New records of Holocene landslide activity in the Western and Eastern Swiss Alps : implication of climate and vegetation changes

Autor(en): **Dapples, Florence / Oswald, Daniel / Raetzo, Hugo**

Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **96 (2003)**

Heft 1

PDF erstellt am: **09.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-169002

Nutzungsbedingungen

Die ETH-Bibliothek ist Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Inhalten der Zeitschriften. Die Rechte liegen in der Regel bei den Herausgebern.
Die auf der Plattform e-periodica veröffentlichten Dokumente stehen für nicht-kommerzielle Zwecke in Lehre und Forschung sowie für die private Nutzung frei zur Verfügung. Einzelne Dateien oder Ausdrucke aus diesem Angebot können zusammen mit diesen Nutzungsbedingungen und den korrekten Herkunftsbezeichnungen weitergegeben werden.
Das Veröffentlichen von Bildern in Print- und Online-Publikationen ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Die systematische Speicherung von Teilen des elektronischen Angebots auf anderen Servern bedarf ebenfalls des schriftlichen Einverständnisses der Rechteinhaber.

Haftungsausschluss

Alle Angaben erfolgen ohne Gewähr für Vollständigkeit oder Richtigkeit. Es wird keine Haftung übernommen für Schäden durch die Verwendung von Informationen aus diesem Online-Angebot oder durch das Fehlen von Informationen. Dies gilt auch für Inhalte Dritter, die über dieses Angebot zugänglich sind.

Ein Dienst der *ETH-Bibliothek*
ETH Zürich, Rämistrasse 101, 8092 Zürich, Schweiz, www.library.ethz.ch

http://www.e-periodica.ch

0012-9402/03/010001-9
DOI 10.1007/s00015-003-1078-1
Birkhäuser Verlag, Basel, 2003

Eclogae geol. Helv. 96 (2003) 1–9

New records of Holocene landslide activity in the Western and Eastern Swiss Alps: Implication of climate and vegetation changes

FLORENCE DAPPLES[1], DANIEL OSWALD[1], HUGO RAETZO[2], TOMASO LARDELLI[3] & PETER ZWAHLEN[4]

Key words: Landslide activity, Holocene, Swiss Alps, climatic changes, vegetation fluctuations, anthropogenic impact

ABSTRACT

This paper presents a new chronology of landslide events during the Late-Glacial and the Holocene, inferred from several landslides located in the Western and Eastern Swiss Alps. Five periods of enhanced landsliding are evidenced during the Holocene, namely 11’500-10’250, 6’250-4’800, 3’500-2’100, 1’700-1’150 and 750-300 calibrated years BP. Such periods can be related to a significant deterioration of the climatic conditions, as well as major changes in the vegetation cover. Compared with climate-related processes, such as glacier fluctuations, solifluction and humidity index, the landslide chronology can be associated with periods of more cold and humid conditions. Apart from climatic influence, Holocene landslide activity occurs together with synchronous vegetation changes, such as human-induced deforestation, as evidenced in the Western Swiss Alps. Climatic changes, vegetation fluctuations and anthropogenic impacts can, therefore, be considered as major factors that contributed to increase landslide susceptibility in the Alps during the Holocene.

RESUME

De nouvelles données sur l’activité des glissements de terrain durant le Tardi-Glaciaire et l’Holocène sont présentées dans cet article. Les données proviennent de nombreux glissements de terrain localisés dans les Alpes de Suisse occidentale et orientale. Cinq périodes d’activité de glissement accrue sont réparties durant l’Holocène, à savoir 11’500-10’250, 6’250-4’800, 3’500-2’100, 1’700-1’150 et 750-300 années calibrées BP. Ces périodes sont liées à des détériorations des conditions climatiques, caractérisées par des phases climatiques plus humides et plus froides. Parallèlement aux influences climatiques, les augmentations de l’activité de glissements de terrain sont également liées aux variations du couvert végétal, en partie liées à la déforestation induite de l’anthropisation progressive des zones de montagne au cours des derniers 4’000 ans. Les changements climatiques, l’évolution de la végétation ainsi que l’impact humain peuvent être considérés comme des facteurs de premier ordre ayant contribué à l’oscillation des fréquences des glissements de terrain dans les Alpes durant l’Holocène.

1. Introduction

Landslides have lately raised much concern in Switzerland, since various major landslide events have occurred during the last decade, resulting in major landscape disturbances, as well as costly damage to the infrastructure. Studies of past and present landslide activity were carried out at the Institute of Geology of the University of Fribourg, Switzerland, in order to determine the dynamics of large landslides and their relationship with climatic parameters (Dapples et al. 2001). The description and understanding of past landslide activities is a prerequisite for greater effectiveness of any present landslide surveys. This paper aims to identify the periods of increased landslide frequency during the Holocene, and intends to specify the relative role of key parameters such as climate and vegetation changes and the anthropogenic impact as possible triggering or conditioning factors of landslides.

