Studi Trent. Sci. Nat., 85 (2009): 91-106
© Museo Tridentino di Scienze Naturali, Trento 2009

ISSN 2035-7699

Application of relative and absolute dating techniques in the Alpine environment

Filippo FAVILLI[1*], Markus EGLI[1], Giacomo SARTORI[3], Paolo CHERUBINI[2], Dagmar BRANDOVA[1] & Wilfried HAEBERLI[1]

[1]Department of Geography, University of Zurich-Irchel, Winterthurerstrasse 190, 8057 Zurich, Switzerland
[2]WSL Swiss Federal Institute for Forest, Snow and Landscape Research, Zurcherstrasse 111, 8903 Birmensdorf, Switzerland
[3]Museo Tridentino di Scienze Naturali, Via Calepina 14, 38122 Trento, Italy
[*]Corresponding author e-mail: *filippo.favilli@geo.uzh.ch*

SUMMARY - *Application of relative and absolute dating techniques in the Alpine environment* - The Late Pleistocene and Early Holocene climate oscillation and the Alpine landscape evolution of Val di Rabbi (Trentino, Italy) were reconstructed using a combined methodology of relative and absolute dating techniques. The research was carried out in the following four steps: 1) an earlier study examined the investigated area (aerial photos, soil mapping etc.) to detect and sample the most representative sites (soils and boulders); 2) the extraction of the oldest organic matter fraction from the soil profiles followed by radiocarbon dating; 3) the comparison of the ^{14}C dating results with the ^{10}Be age sequence from representative boulders; 4) the addition of relative dating techniques to the absolute ones to detect signals of Alpine landscape evolution. We found close links among the results obtained from the relative dating and the absolute ones, showing the dynamics of an Alpine landscape within a relatively small area. The combination of relative and absolute dating techniques is a promising tool for the reconstruction of landscape history and to detect human influences in high-elevation Alpine areas on siliceous substrates.

RIASSUNTO - *Applicazione di tecniche di datazioni relative e assolute in ambiente alpino* - L'oscillazione climatica e l'evoluzione del paesaggio alpino della Val di Rabbi (Trentino) durante il tardo Pleistocene e l'inizio dell'Olocene sono stati ricostruiti con l'ausilio di tecniche di datazione relativa e assoluta. La ricerca è stata portata avanti in quattro fasi: 1) lo studio iniziale dell'area per la selezione e il campionamento di siti rappresentativi (suoli e massi, tramite foto aeree e carte dei suoli); 2) l'estrazione dai profili della frazione stabile della sostanza organica e datazione al ^{14}C; 3) il confronto tra la datazione al ^{14}C e la datazione al ^{10}Be effettuata su massi rappresentativi; 4) l'aggiunta di tecniche di datazione relativa a quelle assolute, per il riconoscimento di segnali di evoluzione del paesaggio. Correlazioni significative sono state trovate tra i risultati ottenuti con le tecniche di datazione relativa e assoluta, utili per la comprensione della dinamica dell'ambiente alpino in un'area relativamente piccola. La combinazione di tecniche di datazione relativa e assoluta è uno strumento promettente per la ricostruzione della storia naturale e dell'influenza umana nei territori alpini in quota su materiale parentale siliceo.

Key words: Trentino, Alpine soils, ^{14}C, ^{10}Be, dating techniques, weathering, deglaciation
Parole chiave: Trentino, suoli alpini, ^{14}C, ^{10}Be, tecniche di datazione, alterazione, deglaciazione

---

1. INTRODUCTION

The Alpine environment reflects a long history of climate shifts and glaciers oscillation at the end of the last Ice Age (between 20,000 and 11,500 years ago) and during the Holocene period. These events have shaped the landscape as we can see nowadays. The oscillations of the glaciers result in the deposition of morainic sediments, which creates the base on which soil evolution can take place after the retreat of the ice (Strahler & Strahler 1987). The accumulation of organic material in fractures and microtopographic depressions helps the plant establishment and accelerate the local physical and chemical weathering (Phillips *et al.* 2008).

Soils developed on the glacial sediment can be considered representative of the different glacial and depositional phases. Several dating techniques contribute to the understanding of how the landscape has changed during the millennia of its evolution. These techniques can give a relative or an absolute differentiation of the surfaces and of the geomorphological items. Soil pH, development of clay minerals and the process of podzolisation are typical examples of relative dating. In northern Europe podzolisation is a natural outcome of soil development following colonization of bare soil after glaciation (Lundström *et al.* 2000; Egli *et al.* 2003a, 2003b). The podzolisation process is linked to the duration of soil evolution and can be used as a relative indicator of surface age and stability (Briggs *et al.* 2006). Absolute dating techniques give a numerical age (with a certain error). By using them, we can know when a certain object (i.e., a boulder, a moraine) has been deposited (Gosse *et al.* 1995). This gives precious insights about the timing of deposition and the chronology of deglaciation.

Soil organic matter (SOM) contains a stable fraction with an old radiocarbon age. This fraction can resist to natural decomposition for thousands of years, because it is stabilised in the soil mostly by its interaction with the mineral part or by a specific protection due to chemical recalcitrance (Baldock & Skjemstad 2000; Krull *et al.* 2003; Poirer *et al.* 2003; Wiseman & Püttmann 2006; Favilli *et al.* 2008a; Egli *et al.* 2009). SOM is composed of diverse organic material in different stages of decomposition. The heterogeneity of the different organic components is reflected by their highly variable radiocarbon ages. Therefore, the ^{14}C dating of SOM is always difficult to interpret (Rethemeyer *et al.* 2004). Soil organic matter is continuously renewed by the addition of fresh and undecomposed organic material on the surface horizon. This permanent addition results in the rejuvenation of the age, since the radiocarbon dating is always an average value of the ages of the different fractions, which constitute the total SOM (Wang *et al.* 1996). The isolation of the resilient substances, which are produced at the beginning of soil formation, could clarify the soil dynamic processes and open a window on the timing of sediment deposition and of soil development (Scharpenseel & Becker-Heidmann 1992; Favilli *et al.* 2008a).

In our study, we applied a combined methodology of relative and absolute dating techniques in order to understand the natural processes in the investigated area during the glaciers retreat and readvance phases in the Late Pleistocene and Early Holocene. To isolate the oldest SOM fraction we used an H_2O_2-oxidation technique (Plante *et al.*, 2004; Favilli *et al.* 2008a). The ^{14}C dating of the H_2O_2-residues was used to obtain information about the minimum age of soil formation and the oscillation phases of the glaciers during the Late Pleistocene and Early Holocene (Favilli *et al.* 2008a, 2008b; Egli *et al.* 2009). The following step was to test the reliability of the H_2O_2 extraction technique. The ^{14}C age of the resilient SOM fraction was compared with the cosmogenic ^{10}Be age sequence obtained by the surface exposure dating (SED) method applied on several boulders located in the vicinity of the investigated soils (Favilli *et al.* 2008c).

The subsequent step in this research was to verify the exposure and ^{14}C ages by cross-checking them with the results obtained by the relative dating techniques applied on 9 soils in the investigated area (Favilli *et al.* submitted). This procedure guaranteed an extended interpretation, mutual control of the applied methods and a more accurate estimate of possible error sources. The obtained results have shown the high agreements among the different dating techniques and allowed us to hypothesise the glaciers extension during the Lateglacial in Val di Rabbi.

Referring to all these results, in this paper we wanted to bring together and integrate findings from earlier publications (Favilli *et al.* 2008a, 2008b, 2008c, submitted), in order to illustrate the issues related to the use of relative and absolute dating techniques in the Alpine region. We summarize the sampling strategies and laboratory analyses and point out the implications of our results with respect to future applications of this combined methodology in the Alpine setting.

2. INVESTIGATION AREA

The investigation area is located in Val di Rabbi, a lateral valley of Val di Sole, in the south Alpine belt in northern Italy (Fig. 1). Detailed description of investigated area can be found in Favilli *et al.* (2008a). The investigated soils and boulders (Tabs 1-2; Figs 1-3) were situated between 2083 m a.s.l. and 2552 m a.s.l., i.e. close to timberline and in the high-alpine zone. According to the WRB (World Reference

Tab. 1 - Characteristics of the study sites.
Tab. 1 - Caratteristiche dei siti studiati.

