Geogr. Fis. Dinam. Quat.
33 (2010), 15-24, 10 figg., 4 tabb.

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GLACIER STREAM ACTIVITY IN THE PROGLACIAL AREA OF DEBRIS COVERED GLACIER IN AOSTA VALLEY, ITALY: AN APPLICATION OF DENDROGLACIOLOGY

ABSTRACT: GARAVAGLIA V., PELFINI M. & MOTTA E., *Glacier stream activity in the proglacial area of debris covered glacier in Aosta Valley, Italy: an application of dendroglaciology*. (IT ISSN 0391-9838, 2010).

Dendrochronology has often been used to study past and present glacier dynamics and fluctuations. Miage Glacier is the most important Italian debris covered glacier with a tree coverage growing on its debris layer. In this study we present the possibility to obtain information using tree vegetation growing in the proglacial area of Miage Glacier, highlighting the continuous remobilization of the debris by the glacial stream flow. Dating scars, compression wood and rings width releases and reductions we detected the presence of areas directly affected by glacial discharge and others characterized by boulders falling from the glacier front. The concentration of growth anomalies starting from 1984 probably indicates a more intense glacial activity influencing the forest vegetation. The data from this preliminary work suggest the possibility to extract information about the glacier behaviour not only using trees growing on the glacial tongue but also the tree vegetation colonizing the proglacial environment.

KEY WORDS: Debris covered glacier, Proglacial area, Dendroglaciology, *Larix decidua* Mill., Aosta Valley (Italy).

RIASSUNTO: GARAVAGLIA V., PELFINI M. & MOTTA E., *Dinamica dei torrenti proglaciali di un ghiacciaio nero (debris covered glacier) in Valle d'Aosta, Italia: un'applicazione della dendroglaciologia*. (IT ISSN 0391-9838, 2010).

Gli studi dendrocronologici sono stati spesso utilizzati per ricostruire la dinamica e le fluttuazioni glaciali attuali e del passato recente. Il Ghiacciaio del Miage, il più importante ghiacciaio «nero» italiano (*debris covered glacier*), è caratterizzato da una copertura arborea che colonizza la copertura detritica superficiale in corrispondenza della fronte. In questo studio viene esposta la possibilità di ottenere molteplici informazioni dalla vegetazione arborea presente anche nell'area proglaciale del Ghiacciaio del Miage in quanto le caratteristiche degli anelli di crescita annuale evidenziano la continua rimobilizzazione del detrito da parte delle acque di fusione glaciale. Datando cicatrici, legno di compressione, improvvisi incrementi o riduzioni della larghezza degli anelli è stato possibile individuare le aree direttamente interessate dal *runoff* glaciale e le aree colpite dal crollo di blocchi e massi dalla fronte glaciale. La concentrazione di anomalie di crescita a partire dal 1984 indica probabilmente una più intensa attività glaciale che ha influenzato l'accrescimento della vegetazione arborea. I risultati preliminari di questo studio suggeriscono la possibilità di ricavare dati sulla dinamica glaciale attraverso indagini dendrocronologiche condotte non solo sugli alberi epiglaciali ma anche sulla vegetazione che colonizza l'area proglaciale.

TERMINI CHIAVE: Ghiacciaio nero, Area proglaciale, Dendroglaciologia, *Larix decidua* Mill., Valle d'Aosta.

INTRODUCTION

Glacier shrinkage and transformation from debris-free to debris covered glaciers are nowadays typical characteristics of glacial tongues (Haeberli & *alii*, 2002; Frank & *alii*, 2007). Debris coverage has a great influence on glacier dynamics, limiting ablation rate and frontal movements (Benn & Evans, 1998; Mihalcea & *alii*, 2006).

Where debris coverage is not a continuous layer, for example because of crevasses and ice cliffs at the glacier boundary, ablation increases and the loss of ice mass takes place (Benn & Evans, 1998). The hydrology on a debris-covered glacier is complex: fluctuations in water flows, in supraglacial and marginal lakes are reflected in a changeable glacier stream discharge.

Furthermore, debris coverage represents the base for supraglacial life (e.g. arthropods (Gobbi, 2007), yeasts (Turchetti & *alii*, 2007)) and vegetation like grass, shrubs and, in some places, trees (Fickert & *alii*, 2007; Pelfini & *alii*, 2007). Tree coverage represents a meaningful and precious source of proxy data (e.g. glaciological and climatic data) as demonstrated by recent dendroglaciological studies (Larocque & Smith, 2005; Pelfini & *alii*, 2005; 2007; Pelfini, 2008). In fact tree rings record in their characteristics (ring width, density, morphology etc.) both climate and environmental variations.

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Trees located in proglacial areas can be affected both by glacial activity (glacier pushing, supraglacial debris and block falls) and by glacial runoff fluctuations, recording data about glacial and paraglacial systems (*sensu* Ballantyne, 2002) evolution.

Several authors applied dendrochronological methods to reconstruct past glacial fluctuations (*inter alia* Luckman, 1993; Holzauser & Zumbuhl, 1999; Pelfini, 1999; Kononov & *alii*, 2005; Jackson & *alii*, 2008; Koch, 2009). Dendrochronology and wood anatomy are helpful tools to study forest recolonization on glaciers forefields (Schweingruber, 1988; McCarthy & Luckman, 1993).

Recent works also showed the importance of supraglacial trees in order to investigate the influence of kinematic waves on debris covered glaciers (Pelfini & *alii*, 2007). Few are the studies concerning the effects of the glacial discharge on tree vegetation growing in proglacial areas and the relation between tree growth disturbances and glacial activities. The most significant researches on deglaciated areas are mainly related to the ecesis time (McCarthy & Luckman, 1993; Strumia & Schweingruber, 1996) and the recolonization of deglaciated areas (Winchester & Harrison, 1999; Moreau & *alii*, 2007; Pierson, 2007).

The following study presents the results of a recent research carried out on the sandur area of Miage Glacier (Mount Blanc Massif, Western Italian Alps), the most significant Italian debris covered glacier. The aim of this work is to demonstrate how trees growing close to the glacier terminus and to the glacial stream can contribute to the reconstruction of glacier stream fluctuations and dynamic, providing useful information to better understand the behaviour of debris covered glaciers and glacial discharge. Moreover this information may have an important role in detecting glacial hazard and risk, especially in areas where tourism is well developed and where hiking trails extend near the glaciers, for example when they cross sandur and glacial streams.

STUDY AREA AND PREVIOUS WORKS

The research has been carried out in the proglacial area of Miage Glacier, close to its southern lobe (fig. 1). Miage Glacier (11 km^2) originates from Mont Blanc Massif at an altitude of 4800 m a.s.l.; it flows for 6 km along Veny Valley and it has its terminus at an altitude of 1775 m a.s.l. (Diolaiuti & *alii*, 2005). The lower portion of the tongue is characterized by two main lobes which enclose a smaller one. Debris coverage begins at an altitude of 2400 m and forms rapidly a continuous layer. The debris layer developed during XVIII century (Deline & Orombelli, 2005) and it is supported by frequent rockfalls and debris falls on the glacier surface.