Such interest for past landslide activity in the Fribourg Prealps was initiated by Raetzo-Brülhart (1997), with a special onset offered by the Falli Hölli landslide major crisis in 1994. Other analyses of historical landslide activity were carried out at several sites in Switzerland, such as at Brattas – St-Moritz (Schlüchter 1988), Les Parchets (Schöneich et al. 1997) and La Frasse (Noverraz et al. 1998), revealing the correlation between landslide activity and climate-induced phenomena such as glacier oscillations and extreme precipitations. New records of past landslide activity in the Fribourg Prealps are presented

---

[1] Institut de Géologie et Paléontologie, Université de Fribourg, Pérolles, CH–1700 Fribourg, Switzerland. E-mail: florence.dapples@unifr.ch, daniel.oswald@unifr.ch

[2] Bundesamt für Wasser und Geologie, Ländtestrasse 20, CH-2501 Biel, Switzerland. E-mail: hugo.raetzo@bwg.admin.ch

[3] Büro für Technische Geologie AG, Pfistergasse 3, CH-7002 Chur, Switzerland. E-mail: btg@bluewin.ch

[4] Geotechnisches Institut AG, Seestrasse 22, CH-3700 Spiez, Switzerland. E-mail: peter.zwahlen@geo-online.com

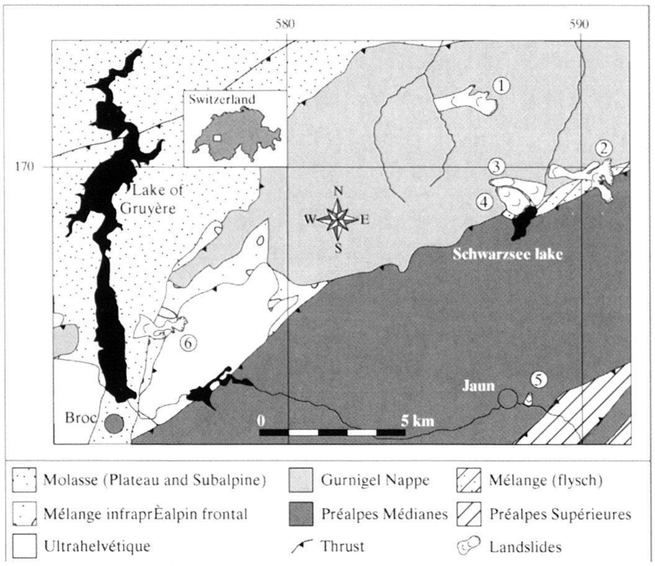

Fig. 1. Location of studied landslides in the Fribourg Prealps (1: Falli Hölli, 2: Hohberg, 3: Schlossisboden, 4: Pürrena, 5: Jaun, 6: Villarbeney), together with simplified tectonic context.

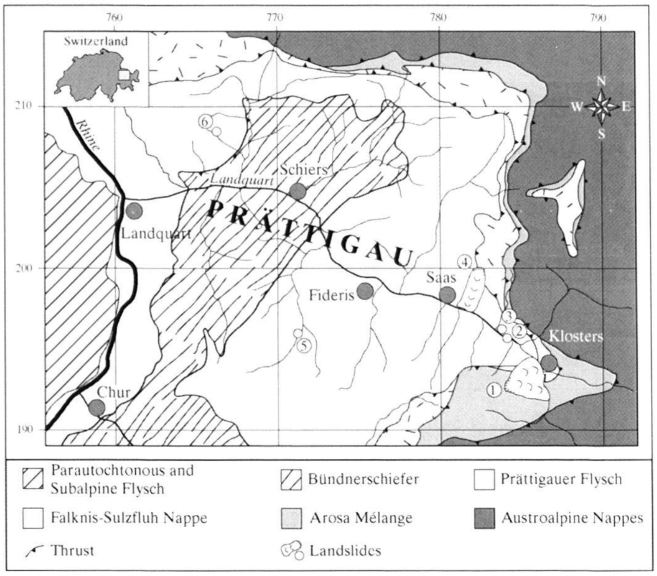

Fig. 2. Location of studied landslides in the Prättigau area (1: Gotschna, 2: Büel, 3: Serneus, 4: Saas, 5: Furnertobel, 6: Seewiser Berg), together with simplified tectonic context.

in this paper, together with data on vegetation changes and Holocene climatic records. In order to enlarge the discussion on past landslide processes, new Holocene data arising from landslides in the Prättigau area (Graubünden, Switzerland) are presented as well, generating interesting comparisons of Holocene landslides between the Western and Eastern Swiss Alps.

2. Geographical and geological settings

2.1 Landslides in the Fribourg Prealps, Western Swiss Alps

The examined landslides are located in the Swiss Prealps, extending between the Lake of Gruyère in the West and the Schwarzsee area in the East (Fig. 1). All landslides affect surface Quaternary material, such as moraine, rockfall, debris flow and alluvial deposits. Depths of sliding planes vary for each landslide, for instance 37 m at Falli Hölli and 18 m at the Hohberg landslide. This originates specific dynamic behaviours for each site, such as rotational, translational or complex slides. The high frequency of slope instability in the Fribourg Prealps is related to specific geological features. Indeed, apart from the Jaun landslide, each landslide presented in Figure 1 is affected by a flysch substrate, either Ultrahelvétique Flysch for the Villarbeney landslide or Gurnigel Flysch for the Falli Hölli, Hohberg, Schlossisboden and Pürrena landslides. Moreoever, a narrow belt of flysch Mélange is inserted between the Préalpes Médianes and Gurnigel Nappes and originates the gully morphology of the Hohberg landslide's upper zone (Oswald & Dapples 2001). Flysch lithologies, characterized by various sandstone to claystone layers have initiated and continuously produced the loose surface material. The resulting high content of silts and clays in the loose material matrix favours the onset of landslides. Therefore, most of the prealpine landscapes concerned by a flysch substrate suffer from slope instability and often demonstrate that such landslide processes started during the Late-Glacial and the early Holocene (Lateltin et al. 1997).

2.2 Landslides in the Prättigau area, Eastern Swiss Alps

The Prättigau valley (Fig. 2) is affected by numerous slope instabilities (Noverraz et al. 1998) related to specific geological conditions and the legacy of the glacial history. The bedrock is characterized by Bündnerschiefer metamorphic schists and Prättigauer Flysch. Such lithologies are thus favouring slope instabilities in the overlying Quaternary, as mentioned for landslide processes affecting the Fribourg Prealps. Most sliding processes seem to have started as a consequence of slope decompression due to glacier retreat during the Late-Glacial (Noverraz et al. 1998). The large landslides of Saas and Gotschna are now still active, even though exposing landslide areas with low slope angles of ca. 15-18°. Such movements are generated by continuous underground water circulation at the landslides toe.

