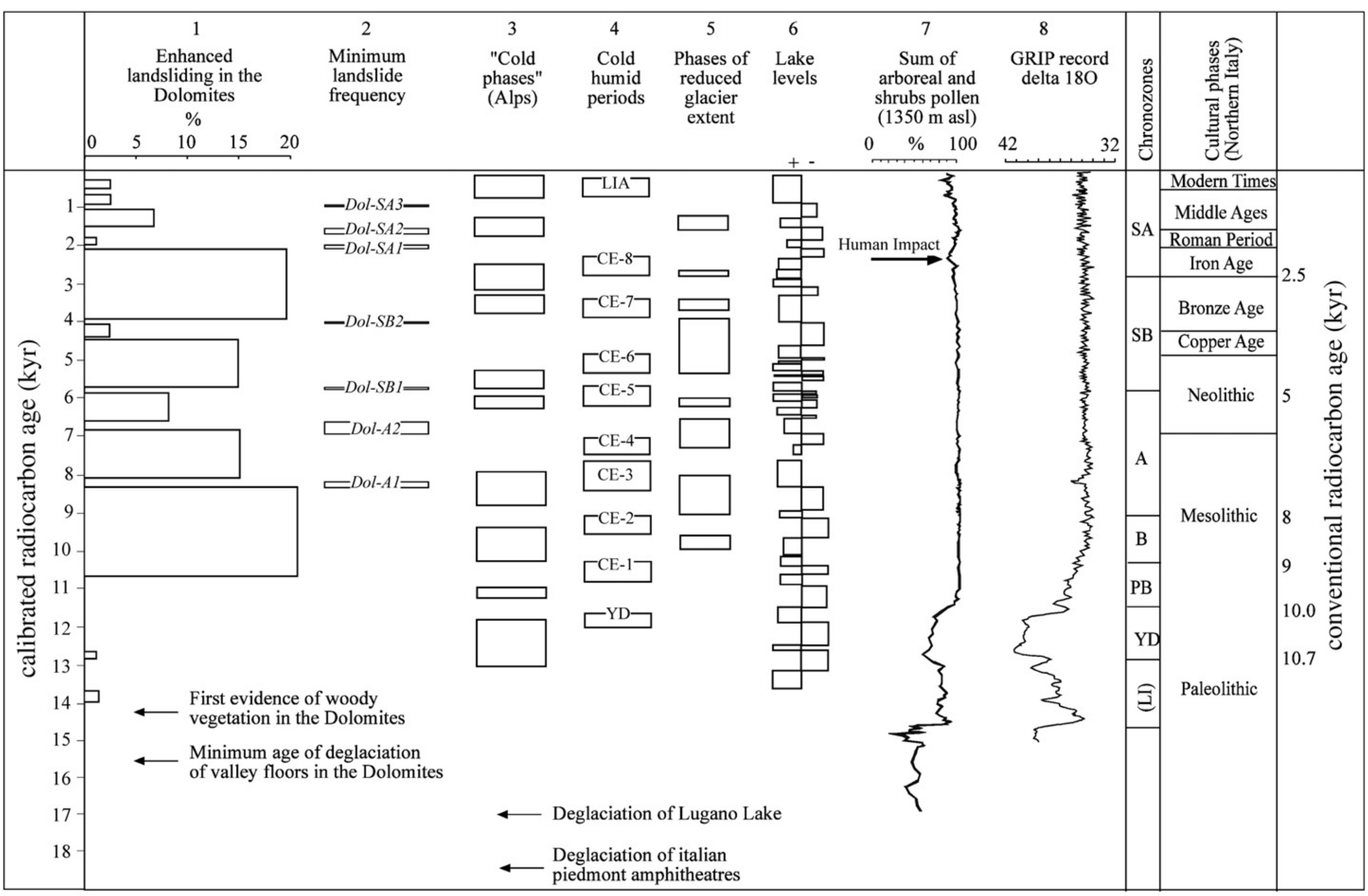


**Fig. 5.** Comparison of different Late Glacial and Holocene paleoclimatic record at different spatial scales (modified after Borgatti et al., 2007). Legend: 1. Enhanced slope instability events in the Dolomites (Borgatti & Soldati, in print); 2. Phases of minimum landslide frequency in the Dolomites (Borgatti et al., 2007); 3 and 4. Cold and humid periods in the Alps and on the Swiss Plateau (Haas et al., 1998; Tinner and Amman, 2001; Tinner and Kalterieder, 2005); 5. Phases of reduced glacier extent, recorded by the retreats of the Unteraar and other Swiss glaciers (Hormes et al., 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 et al., 1997). Cultural periods in Northern Italy (Cardarelli, 1993). The age of deglaciation onset of Italian piedmont amphitheatres is from Monegato et al., (2005). The deglaciation of Lake Lugano is from Niessen and Kelts, 1989. LI: Lateglacial Interstadial, not a chronozone and therefore shown in brackets; YD: Younger Dryas; PB: Preboreal; B: Boreal; A: Atlantic; SB: Subboreal; SA: Subatlantic.

gives a range from 6.98 to 19.81 mm/y over 6.14 m. In the second part of the core, the sedimentation rate is lower, ranging from 4.50 to 6.02- mm/y over 9.7 m. From almost 10,000 to 9100 cal BP, the sedimentation rate appears to be significantly higher than from 9000 to 7300 cal BP, which is in agreement with the record of landslide activity.

The periods of cold and humid climate in the central and eastern Swiss Alps and Plateau have been reported (Haas et al., 1998; Tinner and Kalterieder, 2005). On the other hand, warm periods, recorded by the Unteraar glacier retreat in the Central Swiss Alps, as reported by Hormes et al. (2001), are considered. It is worth notice that in some periods the records display opposite trends, that are mainly due to different time resolutions and to local variability.

The record of mid-European lake levels (Magny, 1999), obtained from the systematic study of littoral sediment sequences in 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. 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). The sum of arboreal and shrub pollen represent the tree line in the Alps as recorded at 1350 m a.s.l. (Pini, 2002), also in comparison with the hemispheric record of delta 18O in GRIP ice cores in central Greenland (Johnsen et al., 1997).