The Miage Glacier is the only glacier in Italy which presents a well-developed tree coverage, growing on the lower part of its tongue: trees on supraglacial debris are mostly *Larix decidua* Mill. and *Picea abies* (L.) Karst. They show typical shapes (twisted and deformed trunks), caused by mechanical disturbances due to the complex glacial movement and the tree-ring characteristics (scars, compression wood, ring-width anomalies etc) record environmental changes. Trees ability to record proxy data allows to investigate surface glacier processes as generally realized with dendrochronological analysis on proglacial trees, buried trunks, trees on moraine edges etc (Lara & *alii*, 2005; Brauning, 2006; Allen & Smith, 2007; Gärtner, 2007; Pelfini, 2007; Jackson & *alii*, 2008).

More in detail, European larches on Miage Glacier allowed to identify and date growth anomalies due to superficial glacial movements (e.g. slide, flows, vertical movements, debris instability) and to analyze the effect of the last kinematic wave that crossed the lower part of the tongue (Pelfini & *alii*, 2007; Pelfini, 2008). Its effect can be observed through a succession of aerial photos (Giardino & *alii*, 2001) and was confirmed by glaciological investigations (Smiraglia, 2001). The dendroglaciological analysis contributed to acquire detailed information about the period during which glacier movements affected supraglacial trees. Trees reacted to glacial strain some years earlier in the southern lobe as well as showing a major number of growth disturbance indicators (Pelfini & *alii*, 2007).

Nevertheless, in relation to the glacier sliding and to the surface velocity, the actual tree spatial distribution does not correspond to the one assumed when the kinematic wave occurred. The 1997 was identified as a year of growth difficulties in a significant number of supraglacial trees: damages on trunks along the inner glacial margin due to boulder falls from the glacier were common. The previous year, 1996, was characterized by important flood events in all the Aosta Valley, related to heavy rains that probably also influenced the dynamics of the glacier.

Moreover the tree life span is controlled by glacier surface velocity and by the evolution of ice cliffs that cyclically open in correspondence of the glacier front. Trees in fact move down-valley in relation to glacier sliding, ice-cliffs retreat and evolve (backwasting and downwasting phenomena), falling down when they reach the glacier terminus or when they are reached by the ice-cliffs moving back. Each summer, on the northern lobe, the ice cliff evolution causes the loss of more than one hundred trees and young plants (Pelfini, 2008).

The studied proglacial area is NE-SW orientated and covers a surface of about 6930 m^2. This area is bordered by two lateral moraines, by the terminus of the southern lobe and by a small bridge, which is part of a tourist trail (fig. 2).

A debris coverage, continuously mobilized by melting water, characterizes the plain. Pebbles and blocks from the glacier surface are present, especially at the front margin where they give place to a small talus. The sandur morphology reflects the direction of water flow: elongated domes and channels are frequent as are deposits due to debris and block fall.

Larix decidua Mill., *Betula alba, Salix* spp. dominate the sandur with only a few individuals of *Picea abies* (L.) Karst: trees and shrubs are grouped and located in areas delimited by water flows. Some trees show regular shaped trunks, in other cases growth disturbances and scars, due

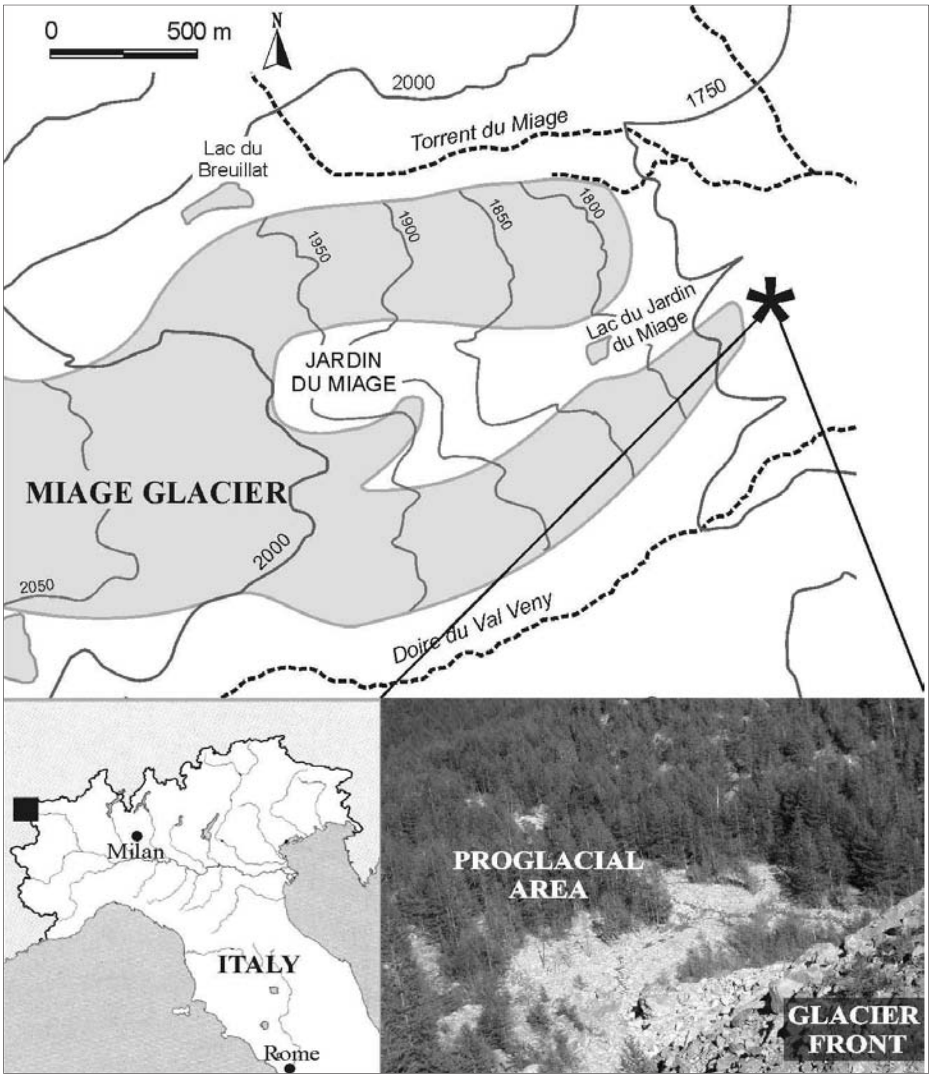

FIG. 1 - Sketch of the northern and southern terminal lobes of the Miage Glacier (Aosta Valley, Western Italian Alps). The black star represents the investigated proglacial area, also showed in the image at the bottom right.