3. Methods

Various dating methods help to establish the paleo-landslide chronology. Radiocarbon dating and dendrochronology are efficient ways to date subfossil wood and paleosoils buried under sliding slopes (Schöneich 1991; Johnson 1987). Both dating methods were used to produce the data presented in this paper. In addition, other techniques, such as lichenometry, thermally ionising mass spectrometry and optically-stimulated-luminescence, have recently improved the possibilities of reconstructing past landslide dynamics (Lang et al. 1999).

3.1 Sampling

The collection of subfossil wood fragments and paleosoils buried and preserved in landslide bodies depends on the possibilities of prospecting and sampling. Such datable material can be collected in various ways:

- Boreholes drilled in landslide material offer the best opportunity to find deeply buried samples, usually of very old ages. Samples from a surface of sliding can reveal precious information on the dynamics of the overlying sliding mass.
- Draining trenches expose surface material down to two meter depth and may cover extended areas of a landslide body through specific dendritic networks.
- Road restoration or stabilization also bring to light shallow material.
- River embankments are periodically subject to fluvial erosion, leading to a renewal of outcrops.
- Major landslide activity, like the Falli Hölli catastrophe in 1994 (Raetzo-Brülhart 1997), leads to large scarp and crack openings, exposing shallow and deeper material.

Collected samples need to be thoroughly described and separately preserved to avoid any contamination that could distort radiocarbon dating. Loose material wrapping the collected samples must also be accurately described and analyzed in order to facilitate the interpretation of datings in terms of landslide events.

3.2 Dendrochronology

The analysis of annual rings of subfossil trees offers numerous possibilities to reconstruct past landslide activity. With the help of reference curves, absolute dating of tree samples can be carried out and additional information can be obtained, such as year or even season of tree death, tree age and species, periods of destabilization during the life of the tree (Schöneich 1991), timespan between tree death and burial and preservation conditions. However, dendrochronological dating requires specific conditions. Only well-preserved trees exposing a wide range of tree-rings can be dendrochronologically analysed. Moreover, the necessity of accurate reference curves for particular species and regions is a restricting factor to the use of this method. Finally, the production of reaction wood, due to tree tilting, does not facilitate the determination of accurate wood sequences. All ten dendrochronological analyses of subfossil tree samples presented in this paper were carried out at the "Laboratoire Romand de Dendrochronologie" in Moudon, Switzerland.

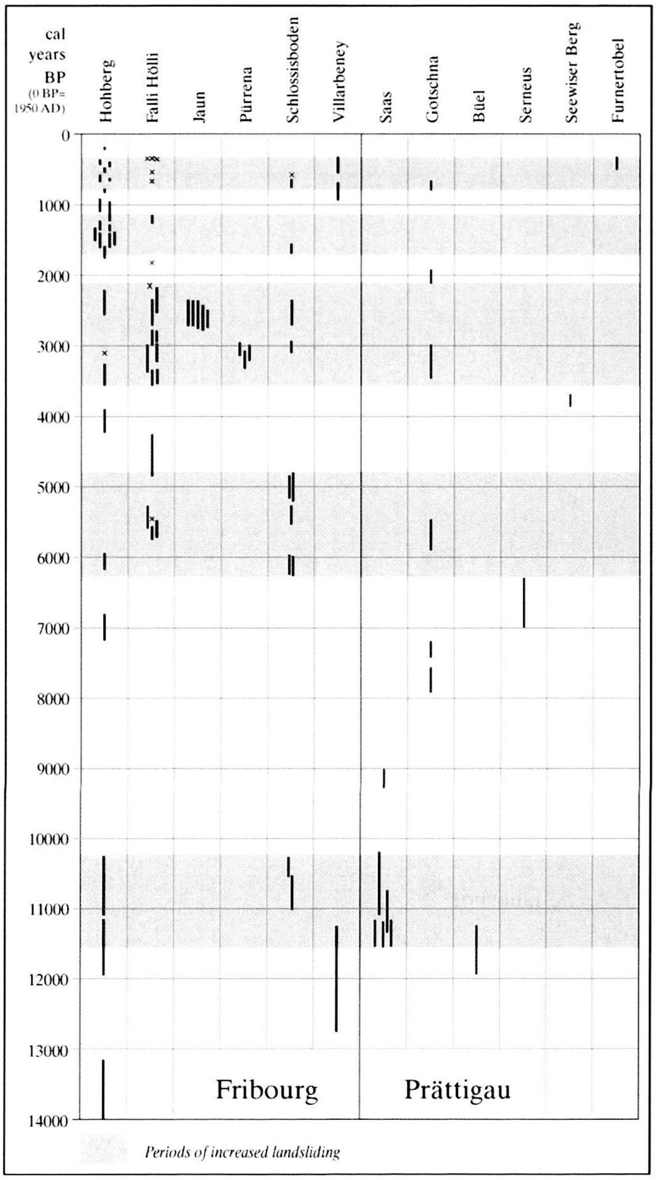

Fig. 3. Distribution of wood datings in the Fribourg Prealps and the Prättigau area during the Late-Glacial and the Holocene. Crosses: dendrochronological datings; bars: radiocarbon datings with 2σ error range. Grey shading represents periods of increased landslide activity, exposing synchronous records of slope instability on distinct sites. Location of landslides in Figures 1 and 2.