Despite the intrinsic difficulties in correlating these records, which are mainly due to different spatial scales (local, regional and global), dissimilar time resolutions and several dating constraints, some remarkable indication 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. It is clear that a positive moisture balance could have occurred under different environmental conditions. On the one hand, an increase in intensity and/or duration of rainfall could be significant at every time scale, together with evapotranspiration variability driven also by temperature regime changes.

The phases of minimum landslide frequency identified from Borgatti et al. (2007) alternating with the enhanced landsliding periods fall within phases of reduced glacier extent, with warmer summers and/or reduced precipitation.

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 clearly induced by the centennial–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 opposite to the actual climate tendencies, as in the case of the clustering around the onset of the Holocene. Also the effects of cold spells are to be stressed, as in the case of the 8.2 ka event, that seems to have left a clear signature in the landscape. Finally, during the upper Holocene, the long-term tendency towards an increased slope stability after the last deglaciation could then be counterbalanced by the effects of human activity, starting from 4 ka cal BP.

## 6. 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 of large landslides are susceptible to prolonged periods of wetness extending over decades.

In this study, the effects of different environmental changes (temperature increase, intense rainfall, vegetation disappearance), seismicity and human impact have been taken into account. The results show that a match exists between the clusters of landslide events so far obtained and the regional and global paleoclimatic framework. 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 reliable 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 source of data, that can be added to a multidisciplinary and comprehensive data archive, towards a common framework.

## Acknowledgements

This research has been funded by the MIUR-COFIN 2002 project *Geomorphological evolution of slopes and climate changes: landslide analysis and palaeoclimatic reconstructions* (coordinator: M. Soldati) and CARG-PAB I Project *Foglio n. 028 Marmolada* (coordinator: M. Panizza). The stimulating comments of the anonymous reviewers have greatly contributed to improve the former version of the manuscript.

## References

Alexandrowicz, S.W., 1997. Holocene dated landslides in the Polish Carpathians. Rapid Mass Movement as a Source of Climatic Evidence for the Holocene: In: Matthews, J.A., Brunsden, D., Frenzel, B., Gläser, B., Weiß, M.M. (Eds.), Paläoklimaforschung — Palaeoclimate Research, vol. 19, pp. 75–83.