Soil profile	Elevation (m a.s.l.)	Aspect (°N)	Slope (%)	Parent material / Location	Vegetation	Land use	WRB (IUSS Working Group 2007)
S1	2100	60	32	Paragneiss / Lateral moraine	*Larix decidua / Juniperus communis*	Natural forest	*Entic Podzol*
S2	2230	70	55	Paragneiss / Lateral moraine	*Rhododendro - vaccinietum extrasilvaticum*	Natural grassland	*Haplic Podzol*
S3	2380	320	5	Paragneiss / Lateral moraine	*Festucetum*	Natural grassland	*Protospodic Leptosol*
S4	2370	300	10	Paragneiss / slope deposits	*Festucetum*	Natural grassland	*Brunic Cambisol*
S5	2083	240	32	Paragneiss / Lateral moraine	*Larix decidua / Juniperus communis*	Natural forest	*Entic Podzol*
S6	2076	5	38	Paragneiss / Lateral moraine	*Larix decidua / Juniperus communis*	Natural forest	*Entic Podzol*
S7	2100	3	43	Paragneiss / Lateral moraine	*Larix decidua / Juniperus communis*	Natural forest	*Umbric Podzol*
S8	2552	200	33	Paragneiss / rockglacier	*Carex curvula / Nardus stricta*	Natural grassland	*Cambic Umbrisol*
S9	2449	90	0	Paragneiss / moraine ridge	*Carex curvula / Nardus stricta*	Natural grassland	*Umbric Podzol*

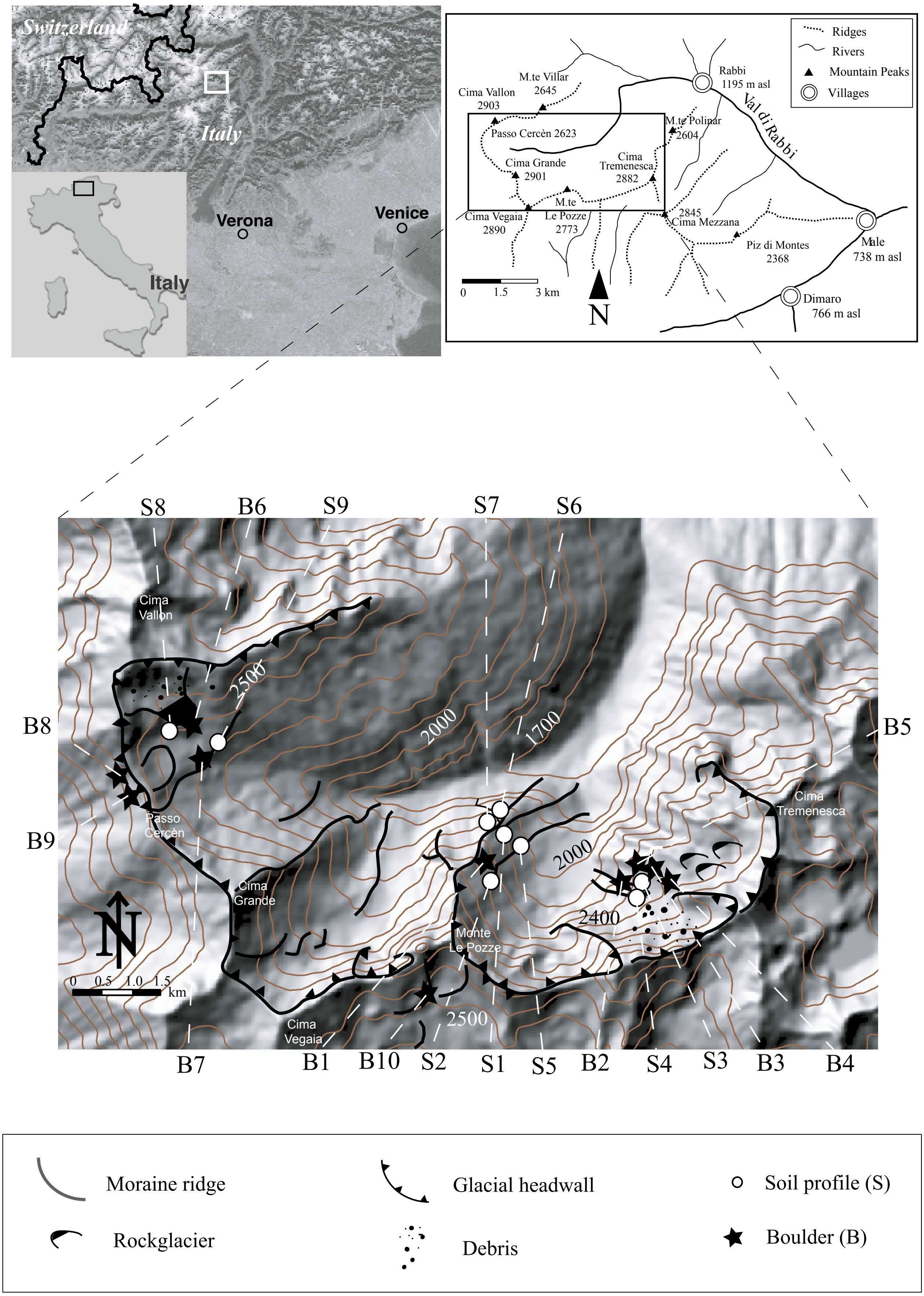

Fig. 1 - Location of the investigation site.
Fig. 1 - Posizione dei siti studiati.

Base, FAO 1998), the soil types were *Entic Podzol*, *Umbric Podzol* and *Haplic Podzol* at lower altitude (2000-2200 m a.s.l.), *Protospodic Leptosol* and *Brunic Cambisol* at around 2300 m a.s.l. and *Cambic Umbrisol* and *Umbric Podzol* at the highest altitude (2500 m a.s.l.).

3. MATERIALS AND METHODS

3.1. *Sampling*

Landscape was investigated with the aim to discover the most representative sampling sites. Soil developed on glacial and periglacial formations like moraines, rock glaciers, debris flows and solifluctions were chosen after a prestudy of the area by aerial photos and soil mapping (Sartori & Mancabelli 2009) (Tab. 1, Fig. 2). This was done in order to sample the most characteristics sites to get precious insights on the reaction and sensitivity of the area in responding to climatic changes and slope processes. Soil material was collected, where possible, down to the BC horizon. Ten large boulders with volumes > 2 m^3 were chosen in order to exclude any long-term effects from slope-movement processes and sampled (Tab. 2, Fig. 3). Quartz sampling strategy can be found in Ivy-Ochs *et al.* (2004).

3.2. *Soil chemistry and physics*

The soil samples were air-dried and sieved to < 2 mm. Total C and N contents of the soil were measured