3.3 Radiocarbon

The radiocarbon dating method is widely applied when dealing with organic matter. Indeed, wood fragments or plant macrofossils can be dated through Accelerator Mass Spectrometry (AMS) or Conventional Radiocarbon, according to sample type and weight. Not much material is therefore needed, which is very helpful when dealing with small wood fragments ex-

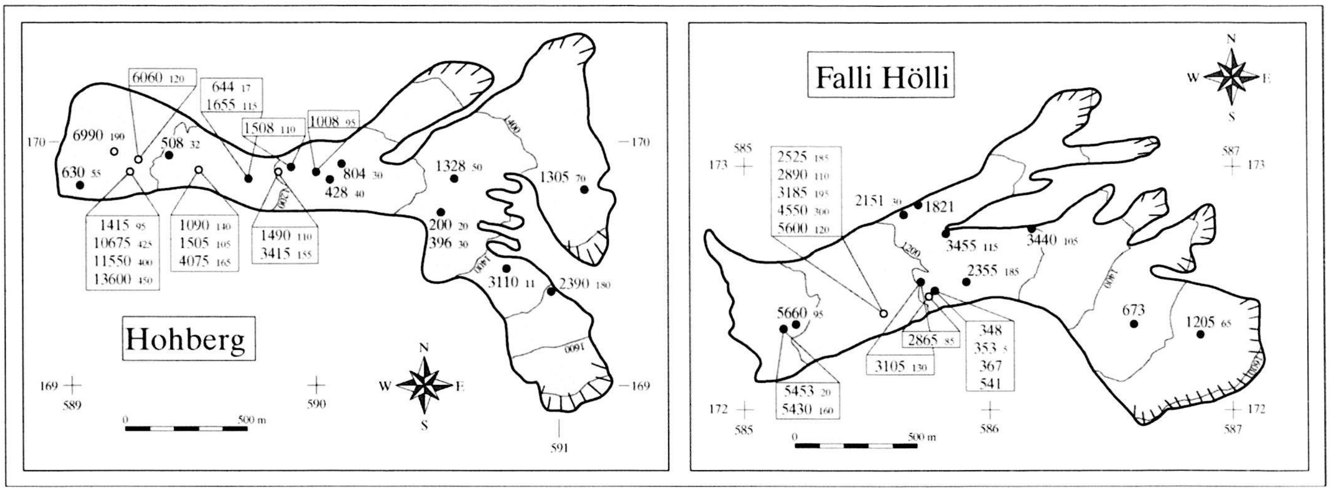

Fig. 4. Location of wood datings on the Hohberg and Falli Hölli landslides. Ages are calibrated years. White circles: location of boreholes. Elevation contour lines in metres.

tracted from a borehole, for instance. However, radiocarbon dating is associated with unavoidable error ranges increasing with sample age. Moreover, due to natural variations of ^{14}C production in the atmosphere (Stuiver et al. 1991), radiocarbon dates have to be corrected if compared with absolute dendrochronological ages. The OxCal software (Bronk Ramsey 1995) was used to calibrate all ^{14}C dates, based on the "IntCal98" calibration curve (Stuiver et al. 1998). Calibrated dates are presented with 2σ error and expressed as "cal BP", 0 BP representing 1950 AD.

A large number of samples were radiocarbon-dated, due to restricted weight of sampled wood, thus preventing dendrochronological analyses. 55 conventional radiocarbon datings were carried out in the ^{14}C Laboratory of the Institute of Physics, University of Bern, Switzerland and 15 in the ^{14}C Laboratory-ARCHEOLABS, St-Bonnet-de-Chavagne, France. Finally, 5 small-size wood sample datings were performed through AMS in the ^{14}C Laboratory of the Institute of Particle Physics, EidgenoessischeTechnische Hochschule, Zürich, Switzerland.

4. Results

4.1 Landslide events in the Fribourg Prealps

Figure 3 presents 59 radiocarbon and 10 dendrochronological wood datings, collected from six distinct landslides located in the Fribourg Prealps (Fig. 1). Most of the samples are from *Picea abies* and *Abies alba* tree species. Dates are interpreted in term of landslide events s.l., as described by Schöneich (1991), trees being cut or laid down and incorporated into the sliding mass. The presence of well-preserved bark on many trees suggests a very rapid burial process following the death of the tree, giving no chance for worms or bacteria to alter the tree structure. Such tree cutting and quick burial are promoted by rapid and destructive processes such as rapid landslides (flowslides) and debris flows.

The first signs of landslide activity in the Fribourg Prealps appear during the Late-Glacial (Fig. 3) with three samples older than 11'500 cal BP. The 66 other dates are heterogeneously distributed during the Holocene, with three samples dated in the early Holocene, thirteen samples scattered between 7'200 and 3'900 cal BP, with a specific cluster of dates between 6'250 and 4'800 cal BP, and the remaining 50 dates concentrated during the last 3'500 cal years. A focus on this recent period starting at 3'500 cal BP reveals three distinct periods of increased landslide activity between 3'500-2'100, 1'700-1'150 and 750-300 cal BP. The particularity of these periods is that records of landslide activity concern more than one landslide at the same time. Indeed, synchronous increased landslide frequency occurs on spatially-distinct landslides, like the 3'500-2'100 cal BP period, exposing signs of landslide activity affecting five distinct landslides locations (Hohberg, Falli Hölli, Jaun, Pürrena and Schlossisboden; Fig. 1).