Arnaud, F., Lignier, V., Revel, M., Desmet, M., Beck, C., Pourchet, M., Charlet, F., Trentesaux, A., Tribovillard, N., 2002. Flood and earthquake disturbance of $^{210}$Pb geochronology (Lake Anterne, NW Alps). Terra Nova 14 (4), 225–232.

Avigliano, R., Di Anastasio, G., Improta, S., Peresani, M., Ravazzi, C., 2000. A new Late Glacial–Early Holocene palaeobotanical and archeological record in the Venetian Pre-Alps: the peat-bog of Palughetto (Cansiglio Plateau). Journal of Quaternary Sciences 15 (8), 789–803.

Berrisford, M.S., Matthews, J.A., 1997. Phases of enhanced rapid mass movement and climatic variation during the Holocene: a synthesis. Rapid Mass Movement as a Source of Climatic Evidence for the Holocene: In: Matthews, J.A., Brunsden, D., Frenzel, B., Gläser, B., Weiß, M.M. (Eds.), Paläoklimaforschung — Palaeoclimate Research, vol. 19, pp. 409–440.

Bertoglio, G., De Simoni, G., 1979. Partizione delle Alpi in 220 gruppi. Boll. A.I.C. XVI 46, pp. 7–17.

Bertolini, G., Tellini, C., 2001. New radiocarbon dating for landslide occurrence in the Emilia Apennines (Northern Italy). Fifth Int. Conf. on Geomorphology, Tokyo, 23rd–28th August 2001. Abstracts of conference papers: Transactions JGU, vol. 22(4).

Bigot-Cormier, F., Braucher, R., Bourles, D., Guglielmi, Y., Dubar, M., Stephan, J.-F., 2005. Chronological constraints on processes leading to large active landslides. Earth and Planetary Science Letters 235 (1–2), 141–150.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. Science 278, 1257–1266.

Bondesan, A., 1999. Una nuova data $^{14}$C nell'anfiteatro morenico di Vittorio Veneto e la costruzione del suo sandur (Pianura del F. Meschio). 8th Italian Glaciological Meeting 'Alpine glaciers and climate change,' Abstract volume, pp. 87–89.

Borgatti, L., Soldati, M., Surian, N., 2001. Rapporti tra frane e variazioni climatiche: una bibliografia ragionata relativa al territorio europeo. Il Quaternario 14 (2), 137–166.

Borgatti, L., Ravazzi, C., Donegana, M., Corsini, A., Marchetti, M., Soldati, M., 2007. A lacustrine record of early Holocene watershed events and vegetation history, Corvara in Badia, Dolomites, Italy. Journal of Quaternary Science 22, 173–189.

Bovis, M.J., Jones, P., 1992. Holocene history of earth flow mass movement in south–central British Columbia: the influence of hydroclimatic changes. Canadian Journal of Earth Sciences 29, 1746–1755.

Buma, J., Dehn, M., 1998. A method for predicting the impact of climate change on slope stability. Environmental Geology 35, 190–196.

Busche, D., 2001. Early Quaternary landslides of the Sahara and their significance for geomorphic and climatic history. Journal of Arid Environment 49 (3), 429–448.

Cardarelli, A., 1993. L'età dei metalli in Italia Settentrionale. In: Guidi, A., Piperno, M. (Eds.), Italia preistorica. Laterza, Roma, pp. 366–419.

Castaldini, D., Panizza, M., 1991. Inventario delle faglie attive tra i fiumi Po e Piave e il Lago di Como (Italia Settentrionale). Il Quaternario 4 (2), 333–410.

Castellarin, A., Cantelli, L., Fesce, A.M., Mercier, J., Picotti, V., Pini, G.A., Prosser, G., Selli, L., 1992. Alpine compressional tectonic in the Southern Alps. Relationships with the Apennines. Annales Tectonicae 6, 62–94.

Corominas, J., 2001. Landslides and Climate. In: Bromhead, E.N. (Ed.), Keynote lectures, VIII ISL, Cardiff, June 2000, CD-ROM.

Corsini, A., Panizza, M., 2003. Conseguenze geomorfologiche di una faglia neotettonica nell'Alta Val Badia (Dolomiti). In: Biancotti, A., Motta, M. (Eds.), Risposta dei processi geomorfologici alle variazioni ambientali. Glauco Brigati Editore, Genova, pp. 163–176.