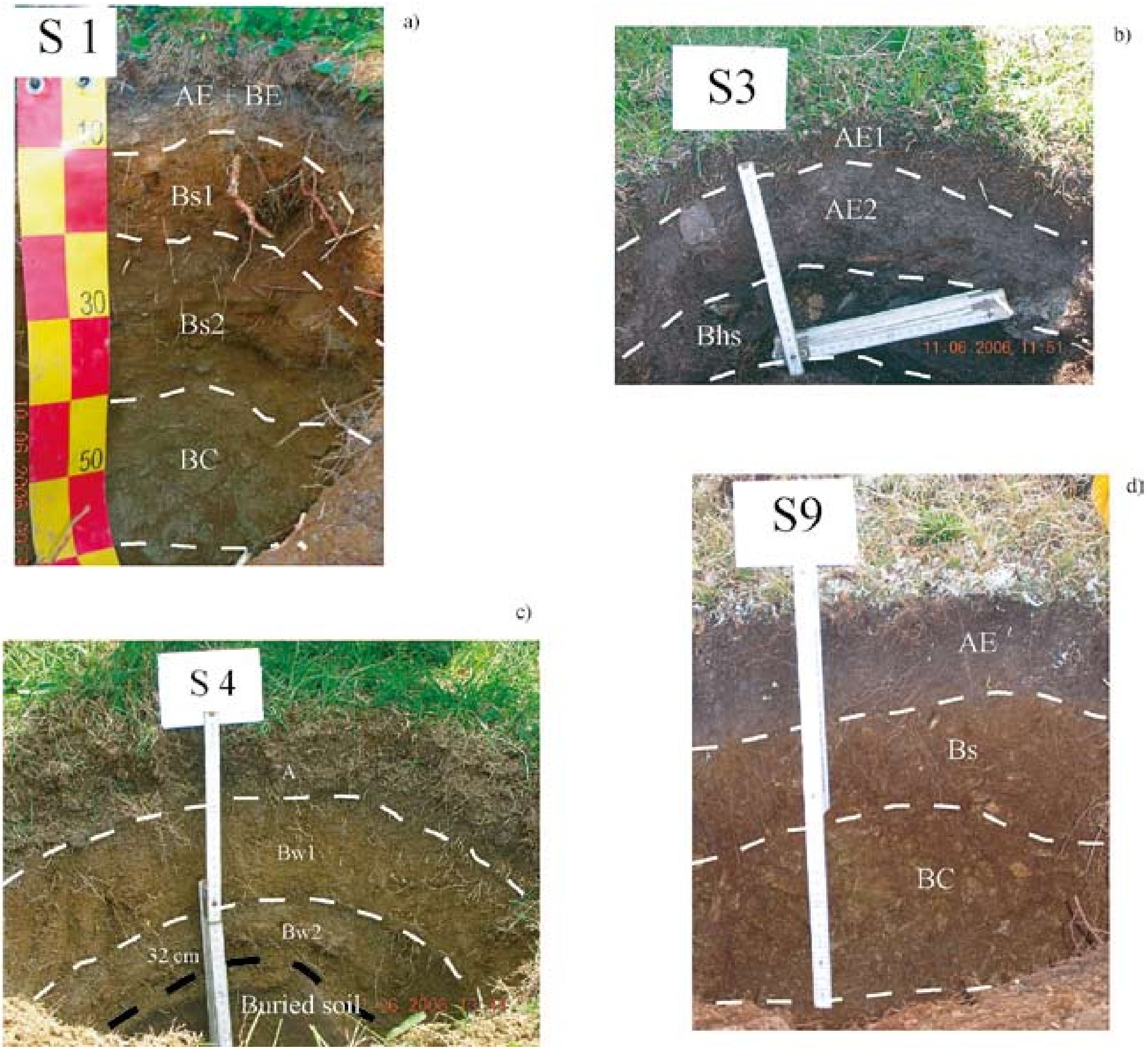

Fig. 2 - a. Soil profile S1, located at 2100 m a.s.l. on a morainic sediment below a *Larix decidua* forest; b. soil profiles S3, located at 2380 m a.s.l. on a morainic sediment; c. soil profile S4, located at 2370 m a.s.l. with indication of the buried horizons; d. soil profile S9, located at 2449 m a.s.l. on a morainic sediment.

Fig. 2 - a. Profilo S1, posizionato a 2100 m s.l.m. su sedimento morenico sotto una foresta di Larix decidua*; b. profilo S3, posizionato a 2380 m s.l.m. su sedimento morenico; c. profilo S4, posizionato a 2370 m s.l.m. con indicazione degli orizzonti sepolti; d. profilo S9, posizionato a 2449 m s.l.m. su sedimento morenico.*

Tab. 2 - List of samples, elevation, latitude of the sample sites, thickness of sample, correction factor for topography, snow, ^{10}Be measured concentration in the sample, measurement error and ^{10}Be date. n.d.= not determined; *= average value of snow cover during 6 months; **= estimated total error including measurement error and the effects of altitude, latitude and topography/depth scaling.

*Tab. 2 - Lista dei campioni, altitudine, latitudine dei siti campionati, spessore dei campioni, fattore di correzione per topografia, neve, concentrazione misurata di Be^{10} nel campione, errore di misurazione ed età (Be^{10}) del campione. n.d.= non misurato; *= copertura media della neve durante 6 mesi; **= stima dell'errore totale incluso errore di misurazione ed effetto della correzione dovuta all'altitudine e alla topografia/profondità.*

Sample	Elevation (m a.s.l.)	Latitude (°N)	Lithology / Location	Sample thickness (cm)	Shield correction	Snow correction (meters)*	^{10}Be (at g^{-1} 1E+5])	Estimated total error** (%)	^{10}Be date (yr)	^{10}Be date (snow corrected) (yr)
B1	2247	46.2263	Gneiss / lateral moraine	3	0.931	1.3	3.23±0.21	10.2	11680±1180	13240±1350
B2	2360	46.2223	Gneiss / moraine crest	5	0.927	0.7	3.25±0.15	8.5	11110±940	11890±1010
B3	2456	46.2223	Gneiss / lateral moraine	5	0.958	0.3	3.15±0.18	7.8	9780±770	9940±770
B4	2446	46.2223	Gneiss / lateral moraine	5	0.959	0.3	2.86±0.19	7.8	8710±680	8850±690
B5	2360	46.2223	Gneiss / lateral moraine	5	0.797	0.7	2.31±0.11	11.8	9190±1090	9840±1160
B6	2552	46.2315	Gneiss / rock glacier	4	0.978	0.5	3.01±0.13	9.6	8720±840	8960±860
B7	2449	46.2302	Gneiss / moraine ridge	5	-	-	-	-	n.d.	n.d.
B8	2597	46.2308	Micaschists / transfluence pass	5	0.986	0.5	4.16±0.20	9.2	11490±1060	12040±1110
B9	2586	46.2308	Micaschists / transfluence pass	5	0.956	0.5	3.84±0.17	7.0	11030±770	11550±810
B10	2453	46.2160	Micaschists / ridge line	5	0.973	0.7	4.22±0.15	5.7	12950±740	13850±790

using a C/H/N analyser (Elementar Vario EL, Elementar Analysensysteme GmbH, Hanau, Germany) on oven-dried (105 °C) and ball-milled fine earth samples. Soil pH (in 0.01 M $CaCl_2$) was determined on air-dried samples of fine earth using a soil solution ratio of 1:2.5. Particle size distribution of the soils was quantified by a combined method consisting of sieving the coarser particles (2000-32 μm) and measuring the finer particles (< 32 μm) by means of an X-ray sedimentometer (SediGraph 5100, Micromeretics, Norcross, GA, USA).

3.3. *Relative dating*

Relative dating techniques using pedogenetic and weathering parameters were applied based on the premise that soil development is time-dependent (Zech *et al.* 2003). The differences in altitude between the sampling sites were minimal and any difference in relative dating could be used as a reflection of the age.

3.3.1. *Soil mineralogy*

The clay fraction (< 2 μm) was obtained from the soil following the procedure presented in Carnicelli *et al.* (1997). Oriented specimens on glass slides were analysed by X-ray diffraction (XRD). The following treatments were performed: Mg saturation, ethylene glycol solvation (EG) and K saturation, followed by heating for 2 h at 335 and 550 °C (Brown & Brindley 1980). Digitised X-ray data was smoothed and corrected for Lorentz and polarisation factors (Moore & Reynolds 1997). Peak separation and profile analysis were carried out by the Origin PFM™ using the Pearson VII algorithm after smoothing the diffraction patterns by a Fourier transform function.

3.3.2. *Calculation of weathering rates*

Total element concentrations in the soil and skeleton were determined by energy-dispersive X-ray fluorescence spectrometry (X-Lab 2000; Spectro, Kleve, Germany) on samples milled to 63 μm. The derivation of mass-balance equations and their application to pedologic processes were discussed in detail by Brimhall & Dietrich (1987) and Chadwick *et al.* (1990), and revised by Egli & Fitze (2000).