Figure 4 illustrates the distribution of wood datings on both Hohberg and Falli Hölli landslides. Owing to major investigative methods and remedial work such as boreholes and trench drains recently carried out on both sites, 46 dates were determined from the Hohberg and Falli Hölli landslides. Spatial correlations could be carried out on each site. At the Falli Hölli landslide, the dates of 3'455 ± 115 and 3'440 ± 105 cal BP reveal the presence of extensive movements affecting the centre part of the landslide in the mid-Subboreal. Similar observations at the Hohberg landslide reveal a concentration of six dated events between 1'305 ± 70 and 1'508 ± 110 cal BP, suggesting a dynamic activity spreading from the upper to the lower part of the landslide body at the end of the Older Subatlantic. Such spatial distribution of landslide events illustrates

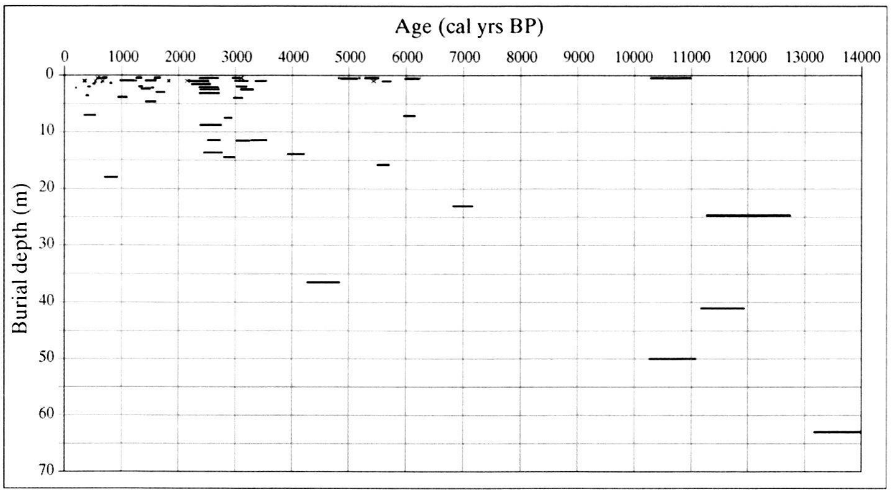

Fig. 5. Relationship between "burial depth" and "age" of the 69 landslide wood datings of the Fribourg Prealps. Crosses: dendrochronological datings; bars: radiocarbon datings with 2σ error range.

the complex evolution of landslide dynamics through time. Reconstitution of landslide history can be carried out for each site, with a chronology and mapping of past events, as was done by Schlüchter (1988) in Brattas – St-Moritz and Schöneich (1991) in Les Parchets.

However, such dates have to be handled very cautiously. Sampling of subfossil wood is highly dependent on prospecting facilities and is, therefore, influenced by such prospection possibilities. Figure 5 illustrates the relationship between burial depth and age of the 69 subfossil wood samples of the Fribourg Prealps (Fig. 3). It clearly brings out that most subfossil tree samples are found at shallow depths, especially in the 0-5m depth range. This is due to favourable sample extraction from shallow trench drains, while deeper wood samples, found in boreholes, involve a higher random factor. The resulting high concentration of young dated samples arising from the shallow layers of a landslide body should therefore not be directly opposed to a "lack" of dated samples during the previous millenia. Dated events younger than 3'500 cal BP are sufficiently numerous to give a fair representation of landslide activity in the Fribourg Prealps during the late Holocene. While dated events older than 3'500 cal BP, more scarce due to prospecting constraints, allow a less accurate interpretation of landslide frequency during the Late-Glacial and the early and middle Holocene. Old events must however be integrated in such a study of past landslide activity as signs revealing the occurrence of increased landsliding prior to 3'500 cal BP. Further prospecting should be carried out to increase the amount of "old" material, in order to determine the distribution of landslide events during the Late-Glacial and the early and middle Holocene.

4.2 Landslide events in the Prättigau area

New data on Holocene landslide events in the Prättigau area are presented in Figure 3. They arise from various studies and investigations recently carried out in the Prättigau valley. Twelve wood samples were found by T. Lardelli in boreholes on the Saas and Gotschna landslides (Fig. 2). These boreholes were drilled as part of an engineering investigation due to the project of the new Prättigau main road on the one hand, and the Zugwald tunnel digging on the other hand. P. Zwahlen collected wood samples from the Furnertobel and Seewiser Berg during fieldwork associated to a mandate of Quaternary mapping of the Prättigau area, issued by the Federal Office for Water and Geology in Bern, Switzerland. The sample Büel was found in a trench digged for the new Sunniberg bridge. The wood material was burried in a small local rockfall mass.

Dated samples are distributed along the last 12'000 cal years. A cluster of six dates from the Saas landslide and Büel rockfall gives evidence of considerable slope instabilities in the early Holocene (Fig. 3). The Saas wood samples were found on the bottom plane of the landslide body, between 33 and 115 m depths, close to the underlying moraine. The dates could, therefore, express the onset of major landslide movements overlapping the moraine and its forested cover. Indeed, the dated wood samples, found very often, in nearly every second borehole, suggest the presence of forest-type vegetation (Kobler 1994) settled on the moraine after glacier retreat, that would have been cut down and integrated at the bottom of the thick sliding mass. The remaining ten dates are spread along the last 9'500 cal years, showing no additional clustering. However, the successive signals of landslide activity expressed by the Gotschna data (Fig. 3) suggest recurrent reactivations affecting distinct areas of the landslide. The 3 dates comprised between 8'000 and 5'500 cal BP give evidence of active landsliding towards the present city of Klosters. In other words, during this period, the northern part of the landslide was sliding downward over valley-bottom fluvial deposits. On the other hand, after 3'500 cal BP, recorded activity signals suggest a forward extent of the southern part of the landslide above moraine and fluvial deposits.