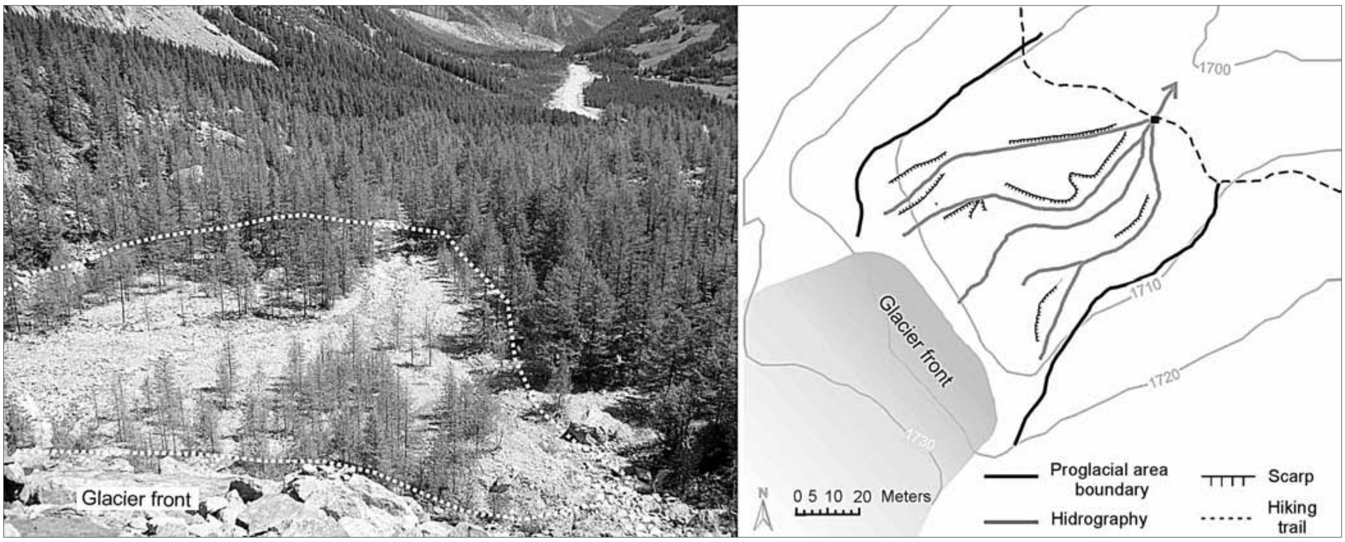

FIG. 2 - The Miage Glacier pro-glacial area and, on the right, its boundaries, including water-flow tracks, the related scarps, the hydrography and the hiking trail that borders the investigated area.

to running water, glacier dynamics and debris fall, can be identified.

The glacier stream frequently changes its origin: spatial distribution in the glacial outflow is constantly in evolution, as observed during the 2007 summer fieldwork (Pelfini, 2008). There are three springs close to glacier terminus but their discharge is not continuous in time and varies during seasons: for example during the survey in summer 2007, glacier stream progressively diminished its run-off, coming to a dry situation in November 2007.

When glacial run-off is significant, the glacial stream can affect the hiking trail near the glacial terminus, increasing risk for hikers.

The glacier surface is also characterized by many small supraglacial lakes and by a typical marginal lake, delimited by an ice cliff and a moraine system. This lake cyclically empties, varying its stream flow discharge also in the proglacial area. Here, the Alpine calving phenomena are well represented and studied in detail (Diolaiuti & *alii*, 2005; 2006).

METHODS

One hundred fifty nine cores from 101 *Larix decidua* Mill. were sampled using an increment borer. In order to identify the glacier stream effect on the tree growth in recent years, sampling took place in the entire investigated area avoiding tree belts between the glacier front margin and spring line or located less than 3 meters from the trail, so as to limit anthropic impact. Cores were collected at the base of the trunk to obtain a cambial age as indicative as possible to the real age (Schweingruber, 1988), in correspondence of scars and growth direction changes.

Particular attention has been paid to the sampling height because it represents one of the factors that could affect the ecesis[1] estimation (Koch, 2009).

Each sample was georeferenced by means of a pocket pc and GPS and all the information was achieved in a database. Cores were prepared following the standard methodology (Schweingruber, 1988, 1996) and they were measured using the LINTAB-TSAP system and the Windendro software (Rinn, 1996; Régent Instrument Inc., 2001). Reference chronologies have been built for the previous study (e.g. Pelfini et al., 2007) using larches growing outside the glacier and they were used for comparison with tree-ring data from proglacial trees. The crossdating of the dendrochronological series was performed using COFECHA (statistical analysis) and TSAP software (visual analysis).

A detailed analysis was carried out on:

- scars, generally due to the impact of blocks and boulders coming from glacier surface or transported by glacial stream;
- compression wood: reaction wood produced by a tree in order to recover its vertical position when tilted by glacier pushing, boulder fall, debris flows, substrate instability etc. Generally trees present an eccentric growth, with wider rings and with a more intense colouring on the side of the trunk which is exposed to the valley (Timell, 1986).

Growth anomalies recognizable only on one side of the stem (up-valley, down-valley) can be associated with mechanical disturbances while narrow or very wide rings along all the stem circumference are commonly associated to general growing conditions.

A ring count was performed to estimate a date of scaring and that of the first ring of compression wood; skeleton plots were built to identify pointer years, comparing ring width to that of previous year (Schweingruber, 1988), in order to obtain a time scale of growth anomalies and spatial maps.

In the present work there will be use of the following terms to indicate sampling direction: SW core (upslope direction), NE core (downslope direction), SE core (hydrographical right) and NW core (hydrographical left).

RESULTS

Tree ages

The reduced size of the trunks (average diameter 12,7 cm) permitted to collect cores with piths, avoiding the classical procedures for estimating lacking rings. The majority of the sampled trees germinated at least between 1976 and 1986 (47%) (fig. 3). Many trees date back to interval 1979-1989; only a few larches germinated between 1928 and 1963: only 6 trees during a period of 36 years (fig. 4). As expected, tree age increases moving away from the glacier front, even if the oldest larches (respectively 74 and 79 years old) are located in the middle of the right sandur margin, probably because of the presence of a more stabilized substrate. On the basis of their spatial location, sampled trees can be divided into five groups (fig. 5). In group A, the plants are 11 to 40 yrs old, with a ma-

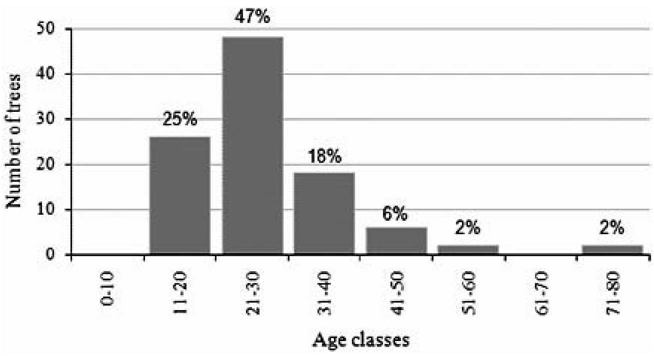

FIG. 3 - Sampled tree age distribution. The majority of the collected cores belonged to trees 21-30 yrs old.