3.3.3. *Podzolisation process*

The age-dependent formation and movement of pedogenic iron, aluminium oxides and hydroxides was used to assess the intensity of soil development and to attest surface stability for the formation of typical eluvial and illuvial horizons. The dithionite- (Fe_d, Al_d) and oxalate-extractable (Fe_o, Al_o) iron and aluminium fractions were extracted according to McKeague *et al.* (1971), and analysed by AAS

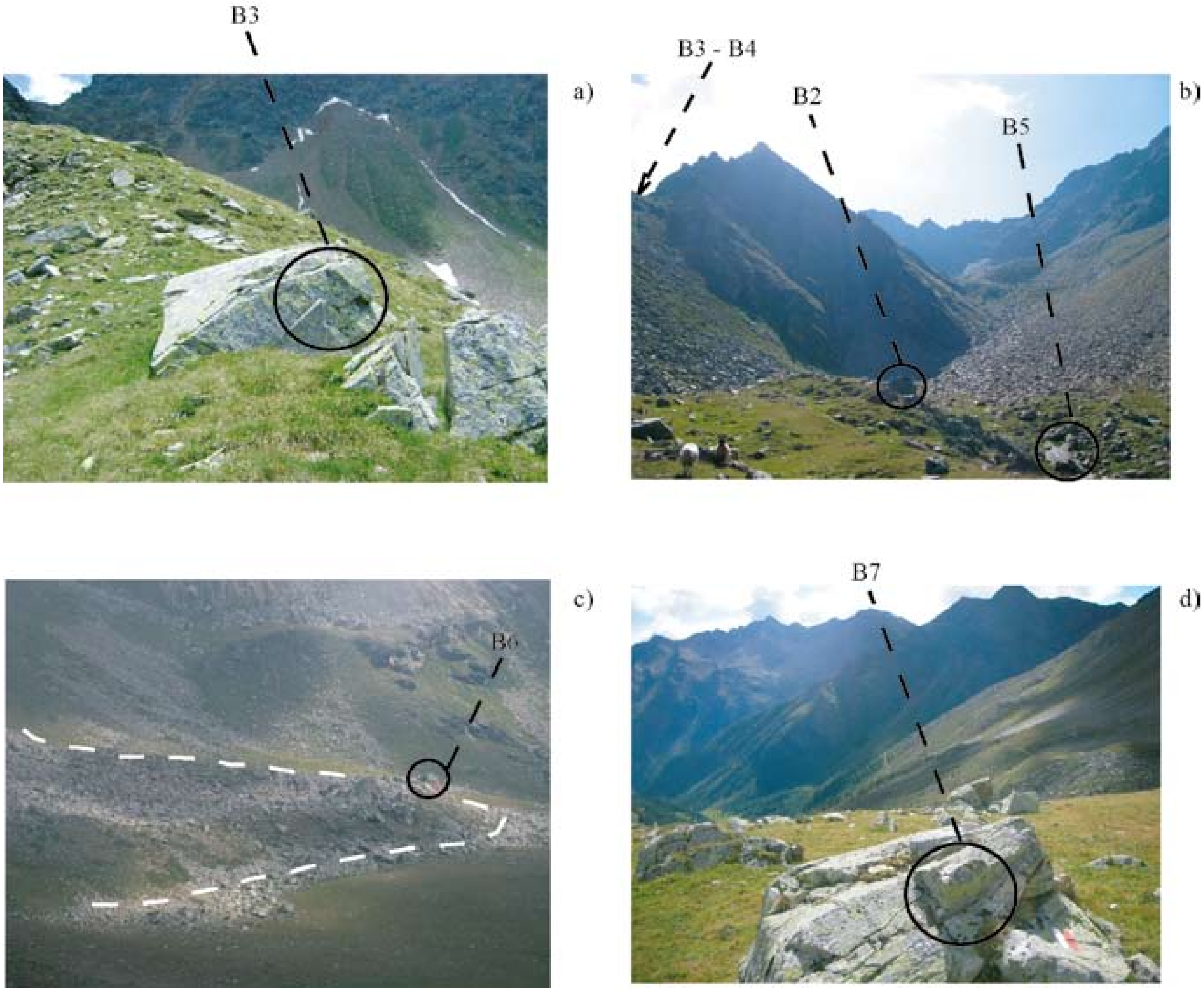

Fig. 3 - a. Location of the boulder B3; b. Location of the boulders B2 and B5; c. Location of the boulder B6 with indication of the inactive rock glacier; d. Location of B7.
Fig. 3 - a. Posizione del masso B3; b. posizione dei massi B2 e B5; c. posizione del masso B6 con indicazione del rock glacier inattivo; d. posizione del masso B7.

(Atomic Absorption Spectrometry – AAnalyst 700, Perkin Elmer, USA).

3.4. *Absolute dating*

Absolute dating was carried on in order to obtain minimum ages of deposition of morainic sediments and of soil formation. Charcoal fragments found in the studied soils were radiocarbon dated to obtain evidences of soil pedogenesis (Carcaillet 2000).

3.4.1. *Isolation of the resilient organic matter*

We compared five chemical extraction techniques referring to previous studies (Plante *et al.* 2004; Eusterhues *et al.* 2005; Mikutta *et al.* 2006; Helfrich *et al.* 2007). The residues obtained after the five tested treatments were chemically analysed and radiocarbon dated (see Favilli *et al.* 2008a for details). The one-week oxidation with 10% H_2O_2 was the most efficient in isolating the oldest organic matter (Favilli *et al.* 2008a). Briefly, air-dried and sieved (< 2 mm) soil was wetted for 10 min with few ml of distilled water in a 250 ml glass beaker. Afterwards, 90 ml of 10% H_2O_2 were added per gram of soil. The procedure was run at a minimum temperature of 50 °C throughout the treatment period. See Favilli *et al.* (2008a) for detailed description of the procedure.

3.4.2. *^{10}Be Cosmogenic Nuclide Dating*

Surface Exposure Dating (SED) was applied on 10 boulders lying on typical representative periglacial forms (moraines, rock glaciers, transfluence passes), using *in situ* cosmogenic ^{10}Be in quartz. Samples were processed using the method of Ivy-Ochs (1996). The ^{10}Be/^{9}Be ratios were measured by AMS (accelerator mass spectrometry) using the Tandem accelerator facility at the Swiss Federal Institute of Technology Zurich (ETHZ). Details of the procedure are given in Favilli *et al.* (2008c).

3.4.3. *Charcoal*

Charcoal fragments were hand picked from the soil material and dried at 40 °C. The individual particles were separated into coniferous and broad-leaved tree species (Schoch 1986), with the aid of a stereo and a reflected-light microscope. The observations were compared with a histological wood-anatomical atlas, using an identification key (Schweingruber 1990).

3.4.4. *Radiocarbon dating*

Necessary preparation and pre-treatment of the sample material for radiocarbon dating was carried out by the ^{14}C laboratory of the Department of Geography at the University of Zurich.

The dating itself was done by AMS with the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology Zurich (ETH).

The calendar ages were obtained using the OxCal 4.0.5 calibration program (Bronk Ramsey 1995, 2001) based on the IntCal 04 calibration curve (Reimer *et al.* 2004). Calibrated ages are given in the 2 σ range (minimum and maximum value).

4. RESULTS

4.1. *Physical characteristics and chemical composition of the soils*

The investigated soils developed on a morainic substratum over a paragneiss parent material. The proportion of rock fragments ranges from 0% up to 68%, increasing with soil depth (Tab. 3), which is typical for Alpine soils (Egli *et al.* 2001a). All investigated soils have a loamy to loamy-sand texture. The physical and chemical characterisation help to distinguish some of the natural slope processes which occurred during the soil evolution. Soil S4 has a polygenetic profile. At 32 cm depth, a buried soil appeared (Fig. 2c). Accordingly, a clear rupture in all physical and chemical characteristics was measurable due to this discontinuity (Tabs 3-4). Due to the high content of skeleton (material > 2 mm in diameter) up to the surface (Tab. 3), the soils S6 and S7 might have been influenced by slope mass movements. These events can be recognized also by the amount of organic carbon in the S7 site, which is almost double in the topsoil compared to S6 and rather constant within the profile (Tab. 4).