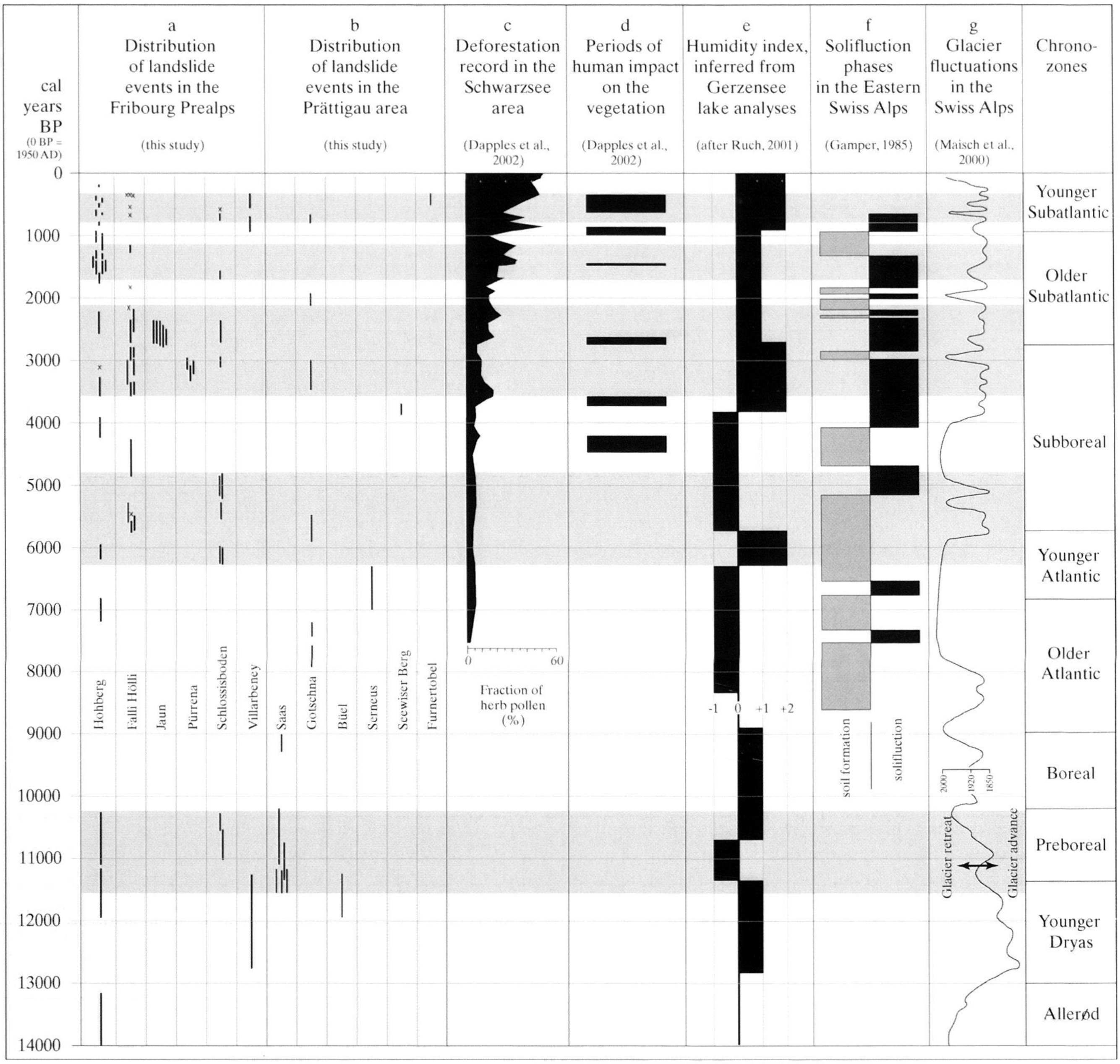

Fig. 6. Comparison of reconstructed landslide events in the Fribourg Prealps (a) and the Prättigau area (b) with records of vegetation changes (c) and anthropogenic impact (d) in the Schwarzsee lake area, Gerzensee lake humidity index (e) (-1: dry; 0: normal; +1: rainy; +2: very wet), periods of enhanced solifluction activity (f) and glacier fluctuations in the Swiss Alps (g). Grey shaded rectangles represent periods of increased landslide activity in the Fribourg Prealps and the Prättigau area.

As mentionned with the Fribourg Prealps data, the small number of collected samples on each landslide of the Prättigau area provides good and interesting information on Holocene landslide activity, but is not sufficient to statistically represent an accurate record of such activity. More prospecting work would improve an accurate landslide chronology of the Prättigau area during the Holocene.

5. Discussion

The chronology of increased landslide activity during the Holocene, recorded in the Western and Eastern Swiss Alps, must now be compared with the Holocene fluctuations of various parameters such as climate, vegetation and anthropogenic impact. Various data illustrating vegetation changes, anthropogenic influence and climatic records during the Holocene are illustrated in Figure 6, together with chronologies of landslide events both in the Fribourg Prealps as well as in the Prättigau areas.

5.1 Comparison with Schwarzsee lake sediments

A first comparison is made between landslide events in the Fribourg Prealps and vegetation changes recorded in the Schwarzsee lacustrine sediments (Fig. 6 a – 6 c; Dapples et al. 2002). The analysis of lake sediments, and especially pollen records, reveals a constant evolution of the lake environment during the late Holocene. The curve reflecting the evolution of upland and moist herb pollen fraction (Fig. 6 c) since 7'500 cal BP reflects a trend of increasing herb pollen starting at about 3'700 cal BP. Such an increasing trend is associated with continuously decreasing tree cover, related to human-induced deforestation. Indeed, pollen records demonstrate that forested areas surrounding Schwarzsee (Fig. 1) were progressively replaced by anthropogenic herb and cereal taxa, such as *Plantago lanceolata*-type, *Urtica*, *Rumex acetosa*-type and *Cannabis*. The appearance or increase of such species is highly dependent on the development of pastures and meadows (Dapples et al. 2002). Six periods of increased human impact on the vegetation in the Schwarzsee area are spread along the past 4'500 cal years (Fig. 6 d), recorded by large positive shifts of the herb pollen fraction. Sustained deforestation during the past 3'700 cal years happens to correlate with the period of increased landsliding starting at 3'500 cal BP. Changes in the vegetation cover seem to have affected slope stability in the Fribourg Prealps during the late Holocene. Indeed, forest clearing can accelerate landsliding (Thornes 1997; Montgomery et al. 2000) since tree cover contributes to mechanical stabilization of superficial soil layers due to the presence of roots and favours soil moisture depletion as a result of transpiration (Nilaweera & Nutalaya 1999). The impact of vegetation cover on the activity of deep landslides and hydrogeological processes can be considered since deep landslide activity may be influenced by shallow mass movements affecting their surface mass balance. Water inputs, and therefore water circulation within landslide bodies, can also vary as a result of fluctuations of the vegetation cover and shallow mass movements.