Corsini, A., Panizza, M., Pasuto, A., Silvano, S., Siorpaes, C., Soldati, M., 1998. Indagini preliminari per la definizione della pericolosità da frana nella conca di Corvara in Badia (Dolomiti). Memorie della Societa Geologica Italiana 53, 207–224.

Corsini, A., Pasuto, A., Soldati, M., 1999. Geomorphological investigation and management of the Corvara landslide (Dolomites, Italy). JGU Transactions 20 (3), 169–186.

Corsini, A., Pasuto, A., Soldati, M., 2000. Landslides and climate change in the Alps since the Late-glacial: evidence of case studies in the Dolomites (Italy). In: Bromhead, E., Nixon, N., Ibsen, M.-L. (Eds.), Landslides in Research, Theory and Practice. Thomas Telford Publishing, London, pp. 329–334.

Corsini, A., Marchetti, M., Soldati, M., 2001. Holocene slope dynamics in the area of Corvara in Badia (Dolomites, Italy). Geografia Fisica e Dinamica Quaternaria 24 (2), 127–139.

Corsini, A., Pasuto, A., Soldati, M., Zannoni, A., 2005. Field monitoring of the Corvara landslide (Dolomites, Italy) and its relevance for hazard assessment. Geomorphology 66, 149–165.

Cruden, D.M., Varnes, D.J., 1996. Landslides types and processes. Landslides: Investigation and Mitigation. : In: Turner, A.K., Schuster, R.L. (Eds.), Transportation Research Board, Special Report 247. National Academy Press, Washington D.C., pp. 36–75.

Dapples, F., Lotter, A.F., van Leeuwen, J.F.N., van der Knaap, W.O., Dimitriadis, S., Oswald, D., 2002. Paleolimnological evidence for increased landslide activity due to forest clearing and land-use since 3600 cal BP in the western Swiss Alps. Journal of Paleolimnology 27, 239–248.

Davis, B.A.S., Brewer, S., Guiot, J., Stevenson, A.C., 2003. The temperature of Europe reconstructed from pollen data. Quaternary Science Reviews 22, 1701–1716.

Dehn, M., Burger, G., Buma, J., Gasparetto, P., 2000. Impact of climate change on slope stability using expanded downscaling. Engineering Geology 55 (3), 193–204.

Dikau, R., Schrott, L., 1999. The temporal stability and activity of landslides in Europe with respect to climatic change (TESLEC): main objectives and results. Geomorphology 30, 1–12.

Doglioni, C., Bosellini, A., 1987. Eoalpine and mesoalpine tectonics in the Southern Alps. Geologische Rundschau 76, 735–754.

Frenzel, B., Matthews, J.A., Gläser, B. (Eds.), 1993. Solifluction and Climatic Variation in the Holocene: Paläoklimaforschung — Paleoclimate Research, vol. 11. 387 pp.

Glade, T., 2003. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. Catena 51 (3–4), 297–314.

González Díez, A., Salas, L., Díaz de Terán, J.R., Cendrero, A., 1996. Late Quaternary climate changes and mass movement frequency and magnitude in the Cantabrian region, Spain. Geomorphology 15 (3–4), 291–309.

Goudie, A., 1992. Environmental Change, Third edition. Clarendon Press, Oxford. 329 pp.

Haas, J.N., Richoz, I., Tinner, W., Wick, L., 1998. Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at the timberline in the Alps. The Holocene 8, 301–304.

Heiri, O., Millet, L., 2005. Reconstruction of Late Glacial summer temperatures from chironomid assemblages in Lac Lautrey (Jura, France). Journal of Quaternary Science 20, 33–44.

Holm, K., Bovis, M., Jacob, M., 2004. The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. Geomorphology 57 (3–4), 201–216.

Hormes, A., Muller, B.U., Schluchter, C., 2001. The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. The Holocene 11, 255–265.

Ibsen, M.L., Brunsden, D., 1997. Mass movement and climatic variation on the south coast of Great Britain. Rapid Mass Movement as a Source of Climatic Evidence for the Holocene: In: Matthews, J.A., Brunsden, D., Frenzel, B., Gläser, B., Weiß, M.M. (Eds.), Paläoklimaforschung — Palaeoclimate Research, vol. 19, pp. 171–182.