[1] Ecesis is the time taken by trees to successfully germinate on a bare surface (McCarthy & Luckman, 1993). According to McCarthy & Luckmann (1993) it represents the minimum (or average) interval that has to be added to the earliest ring date from the oldest tree on a surface to estimate the stabilization date of that surface.

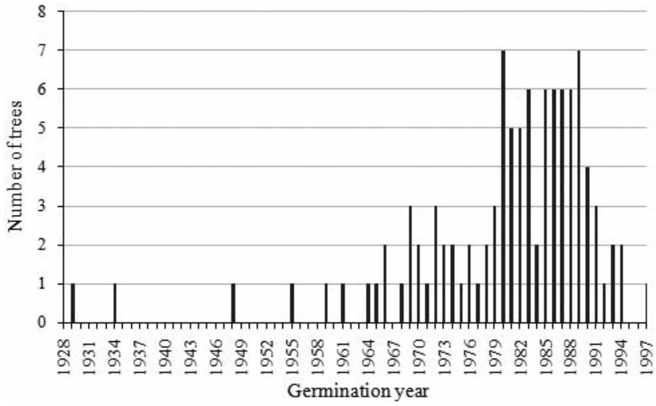

FIG. 4 - Germination years of sampled trees. The majority of them germinated between 1963 and 1993.

jority of trees 11-20 years old. Groups D and E are characterized by few larches: all 21-30 years old in the group B, the oldest specimens in the group E. The majority of the larches in the group C are 21-30 and 11-20 years old. In the entire glacial sandur saplings are not present, except for at the foot of the glacier front.

The tree-age distribution allows to assess that since the 80's the sandur is not affected by disruptive events. The oldest trees belonging to the group 71-80 yrs (E) (fig. 5) document the relative inactivity of this portion of the sandur, marginal located (hydrographical right) if compared to glacial and stream flow in the last decades. The area (A) is characterized by small escarpments and probably it is more active as documented by the region with trees not older than 11-20 yrs. The tree-age spatial distribution allows to exclude the occurrence of dramatic events able to completely destroy the forest vegetation. Nevertheless, tree ring morphologies permit to identify past minor events which caused growth disturbances.

Growth anomalies related to proglacial runoff.

Scars

Thirty-nine scars on 15 trees were detected with a major concentration of damages in year 1993 (fig. 6). Ten trees growing along glacier stream courses show scars below 60 cm in height, probably due to water and debris-flow impact, while sampled larches growing nearest the glacier (5 plants) show scars higher than one meter. In this second case blocks falling from glacier surface can be the most possible cause. In particular a sampled larch, growing at the glacier foot, shows a series of at least three scars during the interval between 1984 and 1990, probably related to 1975-1988 growing phase of Miage Glacier (Gia-

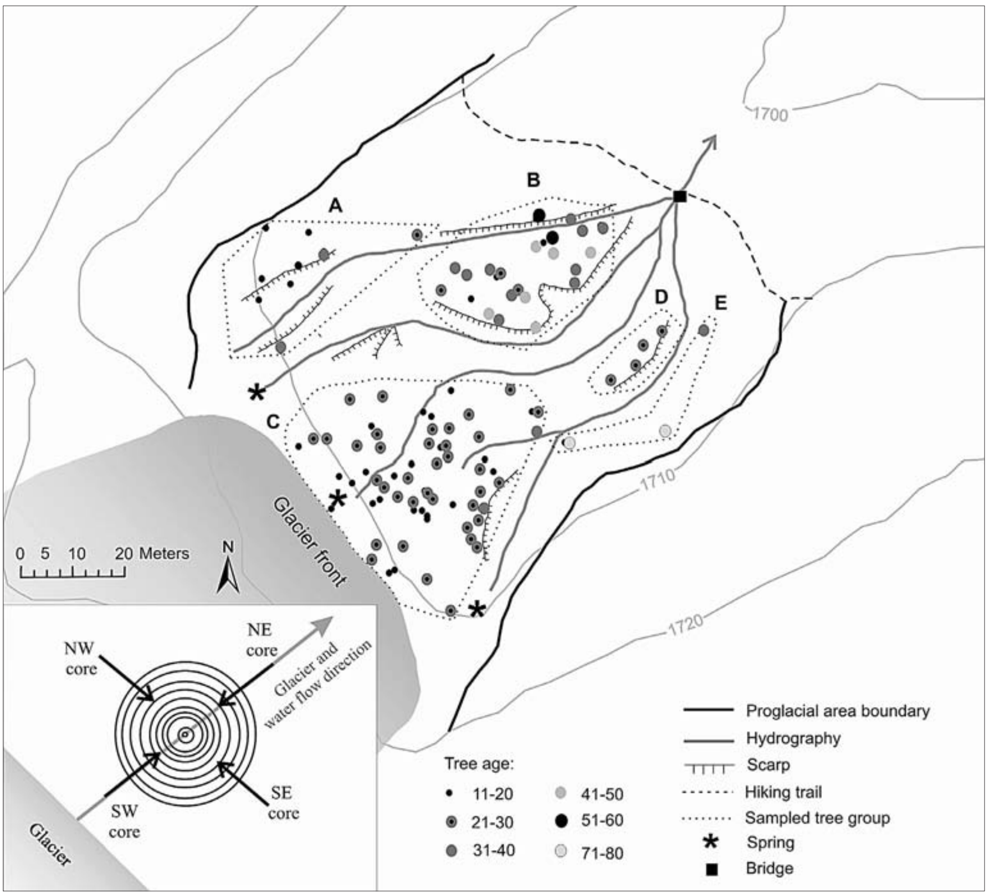

FIG. 5 - Spatial distribution of sampled trees represented on the basis of their minimum age. As expected, the age increases moving away from glacier front. A scheme of sampling directions is also showed in the image at the bottom left.