5.2 Comparison with Gerzensee water-level fluctuations

Apart from deforestation and anthropogenic influence on Holocene landsliding, correlations can be established between Holocene mass movements and climatic records. A humidity index has been demonstrated by Ruch (2001) based on analyses of pollen and mollusc assemblages and stable isotopes in the Gerzensee lake (Fig. 6 e), located 30 km north-east of Schwarzsee lake. This record illustrates humidity oscillations since the Late-Glacial. The Holocene is divided in a succession of periods of dry to very wet climatic conditions. The particularly wet period between 3'800 and 0 cal BP is of great interest since it corresponds with the period of increased landsliding in the Fribourg Prealps. We can, therefore, assert, that beside a distinct influence of vegetation changes, humidity variations, related to precipitation fluctuations, have influenced slope stability during the Holocene. Precipitation rates are of major importance concerning landslide dynamics (Dikau & Schrott 1999; Flageollet et al. 1999), and such a relationship is obviously exposed here covering the last 3'500 cal years and the couple of centuries around 6'000 cal BP.

5.3 Comparison with alpine solifluction records

Additional climatic data arising from solifluction records in the Eastern Swiss Alps (Gamper 1985) are presented in Figure 6f. A dominant trend of solifluction characterizes the period of time ranging from 4'100 to 600 cal BP, matching with increased landsliding in the Fribourg Prealps. Moreover, a detailed observation of the solifluction phases reveals a good correlation with two successive periods of increased landslide activity, namely 3'500-2'100 and 1'700-1'150 cal BP, presenting a slight advance of the solifluction response due to climatic changes compared with the landslide response. According to Gamper (1985), such increased solifluction activity is related to colder and more humid summer seasons together with colder winter seasons. This supports the correlation with the increased humidity conditions of the Gerzensee. Increased landsliding can therefore be correlated with periods of climate change to colder and more humid conditions.

5.4 Comparison with glacier fluctuations

The correlation between increased landslide activity during periods of climate deterioration is also supported by records of glacier fluctuations in the Swiss Alps (Maisch et al. 2000), as presented in Figure 6 g. Glacier advances dominate between 5'800 and 5'000 cal BP, as well as between 3'800 and 200 cal BP, with only restricted shifts of the curve expressing glacier retreat. Increased landsliding can thus be once more correlated with synchronous signs of cold and humid climatic conditions.

5.5 Correlation of landslide activity in the Prättigau area, Eastern Swiss Alps

The chronology of landslide events in the Prättigau area reveals distinct trends during the Holocene. The cluster of datings between 11'500 and 10'700 cal BP gives evidence of major landslide activity that occurred at the end of the Younger Dryas cold period. Such landslide activity is also recorded for the same time in the Fribourg Prealps, more specifically on the Hohberg and Schlossisboden landslides, which reveal signs of slope instability between 11'900 and 10'200 cal BP. Four of the younger dates arising from the Gotschna and Furnertobel landslides also correlate with distinct periods of increased landslide activity in the Fribourg Prealps. As mentioned before, additional dated events would improve the resolution of an event stratigraphy in the Fribourg Prealps and the Prättigau area. But still, a distinct relationship can certainly be established between Holocene landslide activity and parameters such as climatic changes, vegetation fluctuations and anthropogenic impact.

6. Conclusion

The records of historical landslide events presented in this paper yield new conceptions of landslide processes and landslide conditioning factors. The relationship between landslides and climate, namely more cold and humid conditions, has been known and described long ago, and is once again evidenced in this paper. But apart from climatic oscillations, this paper aims to show that additional parameters play an important role in landslide processes, such as vegetation changes and anthropogenic influence. Vegetation history of the Schwarzsee area demonstrates close connections with synchronous landslide activity and must, therefore, be taken into consideration in the determination of factors contributing to increase landslide probability. The complex interactions between climate, vegetation and man prevent any hazard assessment on which factor might have the strongest influence on landslide actvity. Every climate deterioration and landscape denudation are likely to affect slope stability negatively. The occurrence and the combination of both parameters increase the probability of augmented landslide occurrences. For instance, the global environment alteration, starting at ca 3'800 cal BP, characterized by simultaneous climate deterioration such as cooling and moisture increase, as well as continuous human forest clearance proves to have induced a major impact on slope stability. Such results should be taken into account in the management of present mass movements and slope instability. Water is a crucial parameter ruling landslide processes, and water inputs in a landslide highly depend on climate s.l., vegetation cover and landuse. Therefore, efficient management of vegetation cover and landuse should prevail in any landslide-prone area, in order to reduce landslide occurrences.