4.2. *Absolute dating*

4.2.1. *Radiocarbon age of soil organic matter*

A decreasing age with soil depth was measured in the profiles S1, S5, S8 and S9 (Tab. 5). Soil profile S1, revealing an age of around 16,785-17,840 cal BP, may represent the first stage of deglaciation that occurred in the studied area and the oldest morainic material deposited after the LGM. The other soils belong to younger surfaces and refer to the Bølling-Allerød interstadial and to the Holocene period (Fig. 4). The polygenetic structure of the site S4 was confirmed by the ^{14}C results. Soil formation in the buried layer started around 13,600-13,990 cal BP and ended, due to an accumulation of eroded material, probably slope deposits, between 2370 and 2745 cal BP (Tab. 5). This event

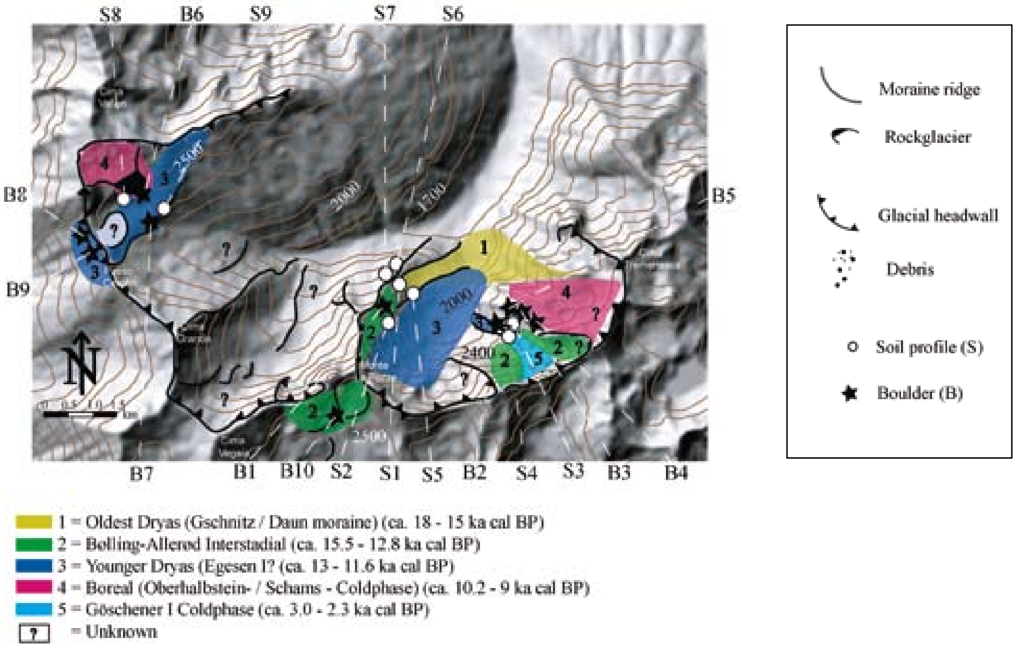

Fig. 4 - Reconstruction of the extension of glaciers and periglacial processes during the Lateglacial/Holocene in the investigated area according to ^{14}C and ^{10}Be ages and location of the investigated soil profiles and boulders (according to the obtained ages and to several authors, e.g., Maisch 1987; Maisch *et al.* 1999; Kerschner *et al.* 1999; Ivy-Ochs *et al.* 2004).

Fig. 4 - Ricostruzione dell'estensione dei ghiacciai nell'area studiata durante il Tardoglaciale, in base alle età del ^{14}C e del ^{10}Be con indicazione della posizione dei suoli e massi studiati (secondo le età ottenute e vari autori: Maisch 1987; Maisch et al. *1999; Kerschner* et al. *1999; Ivy-Ochs* et al. *2004).*

Tab. 3 - Physical characteristics of the investigated soils. [1)]= skeleton= material> 2mm; [2)]= size fractions: sand= 2000-62 µm, silt= 62-2 µm, clay= <2 µm.; n.d.= not determined.

Tab. 3 - Caratteristiche fisiche dei suoli studiati. [1)]*= scheletro= materiale> 2mm;* [2)]*= dimensione delle frazioni: sabbia= 2000-62 µm, limo= 62-2 µm, argilla= <2 µm.; n.d.= non determinato.*

Site	Soil horizon	Depth (cm)	Munsell colour (moist)	Skeleton[1)] (%)	Sand[2)] (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
S1							
	AE	0-4	10YR 3/3	5	455	280	265
	BE	4-8	5YR 4/4	11	515	280	205
	Bs1	8-20	7.5YR 4/4	51	575	286	139
	Bs2	20-45	10YR 4/4	45	671	275	54
	BC	45-60	10YR 5/4	34	n.d.	n.d.	n.d.
S2							
	AE	0-9	7.5YR 2/1	3	397	398	205
	Bhs	9-20	7.5YR 3/3	19	717	209	74
	Bs	20-40	7.5YR 4/3	58	709	252	39
S3							
	AE1	0-4	10YR 2/3	8	457	223	320
	AE2	4-12	10YR 3/2	21	576	212	212
	Bhs	12-20	10YR 4/2	45	638	172	190
S4							
	A	0-8	10YR 3/2	0	352	496	152
	Bw1	8-20	10YR 4/4	1	409	437	154
	Bw2	20-32	10YR 4/4	32	692	258	50
	Ab	32-35	10YR 3/3	2	309	498	193
	Bb	35-40	10YR 4/4	49	839	136	25
S5							
	AE	0-11	10YR 4/3	7	437	302	261
	Bs1	11-26	5YR 4/6	16	551	344	105
	Bs2	26-50	7.5YR 4/6	47	663	258	79
S6							
	AE	8-17	2.5YR 5/1	54	438	417	145
	Bs1	17-38	5YR 4/6	67	561	317	122
	Bs2	38-45	7.5YR 4/6	68	561	317	122
	BC	45-60	10YR 4/6	56	530	353	117
S7							
	AE	5-10	10YR 2/1	43	498	290	212
	Bs1	11-25	10YR 3/3	63	544	323	133
	Bs2	25-50	10YR 3/3	44	536	331	133
	BC	50-60	10YR 3/3	60	532	333	135
S8							
	AE	0-20	7.5YR 3/2	37	486	374	140
	Bs	20-25	5YR 2/4	59	599	360	41
	BC	25-48	10YR 4/6	54	632	345	23
S9							
	AE	0-11	7.5YR 3/2	16	381	416	203
	Bs	11-23	7.5YR 3/3	27	497	400	103
	BC	23-40	7.5YR 4/4	46	654	310	36

Tab. 4 - Chemical characterisation of the investigated soils. n.d.= not determined; o= oxalate extractable content; d= dithionite extractable content.

Tab. 4 - Caratteristiche chimiche dei suoli studiati. n.d.= non determinato, o= contenuto estraibile in ossalato; d= contenuto estraibile in ditionito.