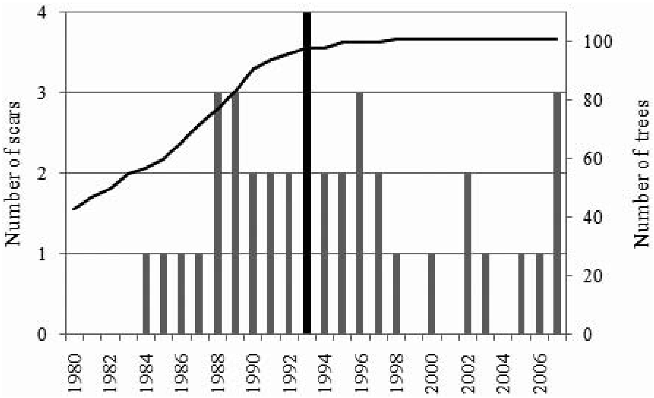

FIG. 6 - Scars distribution in time: the major number of damages were detected in 1993 (the black bar).

TABLE 2 - Distribution of reaction wood in the sampled trees in relation to sampling direction: SW cores (upslope direction), NE core (downslope direction), SE core (hydrographical right) and NW core (hydrographical left). Group I collects all the trees with RW in one sampling direction, Group II includes tree with RW on more sampling directions (see table 1)

	Sampling direction	Number of sampled trees	%
I)	SW	5	9.8
	NE	38	74.5
	SE	3	5.9
	NW	5	9.8
	Tot	51	100
II)	SE & NW	1	9.1
	SW & NE	8	72.7
	NE & SE	2	18.2
	Tot	11	100

rdino & *alii*, 2001) and associated to debris-fall events from the glacier front.

The widespread scar distribution documents the occurrence of on-going disturbance processes affecting trees. It is not easy to detect the main cause: the snow coverage and the glacier stream discharge continuously stress proglacial vegetation. Moreover the number of scars could be underestimated because all the samples have been collected in correspondence of visible scars and, as a consequence, it is possible that others scars, not visible were not samples. Nevertheless the concentration of wounds in the years 1989-1990, 1993 and 1996 and 2007 shows that several events occurred in these periods.

Reaction wood

Sixty-one percent of sampled trees presents compression wood (62 plants out of a total of 101 sampled trees, tab. 1); 18% of this reaction wood has been detected in different positions along the stem circumference, suggesting a continuous destabilization of plants growing on the glacial sandur. Eight larches present reaction wood just on the sides which face down-valley and up-valley.

Eighty-two percent of the 62 trees with reaction wood shows this growth anomaly just in one position along the stem circumference (tab. 1). The majority of its occurrence is on the side facing down-valley (38 plants, 74.5%) (tab. 2), highlighting their destabililization towards down-valley.

The calendar years mostly affected by reaction wood are 1997 (36 plants, 35% of sampled trees), 2001 (19 plants, 19%) and 2006 (15 plants, 15%); other intervals characterized by this growth anomaly have been detected in small groups of sampled trees.

Eccentric growth

Eccentric rings, with positive (increase) or negative (decrease) ring-width variations over several years, are present practically in all samples.

One hundred fifty-six symmetric anomalies (37 growth increases and 119 growth decreases) were identified, compared to 851 eccentric ring-width variations (295 growth releases and 556 growth suppressions) (tab. 3). We considered symmetric growth anomalies to be related to climate, and eccentric growth increases or decreases caused by geomorphic processes. An unfavourable year for tree growth is recorded by narrow rings while a deviation from the vertical growth is recorded by an increase in wood production only on one side (generally associated with compression wood) (Schweingruber, 1996). In this case, the glacial stream flow was recognized as the principal source of growth disturbances. In fact the area is characterized by a very gentle slope and snow creep can be excluded. Growth releases related to the presence of compression wood were not recorded as eccentric growths.

The majority of growth anomalies (tab. 4) are concentrated on the trunk side facing down-valley (NE sampling direction) and on the trunk side facing up-valley (SW sampling direction), concordant with water-flow trajectory in

TABLE 1 - Distribution of reaction wood (RW) in the sampled trees. Trees with this growth anomaly on one sampling direction are categorized differently from plants with reaction wood on more sampling directions

	Number	%
RW on one sampling direction	51	82
RW on more sampling direction	11	18
Tot plants with RW	62 (61% of 101 trees)	100

TABLE 3 - Symmetric and eccentric growth anomalies distribution in sampled trees. Symmetric anomalies: anomalies detected on down-valley and up-valley sampling directions; eccentric anomalies: anomalies detected just on one sampling direction

	Growth release	Growth suppression	Total
Symmetric anomaly	37	119	156
Eccentric anomaly	295	556	851

TABLE 4 - Eccentric growth anomalies distribution on the basis of sampling direction

	Eccentric growth anomalies				
	Number			%	
Sampling direction	increases	decreases	Tot	increases	decreases
SW	128	231	359	43	42
NE	160	305	465	54	55
SE	3	12	15	1	2
NW	4	8	12	1	1
Tot	295	556	851	100	100

proglacial sandur. Few eccentric growth anomalies were detected in SE and NW sampling directions.

The concentration of eccentric-growth anomalies in water-flow direction suggests that glacier stream flow has a more significant impact than other geomorphic processes.

Observing the spatial distribution of growth anomalies, we detected that eccentric growth in SE and NW sampling direction is principally related to escarpments associated to channels carved by water flow, which cause plant instability. Others are visible in areas characterized by an apparent substrate stability but where heavily disturbed plants were growing (fig. 7). We hypothesized the presence of seasonal ice in soil, affecting vertical growing.

More in detail, coeval anomalies present a disposition following alignment parallel to glacier terminus; during time (precisely in years 1971, 1972, 1973, 1988, 2006) (fig. 8) this line-up seems to change its position, and it could be

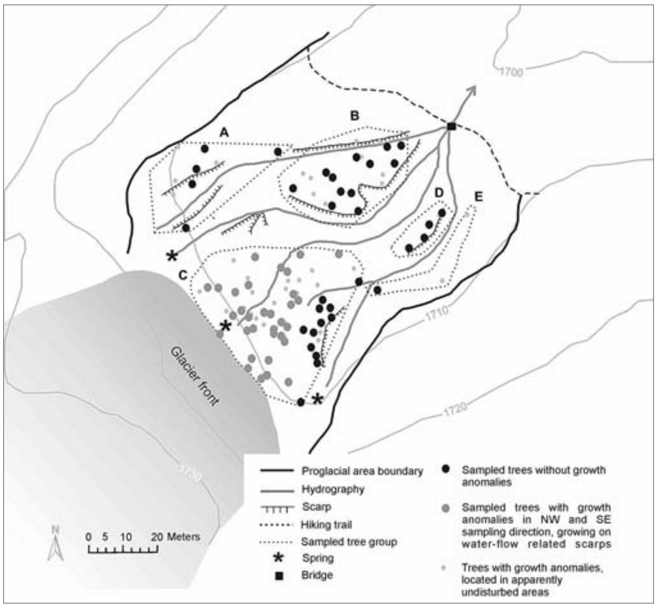

FIG. 7 - Spatial distribution of growth anomalies: little grey points represent sampled trees without growth anomalies in SE or NW sampling direction (up-valley and down-valley side) (fig. 3). Black circles are trees growing on water flow-related scarps, with growth disturbances; the bigger grey circles show trees with growth anomalies and located in an area apparently undisturbed.