Acknowledgements

The authors express their thanks to all persons, agencies and institutions that technically or financially contribute to the fulfillment of landslide research projects carried out at the Institute of Geology of the University of Fribourg, Switzerland. Numerous wood datings were performed thanks to financial support from the Federal Office for Water and Geology (FOWG), Bern, Switzerland and the Etablissement Cantonal d'Assurance des Bâtiments (ECAB), Fribourg, Switzerland. We thank all people working at the Laboratoire Romand de Dendrochronologie, Moudon, Switzerland, and at the ^{14}C Laboratory of the University of Bern, for their kind help and valuable discussions concerning wood dating. We warmly thank Dr Roger van Vloten, San Miguel de Allende, Mexico, for his help with improving the manuscript.

REFERENCES

Bronk Ramsey C. 1995: Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Radiocarbon 37, 425–430.

Dapples, F., Oswald, D. & Raetzo, H. 2001: Landslides in the western Swiss Alps – Causes, triggers and dynamic aspects from former to present times. In: International Conference on Landslides – Causes, Impacts and Countermeasures (Ed. by Kühne, M., Einstein, H.H., Krauter, E., Klapperich, H. & Pöttler, R.). Verlag Glückauf Essen, 3–11.

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. J. Paleolim. 27 (2), 239–248.

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.

Flageollet, J.-C., Maquaire, O., Martin, B. & Weber, D. 1999: Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France). Geomorphology 30, 65–78.

Gamper, M. 1985: Morphochronologische Untersuchungen an Solifluktionszungen, Moränen und Schwemmkegeln in den Schweizer Alpen: eine Gliederung mit Hilfe der ^{14}C-Alterbestimmung fossiler Böden. Physische Geographie. Zentralstelle der Studentenschaft, Zürich 17.

Johnson, R.H. 1987: Dating of ancient, deep-seated landslides in temperate regions. In: Slope stability (Ed. by Anderson, M.G. & Richards, K.S..). John Wiley and Sons Ltd. 561–600.

Kobler, E. 1994: Die Späteiszeitlichen Gletscherstände im Prättigau. Jber. Natf. Ges. Graubünden 107, 45–128.

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: Instabilités de pente en terrain de flysch et changements climatiques. Rapport Final PNR31, vdf, Hochschulverlag AG an der ETH Zürich.

Maisch, M., Wipf, A., Denneler, B., Battaglia, J. & Benz, C. 2000: Die Gletscher der Schweizer Alpen. Gletscherhochstand 1850, Aktuelle Vergletscherung, Gletscherschwund-Szenarien. 2. Auflage, vdf, Hochschulverlag AG ETH Zürich.

Montgomery, D.R., Schmidt, K.M., Greenberg, H.M. & Dietrich, W.E. 2000: Forest clearing and regional landsliding. Geology 28, 311–314.

Noverraz, F., Bonnard, C., Dupraz, H. & Huguenin, L. 1998: Grands glissements de versants et climat – VERSINCLIM – Comportement passé, présent et futur des grands versants instables subactifs en fonction de l'évolution climatique, et évolution en continu des mouvements en profondeur. Rapport Final PNR31, vdf, Hochschulverlag AG an der ETH Zürich.

Nilaweera, N.S. & Nutalaya, P. 1999: Role of tree roots in slope stabilisation. Bull. Eng. Geol. Env. 57, 337–342.

Oswald, D. & Dapples, F. 2001: Interprétation géologique de la région «Hohberg-Rohr»: descriptions lithologiques du substrat rocheux. Institut de Géologie, Université de Fribourg. Unpublished.

Raetzo-Brülhart, H. 1997: Massenbewegungen im Gurnigelflysch und Einfluss der Klimaänderung. Schlussbericht NFP31, vdf, Hochschulverlag AG ETH Zürich.

Ruch, P. 2001: Comparaisons des signatures isotopiques, chimiques, minéralogiques et biologiques dans le Gerzensee (BE). Rapport Final PNR31, vdf, Hochschulverlag AG an der ETH Zürich.

Schlüchter, C. 1988: Instabilities in the area of St. Moritz, Switzerland – Geology, chronology, geotechnology. In: Landslides (Ed. by Bonnard C.). Proceed. Fifth Internat. Symposium on Landslides 2. Balkema, Rotterdam, Brookfield, 1375–1380.

Schöneich, P. 1991: La datation des glissements de terrain. In: Landslides (Ed. by Bell D.H.). Proceed. Sixth Internat. Symposium on Landslides 1. Balkema, Rotterdam, Brookfield, 205–212.

Schöneich, P., Tercier, J., Hurni, J.-P. & Orcel, C. 1997: Datation par dendrochronologie du glissement des Parchets (Les Diablerets, Préalpes vaudoises). Eclogae geol. Helv. 90 (3), 481–496.

STUIVER, M., REIMER, P.J., BARD, E., BECK, J.W., BURR, G.S., HUGHEN, K.A., KROMER, B., MCCORMAC, G., VAN DER PLICHT, J. & SPURK, M. 1998: IntCal98 radiocarbon age calibration, 24'000-0 cal BP. Radiocarbon 40/3, 1041–1084.

STUIVER, M., BRAZIUNAS, T.F., BECKER, B. & KROMER, B. 1991: Climatic, solar, oceanic, and geomagnetic influences on Late-Glacial and Holocene atmospheric $^{14}C/^{12}C$ change. Quaternary Res. 35, 1–24.

THORNES, J. 1997: Mass failure and climate change in a Mediterranean climate: the case of the Sierra Nevada, south-east Spain. In: Rapid mass movement as a source of climatic evidence for the Holocene (Ed. by MATTHEWS, J.A., BRUNSDEN, D., FRENZEL, B., GLÄSER, B. & WEISS, M.M.). Paläoklimaforschunng, Palaeoclimate Research, Gustav Fischer Verlag, Stuttgart, 85–96.

Manuscript received February 19, 2002
Revision accepted November 24, 2002