Site	Soil horizon	pH ($CaCl_2$)	Org. C (g kg^{-1})	Total N (g kg^{-1})	C/N	Al$_o$ (g kg^{-1})	Fe$_o$ (g kg^{-1})	Fe$_d$ (g kg^{-1})	Al$_d$ (g kg^{-1})
S1									
	AE	3.7	103.7	5.7	18	1.73	5.57	15.90	2.50
	BE	3.6	61.0	2.9	21	1.91	6.06	20.50	2.80
	Bs1	4.1	39.4	1.8	22	10.27	19.62	44.10	14.70
	Bs2	4.4	17.0	0.7	24	5.84	9.37	21.40	7.30
	BC	4.5	7.5	0.6	12	4.04	1.67	6.90	5.60
S2									
	AE	3.4	184.6	28.1	7	2.78	5.67	14.53	3.94
	Bhs	3.7	63.8	11.8	5	6.31	24.90	45.33	5.96
	Bs	4.1	25.4	8.8	3	6.41	8.81	30.13	10.65
S3									
	AE1	3.4	124.9	6.8	18	2.03	2.47	8.50	2.80
	AE2	3.5	48.0	2.2	22	2.48	4.33	11.00	3.20
	Bhs	3.8	71.4	3.1	23	8.30	13.76	27.10	14.20
S4									
	A	3.8	55.3	3.8	15	3.05	7.05	21.90	5.40
	Bw1	4.0	20.7	1.5	14	2.47	9.61	30.80	5.00
	Bw2	4.1	19.5	1.3	15	1.58	4.21	20.60	3.30
	Ab	3.9	62.0	3.9	16	4.39	6.52	23.10	7.50
	Bb	4.2	9.1	0.5	18	1.57	3.70	15.30	2.70
S5									
	AE	3.5	56.9	2.7	21	2.18	7.13	21.10	3.10
	Bs1	3.8	35.3	1.7	21	6.42	20.19	50.70	9.50
	Bs2	4.3	22.8	1.1	21	6.35	10.08	24.50	8.60
S6									
	AE	3.5	76.5	4.1	19	1.49	3.88	13.54	1.82
	Bs1	4.0	45.3	1.8	25	5.60	16.46	35.81	8.21
	Bs2	4.1	47.6	1.6	30	5.53	15.57	35.18	9.20
	BC	4.2	35.5	1.1	32	4.09	14.42	30.47	6.57
S7									
	AE	3.1	143.9	6.4	22	0.89	1.52	8.06	1.33
	Bs1	3.7	48.5	1.4	35	1.92	4.39	12.64	3.26
	Bs2	3.7	48.3	1.6	30	1.81	3.54	10.43	2.89
	BC	3.7	48.7	1.5	32	1.90	3.64	11.12	3.23
S8									
	AE	3.8	43.0	2.3	19	4.63	6.18	22.82	7.82
	Bs	4.2	29.5	1.4	21	6.21	6.32	19.09	8.69
	BC	4.4	8.0	0.5	16	3.30	1.97	13.92	4.40
S9									
	AE	3.2	56.4	3.8	15	3.15	4.60	12.65	3.04
	Bs	3.8	37.8	1.6	24	7.32	10.74	31.06	8.30
	BC	4.1	17.9	0.7	26	4.08	4.01	18.64	5.91

was inferred from dating root residues in the Ab horizon. Weathered and mixed sediment, containing already organic material (having an age of 8370-9075 cal BP; Tab. 5, Fig. 2c), was deposited on the top of the original soil. The age of the soils S2, S3, S5 and S9 (Tab. 5) refer to the same period and give a general overview of the extent of glaciation at the end of the Younger Dryas (Egesen) (Fig. 4).

4.2.2. *^{10}Be exposure ages*

The ^{10}Be ages of the sampled boulders range between 13,850 and 8850 years (Tab. 2). The sampled boulders were deposited in the time range between the transition Bølling-Allerød / Younger Dryas (around 13-14 ka; Alley *et al.* 1993; Maisch *et al.* 1999; Schaub *et al.* 2008) and the Boreal (9.0-10.2 ka; Maisch *et al.* 1999) chronozones (Fig. 4). The position of the boulders and their age have been explained with respect to the timing of deposition of the morainic till (Figs 3-4). The obtained ^{10}Be ages allowed the deciphering of the periglacial processes which occurred in the investigated area. The boulder B5 (9840±1160 years, ^{10}Be), located near the same moraine where B3 (at 2456 m a.s.l.) was found, has been shifted away from the crest of the morainic sediment (Fig. 3b). The boulder B5 was probably deposited together with B3; in fact, they show a very comparable age (Tab. 2). We assume that the boulder B5 was probably deposited together with B3 and then moved downward due to boulder instability to the actual stable position (e.g., Ivy-Ochs *et al.* 2007).

4.2.3. *Charcoal*

Dating of charcoal fragments from the horizons of one of the most developed profile (S5) gave increasing ^{14}C ages with soil depth with 3080-3380 cal BP in the upper horizon to 10,215-10,510 cal BP in the lower one (Tab. 5). According to the plant succession of Burga (1999), after about 150-300 years of soil formation, *Larix*-trees are able to growth at 2000-2100 m asl of altitude. The measured age of 10,212-10,509 cal BP of the charcoal and the addition of the minimum time necessary for tree-growth would give a minimum age of soil formation of about 10,500-10,800 cal BP. This age corresponds very well to the measured age of the resilient organic matter fraction after the H_2O_2 extraction (in the surface horizon).

4.3. *Relative dating*

4.3.1. *Podzolisation*

All the investigated soils show the tendency to develop toward podzols. Among the nine studied soils, seven of them (S1, S2, S3, S5, S6, S7, S9) showed the typical eluviation and illuviation of Fe and Al (Tab. 4; Figs 2a, 2b, 2d). Soil S3 developed during the last 10,435-11,075 years under strong leaching conditions (Tab. 5). This soils shows a clear downward movement of Fe, Al and organic matter, which have contribute to the formation of a Bhs horizon (Fig. 2b). The present topsoil of S4 (Fig. 2c), which is located near S3 (Fig. 1), showed a first translocation of Fe and Al in the Bw1 horizon (Tab. 4). According to the 2370-2745 years of its undisturbed evolution (Tab. 5), it is clear the tendency to develop towards a typical podzol (Tab. 4; Egli *et al.* 2003a, 2003b). Between the soils S6 and S7, the degree of podzolisation (i.e., migration of Fe and Al forms in the profile) is much more pronounced at the S6 site. The soil S6 shows a clear horizon differentiation, as visible by the Munsell colour (Tab. 3) and presents a double amount of migrated sesquioxides compared to S7. Soil S7 does not show a clear horizon differentiation (Tab. 3).

4.3.2. *Clay minerals*

In the surface soil horizon, smectite and vermiculite compounds were measurable in all podzolised soils except in the top horizons of the soils developed at the highest altitude (S8 and S9) and in the topsoil of the polygenetic soil (S4). The accumulated material on the top of the former soil at S4 (A, Bw1 and Bw2 horizons) showed no major clay mineral transformations. This agrees well with the ^{14}C age (2370-2745 cal BP) derived from the (untreated) roots remaining in the buried horizon (Ab), which gives an approximate date of the burial event. An overview of the identified clay minerals in the investigated soils is given in the table 6. For a detailed description of the clay minerals identification see Favilli *et al.* (2008b, ~~submitted~~).

4.3.3. *Mass balance calculations*

The composition of the investigated material reflects the acidic character of the soils. Minor differences occurred in the chemical composition of the C (BC) horizon between the sites. The Al_2O_3 content of the parent material at the sites located below timberline (S1, S5, S6 and S7) seems to be slightly higher compared to the other sites. Substantial losses of Na, Ca, Mn and Mg up to 70% were observed in the soils S1, S2, S3, S5 and S9 (Tab. 7). The polygenetic soil S4 showed losses in the present top horizon (A horizon) partially up to 70% only in Ca, Mn and Na and slightly lower losses in the buried top horizon (Ab). The open-system mass transport functions have been calculated according to the depth for each soil and element. Generally negative values and thus losses of elements are observed with increasing age of the soil.