Ivy-Ochs, S., Kerschner, H., Kubik, P.W., Schlüchter, Ch., 2006. Glacier response in the European Alps to Heinrich event 1 cooling: the Gschnitz stadial. Journal of Quaternary Science 21 (2), 115–130.

Johnsen, S.J., Clausen, H.B., Dansgaard, W., Andersen, K.K., Hvidberg, C.S., Dahl-Jensen, D., Steffensen, J.P., Shoji, H., Sveinbjörndottir, A.E., White, J.W.C., Jouzel, J., Fisher, D., 1997. The δ18O record along the Greenland Ice Core Project deep ice core and the problem of possible Eemian climatic instability. Journal of Geophysical Research 102 29397-26410.

Lang, A., Moya, J., Corominas, J., Schrott, L., Dikau, R., 1999. Classic and new dating methods for assessing the temporal occurrence of mass movements. Geomorphology 30, 33–52.

Lateltin, O., Beer, C., Raetzo, H., Caron, C., 1997. Landslides in Flysch terranes of Switzerland: causal factors and climate change. Eclogae Geologicae Helveticae 90, 401–406.

Magny, M., 1999. Lake-level fluctuations in the Jura and French subalpine ranges associated with ice-rafting events in the North Atlantic and variations in the Polar Atmosferic Circulation. Quaternaire 10 (1), 61–64.

Magny, M., 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quaternary International 113 (1), 65–79.

Margielewski, W., 2001. Late glacial and Holocene climatic changes registred in forms and deposits of the Klaklowo landslide (Beskid Średni range, outer Carpathians). Studia Geomorphologica Carpatho-Balcanica XXXV, 63–79.

Matthews, J.A., Brunsden, D., Frenzel, B., Gläser, B., Weiß, M.M. (Eds.), 1997. Rapid Mass Movement as a Source of Climatic Evidence for Holocene: Paläoklimaforschung — Palaeoclimate Research, vol. 19. 444 pp.

Monegato, G., Donegana, M., Pini, R., Ravazzi, C., Wick, L., Calderoni, L., 2005. LGM Chronology and Palaeoenvironment in the SE Alpine Foreland: Evidences of a Two-fold Glacial Advance in the Tagliamento Morainic Amphitheatre. INQUA-SEQS Abstract Volume, Bern, Switzerland, pp. 34–35.

Nicolussi, K., Patzelt, G., 2000. Discovery of Early Holocene wood and peat on the forefield of the Pasterze Glacier, Eastern Alps, Austria. The Holocene 10 (2), 191–199.

Niessen, F., Kelts, K., 1989. The deglaciation and Holocene sedimentary evolution of southern perialpine Lake Lugano — implications for Alpine paleoclimate. Eclogae Geologicae Helveticae 82/1, 235–263.

Orombelli, G., Ravazzi, C., Cita, M.B., 2005. Osservazioni sul significato dei termini LGM (UMG), Tardoglaciale e postglaciale in ambito globale, italiano ed alpino. Il Quaternario — Italian Journal of Quaternary Sciences 18 (2), 147–155.

Panizza, M., 1990. The landslides in Cortina d'Ampezzo (Dolomites, Italy). In: Cancelli, A. (Ed.), ALPS 90-6th ICFL, Switzerland–Austria–Italy, Aug. 31st–Sept. 12th, Conference Proceedings. Università degli Studi di Milano, pp. 55–63.

Panizza, M., Pasuto, A., Silvano, S., Soldati, M., 1996. Temporal occurrence and activity of landslides in the area of Cortina d'Ampezzo (Dolomites, Italy). Geomorphology 15 (3–4), 311–326.

Pasuto, A., Silvano, S., Soldati, M., 1997. Deformazioni gravitative profonde di versante e frane: casi di studio nella Valle del Boite (Dolomiti, Italia). Geografia Fisica e Dinamica Quaternaria 20, 107–111.

Pini, R., 2002. A high-resolution Late-Glacial–Holocene pollen diagram from Pian di Gembro (Central Alps, Northern Italy). Vegetation History and Archaeobotany 11 (4), 251–262.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 Terrestrial radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46, 1029–1058.

Schoeneich, P., 1991. Les datation des glissements de terrain. In: Bell, D.H. (Ed.), Landslides. : Proc. 6th ISL, Christchurch, 10–14 February 1992. Balkema, Rotterdam, pp. 205–212.