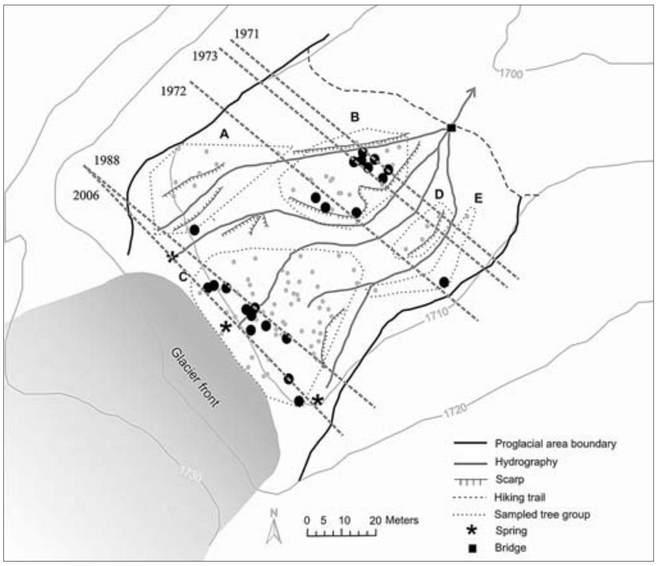

FIG. 8 - Alignments of damaged sampled trees with parallel trends in relation to glacier terminus. Growth anomalies distribution suggests a steady advancement of these hy pothetical lines.

partially related to the 1975-1988 growing phase of the glacier (Giardino & *alii*, 2001).

DISCUSSION AND CONCLUSIONS

The studied area has a small surface and obviously the results can not be extended or generalized. Nevertheless much information about the recent glacier behaviour and dynamic can be extracted, confirming the important role of a natural archive that dendrochronological data represent. In fact, tree rings are well known as important tools for recording and dating geomorphological and glacial processes (Watson & Luckman, 2005; Wiles & *alii*, 1996; Pelfini & *alii*, 2007) and the results proposed here, allow us to include proglacial vegetation as a useful indicator of glacier-correlated dynamics.

The first kind of information easily gained from tree age is the absence of disruptive phenomena and more detailed data about the stability variation of the substrate.

On the Miage sandur the maximum tree age (about 30 yrs) indicates that since 1977 (minimum age) the southern proglacial area has not been affected by important fluctuations of glacial front, as suggested by debris-covered glacier general behaviour (Benn & Evans, 1998), by mass-wasting events or by great stream-flow activity. The tree-age spatial distribution permits to reconstruct changes in shape and dimension of the single morphological units (groups A, B, C, D, E) affected by glacial stream activity and snow coverage disturbances.

In conclusion, it is possible to identify areas characterized by a more intense stream activity at least before 1977, between 1977 and 1982 and after 1982 as shown in figure 9. These dates represent minimum ages.

The great number of growth disturbance indicators suggests a continuous evolution of the proglacial area and the substrate stability. Nevertheless the identified and dated tree-rings damages do not show an evident correlation with flood events or important snowfalls (fig. 10), confirming a modification, during time, in the extension of the more affected areas.

It is possible to hypothesize a relation between tree responses and Miage lake outbursts. The famous marginal ice-contact lake has been interrupted by several drainage events during last century (meteorological data kindly provided by G.E.I.E. Traforo del Monte Bianco; Diolaiuti & *alii*, 2005). Tree-growth anomalies seem to decrease in the years following the lake outburst like in 1990 and 2004, even if the 1986 event is not concordant and the 1975 is characterized by few damaged trees. More in detail, in these years a major number of growth releases are present, respect to compression wood, scars and growth suppressions, probably related to the major availability of water in the growth season. On the contrary, the small increment in growth suppressions in the 1987 could be a consequence of the 1986 flood event (fig. 9).

A complex situation emerges from the results: rainstorms and rainfalls are important for the glacier discharge but also the ice melting, related to the temperature increase, and the snow melting, when the snow layer is thick, have a significant role. The new data coming from this work suggest the possible relation with the glacial lake dynamics.

A previous study (i.e. Pelfini & *alii*, 2007) points out the areal and temporal distribution of growth anomalies recognized also on supraglacial trees, that corresponds to some data extracted from proglacial trees near the southern lobe.

In detail, using procedures proposed in Pelfini & *alii*, 2007, similar abrupt growth changes on the southern lobe have been identified in 1976, 1988, 1989 and 1997, indicating a response to glacial activity. Compression wood is largely present in 1997, related to several boulder falls and to an active glacier dynamic. It has not been possible to identify exactly the kinematic wave crossing the southern lobe in 1984-90 but the presence of a concentration of growth anomalies in 1988-1990 (fig. 10) seems to confirm a more pronounced glacial dynamic influencing the Miage runoff.

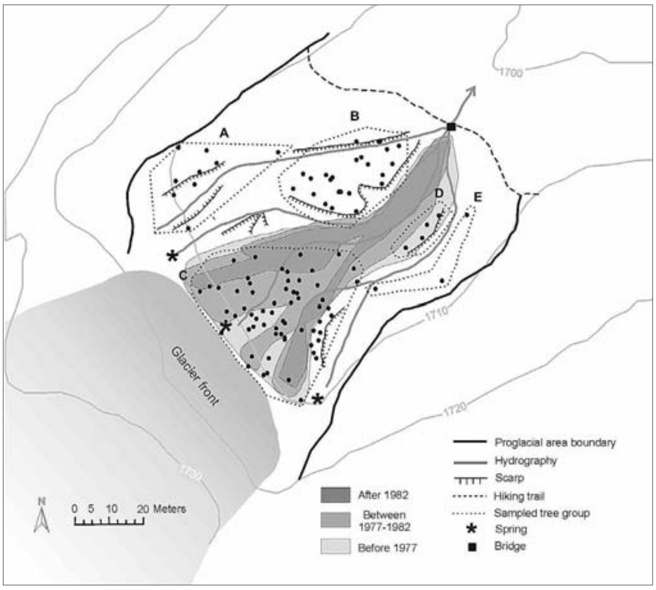

FIG. 9 - Three surfaces affected by the pro-glacial stream activity in different periods: before 1977, between 1977 and 1982, after 1982. Areas were delimited using growth anomalies detected in sampled trees.

Proglacial vegetation seems to store information as supraglacial vegetation does, but related to glacial discharge rather than only to direct glacial mass movement. In this specific case, European larches growing in proglacial areas and affected by glacial runoff, recorded the same anomalies detected in the supraglacial vegetation. Different processes, glacial stream-flows and glacial tongue dynamic, have been recorded in tree ring anomalies identified both in trees colonizing the supraglacial debris layer and in proglacial vegetation.