5. DISCUSSION

5.1. *Absolute dating techniques*

The H_2O_2 technique was able to remove the younger fractions without affecting the oldest one. The isolated pool of organic matter after the H_2O_2 treatment was an inert fraction of SOM with a mixture of charcoal and organic materials strongly adsorbed on or trapped in clays (Favilli *et al.* 2008a). The residues were enriched in aromatic and aliphatic C and N-containing compounds, as found by other authors (Cheshire *et al.* 2000; Eusterhues *et al.* 2005; Helfrich *et al.* 2007). The ages of the soils and of the exposed boulders gave good indications about the evolution and timing of glacier retreat and – in a general sense – the dynamics of Alpine landscape formation. Soil development in Alpine mountains began after the deposition and exposure of superficial material (Birkeland *et al.* 1987). The combination of absolute dating techniques resulted in good agreement (Favilli *et al.* 2008c), but the processes relating to the stabilisation of OM in Alpine soils are still not completely clear. The age sequences obtained from ^{14}C and ^{10}Be allowed us to make hypotheses about the different

Tab. 5 - Measured and calibrated radiocarbon ages of untreated and H_2O_2- treated soil samples. Calibrated ^{14}C ages are given in the 2 σ range. -= not determined.
Tab. 5 - Età misurate e calibrate dei campioni non trattati e trattati con H_2O_2. *Le età calibrate sono presentate nell'intervallo 2* σ. *-= non determinato.*

Site	Soil type, depth (cm)	Soil horizon	Uncal ^{14}C untreated	Cal ^{14}C untreated	Uncal ^{14}C H_2O_2-treated	Cal ^{14}C H_2O_2-treated	Uncal ^{14}C charcoal	Cal ^{14}C charcoal
S1	*Entic Podzol*							
	0-4	AE	-650±40	Modern	12,470±90	1416-14,965		
	4-8	BE	-30±40	Modern	14,410±110	16,785-17,840		
	8-20	Bs1	780±40	670-775	10,060±85	11,275-11,970		
	20-45	Bs2	2815±45	2795-3065	9735±75	10,790-11,270		
	45-60	BC	-	-	-	-		
S2	*Haplic Podzol*							
	0-9	AE	-	-	2360±50	2207-2700		
	9-20	Bhs	-	-	-			
	20-40	Bs	-	-	9775±70	10,825-11,390		
S3	*Protospodic Leptosol*							
	0-4	AE1	-	-	5115±55	5730-5990		
	4-12	AE2	-	-	-			
	12-20	Bhs	650±50	550-680	9425±75	10,435-11,075		
S4	*Brunic Regosol*							
	0-8	A	-	-	7655±65	8370-8585		
	8-20	Bw1	-	-	-	-		
	20-32	Bw2	-	-	8025±60	8650-9075		
	32-35	Ab	2505±50	2370-2745	11,920±85	13,600-13,990		
	35-40	Bb	-	-	-	-		
S5	*Entic Podzol*							
	0-11	AE	85±50	10-240	9495±75	10,575-11,100	3055±50	3080-3380
	11-26	Bs1	570±50	520-655	8125±70	8790-9295	3065±55	3080-3395
	26-50	Bs2	1525±50	1320-1525	7700±75	8380-8630	9160±70	10,215-10,510
S6	*Entic Podzol*							
	8-17	AE	-	-	2825±50	2795-3080		
	17-38	Bs1	-	-	-	-		
	38-45	Bs2	-	-	4235±50	4585-4875		
	45-60	BC	-	-	-	-		
S7	*Umbric Podzol*							
	5-10	AE	-	-	2880±50	2870-3200		
	11-25	Bs1	-	-	-	-		
	25-50	Bs2	-	-	4710±50	5320-5585		
	50-60	BC	-	-	-	-		
S8	*Cambic Umbrisol*							
	0-20	AE	-	-	8195±60	9010-9400		
	20-25	Bs	-	-	-	-		
	25-48	BC	-	-	6445±55	7270-7435		
S9	*Umbric Podzol*							
	0-11	AE	-	-	9795±85	10,795-11,600		
	11-23	Bs	-	-	-	-		
	23-40	BC	-	-	7200±70	7875-8175		

stadial and interstadial phases that occurred in the investigated area and about the glaciers oscillations during the Lateglacial (Fig. 4).

The investigation area experienced deglaciation between 18,000 and 9000 cal BP, with several phases of retreat and readvance. All the events we recognised in this work contributed to the shaping of the area and helped us to understand how this valley reacted to past climatic shifting.

The portion of the Val di Rabbi we studied is mostly covered by Quaternary deposits (Fig. 5) over a paragneiss/mica schists parent material. The age of these deposits refers to the Late Pleistocene and Early Holocene period, according to our analyses (Tabs 2, 5). The highest part of the investigated area are not fully covered by glacial deposits, which are present up to 2300 m a.s.l. in the north-facing side (soils S1-S5; boulders B1-B5) and up to 2600 m a.s.l. in the east-and south-facing side (soils S8, S9; boulders B6, B7 and B10) (Figs 1, 4, 5). Deglaciation processes in Val di Rabbi were far advanced around 14,000 cal BP, reaching 2453 m a.s.l. in the south-facing side (boulder B10) and 2370 m a.s.l. in the north-facing side (site S4). Glacier oscillations have affected the highest part of the region until about 9000 cal BP. The age around 13.5-14 ka (B1) does not fit perfectly with the beginning of the Younger Dryas readvance phase (Maisch *et al*. 1999). This boulder required more than 10% of snow correction to the exposure age with an assumed snow density of 0.3 g cm^{-3}. Snow is the most common cause for surface coverage corrections and its presence on the surface reduces the cosmic radiation (Gosse & Phillips 2001). The mean snow cover duration was estimated according to Auer *et al.* (2003) and to climatic data supplied by the Provincia Autonoma di Trento (Dipartimento Protezione Civile e Tutela del Territorio – Ufficio Previsioni e Organizzazione). In our case the snow correction increased some of the exposure ages significantly (Favilli *et al.* 2008c, ~~submitted~~). Snow depth during the Lateglacial and Holocene is difficult to quantify (Kelly *et al.* 2004). This boulder may have been deposited early on during the Egesen stadial or it may have been deposited during the Daun stadial (Maisch *et al.* 1999).

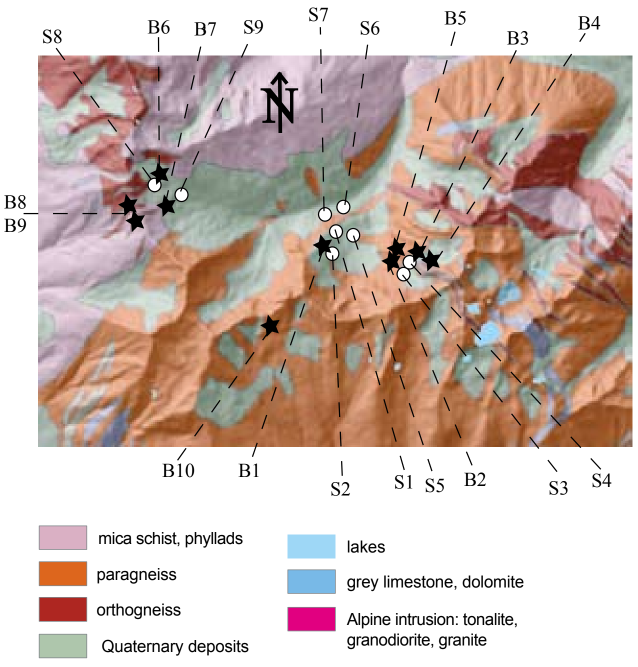

Fig. 5 - Overview of the investigated area with indications about the geology and the locations of the sites.

Fig. 5 - Vista generale dell'area studiata con indicazione della geologia e della localizzazione dei siti.

The distinct warming of climate after the Boreal chronozone (around 9000 years ago) gave rise to a rapid melting of the glaciers and enabled the Mesolithic human settlements up to the main Alpine range (Bassetti & Angelucci 2007). No morainic sediments were dated back to the Little Ice Age (LIA) glacial phases (Ivy-Ochs *et al.* 2008). With the absolute dating of the area it was possible to detect some local periglacial processes which interested the area until recent times (i.e., burial of soil S4).

5.2. *Relative dating techniques*

Podzolisation processes are going on in these soils, even in the ones which do not show a clear albic and a spodic horizon (Tab. 4). Eluviation and illuviation of Fe and Al forms were evident in most soils. With increasing time of soil development, more Al and Fe migrate and accumulate in the spodic horizon. The downward migration of Fe and Al and the advance in the podzolisation process are a function of the weathering stage and of the time since exposure (Tabs 4, 7). Therefore, the migration of Fe and Al in the profile seems to be a good indicator of the soil age and of the surface stability (Briggs *et al.* 2006).