Schoeneich, P., Tercier, J., Hurni, J.-P., Orcel, C., 1997. Datation par dendrochronologie du glissement des Parchets (Les Diablerets, Alpes vaudoises). Eclogae Geologicae Helveticae 90 (3), 481–496.

Schmidt, J., Dikau, R., 2004. Modeling historical climate variability and slope stability. Geomorphology 60 (3–4), 433–447.

Sidle, R.C., Taylor, D., Lu, X.X., Adger, W.N., Lowe, D.J., de Lange, W.P., Newnham, R.M., Dodson, J.R., 2004. Interactions of natural hazards and society in Austral–Asia: evidence in past and recent records. Quaternary International 118–119, 181–203.

Smith, L.N., 2001. Columbia Mountain landslide: late-glacial emplacement and indications of future failure, Northwestern Montana, USA. Geomorphology 41, 309–322.

Soldati, M., 1999. Landslide hazard investigations in the Dolomites (Italy): the case study of Cortina d'Ampezzo. In: Casale, R., Margottini, C. (Eds.), Floods and Landslides: Integrated Risk Assessment. Springer-Verlag, Berlin, pp. 281–294.

Soldati, M., Corsini, A., Pasuto, A., 2004. Landslides and climate change in the Italian Dolomites since the Lateglacial. Catena 55 (2), 141–161.

Soldati, M., Borgatti, L., Cavallin, A., De Amicis, M., Frigerio, S., Giardino, M., Mortasa, G., Pellegrini, G.B., Ravazzi, C., Surian, N., Tellini, C., in collaboration with Alberto, W., Albanese, D., Chelli, A., Corsini, A., Marchetti, M., Palomba, M., Panizza, M., 2006. Geomorphological evolution of slopes and climate changes in Northern Italy during the Late Quaternary: spatial and temporal distribution of landslides and landscape sensitivity implications. Geografia Fisica e Dinamica Quaternaria 29 (2), 165–183.

Starkel, L., 1997. Mass movements during the Holocene: the Carpathian example and the European perspective. Rapid mass movement as a source of climatic evidence for the Holocene: In: Matthews, J.A., Brunsden, D., Frenzel, B., Gläser, B., Weiß, M.M. (Eds.), Paläoklimaforschung — Palaeoclimate Research, vol. 19, pp. 385–400.

Stuiver, M., Reimer, P.J., Reimer. R., 2004. Calib Radiocarbon Calibration (version 5.0.2). http://calib.qub.ac.uk/calib/calib.html (October 2009).

Tecchiati, U. (Ed.), 1998. Sotciastel. Un villaggio fortificato dell'età del bronzo in Val Badia. Istitut Ladin “M. de Rü” and Soprintendenza Provinciale ai BBCC di Bolzano–Alto Adige, 400 pp.

Thomas, M.F., 1999. Evidence for high energy landforming events of the central African plateau: eastern province, Zambia. Zeitschrift Geomorphologie N.F. 43 (3), 273–297.

Tinner, W., Ammann, B., 2001. Timberline paleoecology in the Alps. Pages News 9 (3), 9–11.

Tinner, W., Kalterieder, P., 2005. Rapid response of high-mountain vegetation to early Holocene environmental changes in the Swiss Alps. Journal of Ecology 93 (5), 936–947.

Trauth, M.H., Alonso, R.A., Haselton, K.R., Hermanns, R.L., Strecker, M.R., 2000. Climate change and mass movements in the NW Argentine Andes. Earth and Planetary Science Letters 179 (2), 243–256.

Trauth, M.H., Bookhagen, B., Marwan, N., Strecker, M.R., 2003. Multiple landslide clusters record Quaternary climate changes in the northwestern Argentine Andes. Palaeogeography, Palaeoclimatology, Palaeoecology 194 (1–3), 109–121.

von Grafenstein, U., Erlenkeuser, H., Brauer, A., Jouzel, J., Johnsen, S.J., 1999. A mid-European decadal isotope-climate record from 15,500 to 5000 years B.P. Science 284 (5420), 1654–1657.

Zardini, R., 1979. La frana in località Cinque Torri: 1976. Le Dolomiti Bellunese 3, 51.