Several signals associated with geomorphological processes are stored in proglacial vegetation: their analysis is complex and time-consuming but these results represent a great opportunity for future studies on the glacial dynamics of debris-covered glaciers.

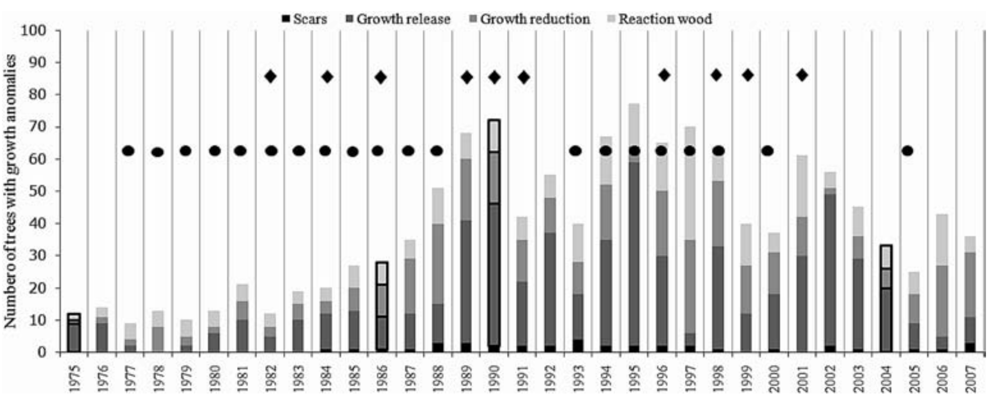

FIG. 10 - Relation between growth anomalies distribution, flood events (black rhombus) and annual snowfalls (black circles). The bars represent the number of trees with different growth anomalies (identified by colours); the bars with black borders represent the years characterized by the Miage marginal ice-contact lake's drainage events.

FUTURE PERSPECTIVE

Frequently debris covered glaciers are characterized by a thin debris layer not sufficient to support a tree coverage or by a fast dynamic that impedes the tree colonization; the relation between proglacial and supraglacial trees behaviour demonstrated for Miage glacier, allow the consideration of growth anomalies in proglacial trees as a source of data concerning the recent dynamics of debris-covered glaciers.

Even if related to a small area, these results confirm the utility of dendrochronological analysis in research on high mountain environments and they show how trees growing in proglacial areas can represent a source of data not only on glacier dynamic but also on glacial lake fluctuations and glacier stream activities opening new possibilities for investigating these kinds of sites. Dendroglaciological investigation in proglacial areas could be very useful in such territories where debris covered glacier are the most common glacial typology as in Karakorum and Himalayan region.

Finally, the spatial distribution of tree-rings growth anomalies and damages on trunks allows better management of trail networks in glacial and periglacial environments to. The rapid changes in glacier outflow may affect trails, increasing the glacial risk. The reconstruction of past events can contribute to studies about periodicity or frequency of this kind of hazard, deeply studied also on Italian Alps (Smiraglia & *alii*, 2008; Kaab & *alii*, 2007; 2004; Piccazzo & *alii*, 2007; Pelfini & Santilli, 2008). The identification of areas potentially affected by glacier stream activity and the frequency of phenomena in the recent past may contribute to risk mitigation.

REFERENCES

ALLEN S.M. & SMITH D.J. (2007) - *Late Holocene glacial activity of Bridge Glacier, British Columbia Coast Mountains*. Canadian Journal of Earth Science, 44, 12, 1753-1773.

BALLANTYNE C.K. (2002) - *Do periglacial areas evolve under periglacial conditions?* Geomorphology, 52, 149-164.

BENN D.I. & EVANS D.J.A. (1998) - *Glaciers and glaciation*. Publisher Arnold, London, 734 pp.

BRÄUNING A. (2006) - *Tree-ring evidence of «Little Ice Age» glacier advances in southern Tibet*, The Holocene, 13, 3, 369-380.

DELINE P. & OROMBELLI G. (2005) - *Glacier fluctuations in the western Alps durino the Neoglacial as indicated by the Miage morainic amphitheatre (Mont Blanc Massif, Italy)*. Boreas, 34, 1-12.

DIOLAIUTI G., KIRKBRIDE M., SMIRAGLIA C., BENN D.I., D'AGATA C. & NICHOLSON L. (2005) - *Calving processes and lake evolution at Miage glacier, Mont Blanc, Italian Alps*. Annals of Glaciology, 40, 207-214.

DIOLAIUTI G., CITTERIO M., CARNIELLI T., D'AGATA C., KIRKBRIDE M. & SMIRAGLIA C. (2006) - *Rates, processes and morphology of freshwater calving at Miage Glacier (Italian Alps)*. Hydrological processes, 20, 10, 2233-2244.

FICKERT T., FRIEND D., GRÜNINGER F., MOLNIA B. & RICHTER M. (2007) - *Did Debris-Covered Glaciers Serve as Pleistocene Refugia for Plants? A New Hypothesis Derived from Observations of Recent Plant Growth on Glacier Surfaces*. Arctic, Antarctic, and Alpine Research, 39 (2), 245-257.

FRANK P., ANDREAS K. & HAEBERLI W. (2007) - *Recent glacier changes in the Alps observed by satellite: Consequences for future monitoring strategies*, Global and Planetary Change, 56, 1-2, 111-122.

GÄRTNER H. (2007) - *Glacial Landforms, Tree Rings: Dendrogeomorphology*. In: S.A. Elias (ed.), «Encyclopedia of Quaternary Sciences», Vol.2, Elsevier, 979-988.

GIARDINO M., MORTARA G. & BONETTO F. (2001) - *Proposta per la realizzazione di un catalogo aerofotografico dei ghiacciai italiani*, Supplementi di Geografia Fisica e Dinamica Quaternaria, 5, 89-98.

GOBBI M., ROSSARO B., VATER A., DE BERNARDI F., PELFINI M. & BRANDMAYR P. (2007) - *Environmental features influencing Carabid beetle (Coleoptera) assemblages along a recently deglaciated area in the Alpine region*. Ecological Entomology, 32, 6, 682-689.

HAEBERLI W., KAAB A., PAUL F., MORTARA G., CHIARLE M. & MAZZA A. (2002) - *A surge-type movement at Ghiacciaio del Belvedere and a developing slope instability at the east face of Monte Rosa*. Norsk Geografisk Tidskrift, 56, 2,104-111.

HOLZHAUSER H. & ZUMBUHL H.J. (1999) - *Glacier fluctuations in the Western Swiss and french Alps in the 16th century*. Climatic change, 43, 1, 223-237.

JACKSON S.I., LAXTON S.C. & SMITH D.J. (2008) - *Dendroglaciological evidence for Holocene glacial advances in the Todd Icefield area, Northern British Columbia Coast Mountains*. Canadian Journal of Earth Sciences, 45 (1), 83-98.

KAAB A., CHIARLE M., RAUP B. & C. SCHNEIDER (2007) - *Climate change impacts on mountain glacier and permafrost*, Global and Planetary Change, 56, 1-2, 7-9.

KAAB A., HUGGEL C., BARBERO S., CHIARLE M., CORDOLA M., EPIFANI M., HEABERLI W., MORTASA G., SEMINO P., TAMBURINI A. & VIAZZO G. (2004) - *Glacier hazard at Belvedere Glacier and the Monte Rosa east face, Italian Alps: processes and mitigation*. Interpraevent 2004, Riva del Garda, 24-27 Maggio 2004, I/67-78.

KOCH J., (2009) - *Improving age estimates for late Holocene glacial landforms using dendrochronology - Some examples from Garibaldi Provincial Park, British Columbia*. Quaternary Geochronology, 4, 130-139.

KONONOV Y.M, ANANICHEVA M.D. & WILLIS I.C. (2005) - *High-resolution reconctruction of Polar Ural glacier mass balance for the last millennium*. Annals of Glaciology, 42, 163-170.

LARA A., URRUTIA R., VILLALBA R., LUCKMAN B.H., SOTO D., ARAVENA J.C., MCPHEE J.,WOLODARSKY A., PEZOA L. & LEÓN J. (2005) - *The Potential of tree-rings for streamflow and estuary salinity reconstruction in the Valdivian Rainforest Eco-region, Chile.* Dendrochronologia, 22, 155-161.

LAROCQUE S.J. & SMITH D.J. (2005) - *«Little Ice Age» proxy glacier mass balance records reconstructed from tree ring in the Mt Waddington area, British Columbia Coast mountains, Canada.* The Holocene, 15, 5, 748-757.

LUCKMAN B.H. (1993) - *Glacier fluctuation and tree-ring records for the last millennium in the Canadian Rockies.* Quaternary Sciences Reviews, 12, 6, 441-450.

MCCARTHY D.P. & LUCKMAN B.H. (1993) - *Estimating ecesis for tree-ring dating of moraines- a comparative study from the Canadian Cordillera*. Arctic and Alpine research, 25, 1, 63-68.

MIHALCEA C., MAYER C., DIOLAIUTI G., LAMBRECHT A., SMIRAGLIA C. & TARTARI G. (2006) - *Ice ablation and meteorological conditions on the debris-covered area of Baltoro glacier, Karakoram*. Annals of Glaciology, 43, 1, 292-300.

MOREAU M., MERCIER D., LAFFLY D. & ROUSSEL E. (2008) - *Impacts of recent paraglacial dynamics on plant colonization: A case study on Midtre Lovénbreen foreland, Spitsbergen (79°N)*. Geomorphology, 95, 48-60.

PELFINI M. (1999) - *Dendrogeomorphological study of glacier fluctuations in the Italian Alps during the Little Ice Age.* Annals of Glaciology, 28, 123-128.

PELFINI M. (2008) - *Il contributo della dendrocronologia alla glaciologia*. In: M. Romagnoli (ed.), «Dendrocronologia per i Beni Culturali e l'Ambiente», Nardini Editore, ISBN 978-88-404-4172-6, 33-46, Firenze.

PELFINI M., SANTILLI M., LEONELLI G. & BOZZONI M. (2007) - *Investigating surface movements of debris-covered Miage glacier, Western Italian Alps, using dendroglaciological analysis*. Journal of Glaciology, 53, 180,141-152.

PELFINI M., BOZZONI M. & SANTILLI M. (2005) - *Il Ghiacciaio del Miage: un geosito dalla peculiare valenza ecologica*. SLM - Sul livello del mare, 23, 8-15.

PICCAZZO M., BRANDOLINI P. & PELFINI M. (2007) - *Clima e rischio geomorfologico in aree turistiche*. Patron, Bologna, 360 pp.

PIERSON T.C. (2007) - *Dating young geomorphic surfaces using age of colonizing Douglas fir in southwestern Washington and northwestern Oregon, USA*. Earth Surface Processes and Landform, 32, 811-831.

REGEANT INSTRUMENTS INC. (2001) - *Windendro. User Manual*. Régent Instruments, Québec, 86 pp.

RINN F. (1996) - *TSAP. Time series analysis and presentation. Version 3.0 reference manual,* 262 pp.

SCHWEINGRUBER F.H. (1988) - *Tree rings. Basics and applications of dendrochronology*. Kluwer, Academic press, Dordrecht, 276 pp.

SCHWEINGRUBER F.H. (1996) - *Tree rings and environment. Dendroecology*. Swiss Federal Institute for Forest, Snow and Landscape, Birmensdorf, Haupt, Berne, 609 pp.

SMIRAGLIA C., DIOLAIUTI G., PELFINI M., BELÒ M., CITTERIO M., CARNIELLI T. & D'AGATA C. (2008) - *Glacier changes and their impacts on mountain tourism: two case studies from the Italian alps*. In: B. Orlove, E. Wiegandt & Luckman B.H. (2008), «Darkening peaks», University of California Press, 296 pp.

SMIRAGLIA C., DIOLAIUTI G.D., CASATI & KIRKBRIDE M.P. (2000) - *Recent areal and altimetric variations of Miage Glacier (Monte Bianco massif, Italian Alps)*. Debris Covered Glaciers, IAHS Publ., 264, Wallingford, 227-233.

STRUMIA G. & SCHWEINGRUBER F.H. (1996) - *Colonization and tree-ring growth in the forefield of Lys glacier (Western Italian Alps, Italy) since the little ice age*. Dendrochronologia, 14, 165-178.

TIMELL T.E. (1986) - *Compression wood in gymnosperms*. Vol. 1, Springer-Verlag, New York, 706 pp.

TURCHETTI B., BUZZINI P., GORETTI M., BRANDA E., DIOLAIUTI G., D'AGATA C., SMIRAGLIA C. & VAUGHAN-MARTINI A. (2007) - *Psychrophilic yeasts in glacial environments of Alpine glaciers*. FEMS Microbiology Ecology, 63 (1), 73-83.

WATSON E. & LUCKMAN B.H. (2005) - *An exploration of the control of pre-instrumental streamflow using multiple tree-ring proxies*. Dendrochronologia, 22, 3, 225-234.

WILES G.C., CALKIN P.E. & JACOBY G.C. (1996) - *Tree-ring analysis and Quaternary geology: Principles and recent applications*. Geomorphology, 16, 3, 259-272.

WINCHESTER V. & HARRISON S. (2000) - *Dendrochronology and lichenometry: colonization, growth rates and dating of geomorphological events on the east side of the North Patagonian Icefield, Chile*. Geomorphology, 34, 181-194.

(Ms. presented 30 July 2009; accepted 15 February 2010)