Formation and transformation reactions of clay minerals delineate also the weathering stage of the investigated soils. According to Egli *et al.* (2001b), clay mineral transformations mainly occur within the first 3000 years of soil formation and distinct amounts of smectite can be discernible in well developed soils after 8000 years (Tab. 6). The formation of smectite can be traced back to the transformation of chlorite and mica over transitional steps such as hydroxy-interlayered vermiculite (or smectite), irregularly interstratified mica-vermiculite or mica-smectite (Righi *et al.* 1999; Egli *et al.* 2003b). The presence of smectite in soils is due to strong leaching and weathering conditions (Carnicelli *et al.* 1997; Mirabella & Sartori 1998; Egli *et al.* 2003b), and can be used as an age indicator. The 2600 years time span of the present soil surface of S4 (Tab. 5) was obviously not sufficiently long for the development of major amounts of secondary minerals (Tab. 6).

Mass balance calculation indicated that extensive mineral weathering resulted in significant losses of Si, major base cations, Al and Fe (Tab. 7). These mass balances could be related to the weathering degree and time of exposure. The most weathered soils (S1, S2, S3 and S5), which developed within a glacial cirque are podzolised, have a high radiocarbon age and high element losses. Chemical and mineralogical data of the soil profile S7 suggest that this soil was affected by greater disturbances compared to S6 during the 5000 years of its evolution. Chemical weathering, therefore, supports the findings obtained from numerical dating.

6. CONCLUSIONS

Here we present a methodology for understanding Late Pleistocene and Holocene Alpine landscape evolution.

The H_2O_2 technique is able to isolate the resilient fraction of the soil organic matter (SOM). The chemical characterisation of the organic residues is in line with the findings of others about the resilient fraction of the organic matter (see Favilli *et al.* 2008a and references therein). Further research about the H_2O_2 resistant organic fraction is needed, also for developing new extraction methods.

The radiocarbon dating of the resilient organic matter gives reliable ages about an ice-free surface and the first stages of soil organic matter formation. For a better interpretation of the obtained ages, the data have to be compared with the age estimation from other relative or absolute (numerical) dating techniques.

Tab. 6 - Minerals in the clay fraction of the investigated soil horizons: an overview n.d.= not determined; (+)= traces (0-5%); += present in significant amount (5-20%); ++= present in high amount (> 20%); (-)= not present; [a] Smec = smectite; Verm = vermiculite; HIV= hydroxy-interlayered vermiculite.

Tab. 6 - Minerali nella frazione argillosa degli orizzonti del suolo studiati: visione generale. n.d.= non determinato; (+)=tracce (0-5%); += presente in quantità significative (5-20%); ++= presente in grandi quantità (> 20%); (-)=non presente; [a] Smec= smentite; Verm= vermicultite; HIV= vermiculite intercalata con idrossido.

Site	Soil horizon	Smec[a]	Verm[a]	Mica/smec	mica/HIV	HIV[a]	Chlorite	Mica	Kaolinite
S1	AE	++	+	+	+	(+)	-	++	+
	BE	+	+	++	-	+	-	++	+
	Bs1	+	+	+	+	+	+	++	+
	Bs2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	BC	-	+	-	++	(+)	+	++	(+)
S2	AE	+	++	++	-	+	-	+	+
	Bhs	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Bs	-	+	-	++	+	(+)	+	+
S3	AE1	++	+	++	++	+	-	+	+
	AE2	+	++	-	-	-	-	++	+
	Bhs	+	-	++	+	(+)	+	++	+
S4	A	-	+	-	++	-	+	++	+
	Bw1	-	+	-	-	-	+	++	++
	Bw2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Ab	++	++	-	-	-	+	++	+
	Bb	-	+	-	-	+	+	++	++
S5	AE	+	(+)	++	+	+	-	++	+
	Bs1	++	+	+	+	+	+	++	+
	Bs2	+	+	++	++	-	+	++	+
S6	AE	++	(+)	++	-	+	(+)	++	+
	Bs1	+	+	++	+	(+)	+	++	+
	Bs2	+	+	++	+	+	+	++	+
	BC	-	++	-	+	+	+	+	+
S7	AE	++	(+)	++	+	+	-	++	+
	Bs1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Bs2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	BC	+	+	+	++	+	-	++	+
S8	AE	(+)	++	-	-	++	+	+	+
	Bs	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	BC	-	++	-	+	(+)	+	++	+
S9	AE	(+)	++	-	-	-	-	++	+
	Bs	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	BC	-	+	-	++	+	+	++	+

The ^{10}Be age sequence and the ^{14}C ages of resilient OM are in good agreement.

Clay minerals are time-dependent. Their development in representative soils enables a relative differentiation of the soil surfaces and avoids possible misinterpretations of the ^{14}C ages (of resilient OM).

Soil mass balance analysis gives important information about the weathering mechanisms which occurred since

Tab. 7 - Strain coefficient ($\varepsilon_{i,w}$) and open-system mass transport function (τ) for each element investigated with respect to the sites and soil depth.

Tab. 7 - Coefficiente di deformazione ($\varepsilon_{i,w}$) e funzione di trasporto di massa del sistema aperto (τ) per ogni elemento investigato in relazione al sito e alla profondità.

Site	Horizons	Depth (cm)	$\varepsilon_{i,w}$	Si	Al	Fe	Mn	Mg	Ca	Na	K
S1											
	AE	0-4	0.36	-0.24	-0.25	-0.49	-0.28	-0.65	-0.03	-0.23	-0.29
	BE	4-8	0.27	-0.20	-0.21	-0.38	-0.25	-0.65	-0.26	-0.26	-0.26
	Bs1	8-20	0.90	-0.11	-0.07	0.20	0.16	-0.28	0.02	-0.01	-0.14
	Bs2	20-45	0.31	0.10	-0.02	0.11	0.14	-0.16	0.68	0.17	-0.14
	BC	45-60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S2											
	AE	0-9	0.66	-0.29	-0.33	-0.48	-0.71	-0.73	-0.50	-0.30	-0.25
	Bhs	9-20	0.15	-0.36	-0.27	-0.07	-0.47	-0.52	-0.54	-0.39	-0.21
	Bs	20-40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S3											
	AE1	0-4	0.24	-0.17	-0.20	-0.61	-0.54	-0.51	-0.41	-0.10	-0.17
	AE2	4-12	0.06	-0.07	-0.11	-0.46	-0.17	-0.35	-0.21	-0.13	-0.08
	Bhs	12-20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S4											
	A	0-8	0.26	-0.37	0.07	0.13	-0.64	0.04	-0.67	-0.51	0.57
	Bw1	8-20	0.20	-0.37	0.09	0.26	-0.63	0.11	-0.66	-0.59	0.62
	Bw2	20-32	0.49	-0.24	0.00	0.06	-0.36	-0.01	-0.40	-0.34	0.37
	Ab	32-35	0.63	0.03	-0.01	0.02	-0.19	0.05	-0.11	-0.12	0.26
	Bb	35-40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S5											
	AE	0-11	0.29	-0.27	-0.21	-0.42	-0.39	-0.54	-0.44	-0.30	-0.23
	Bs1	11-26	0.29	-0.23	-0.16	0.19	0.02	-0.29	-0.37	-0.04	-0.19
	Bs2	26-50	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S6											
	AE	8-17	0.21	-0.16	-0.09	-0.27	-0.18	0.02	0.29	0.15	-0.24
	Bs1	17-38	-0.12	-0.13	0.01	0.19	0.13	0.51	-0.10	-0.03	-0.02
	BC	45-60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S7											
	AE	5-10	0.70	-0.15	0.01	0.06	-0.19	0.04	0.14	-0.10	0.02
	Bs1	11-25	0.51	-0.02	-0.02	0.00	-0.04	0.17	0.39	0.09	-0.06
	BC	50-60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S8											
	AE	0-20	0.73	0.01	0.03	0.00	-0.19	-0.31	-0.32	0.12	-0.01
	BC	25-48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S9											
	AE	0-11	1.21	-0.25	-0.22	-0.59	-0.77	-0.73	-0.80	-0.39	-0.23
	BC	23-40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

the Lateglacial. This method provides detailed insights into the processes of a soil and also indication about its age.

The combined methodology here presented offers new perspectives in deciphering landscape history. Applying together a relative and an absolute differentiation of the surfaces, this procedure is a promising tool for a better understanding of the geomorphology and palaeoclimate of relatively small catchments in Alpine environments. Further applications of the methodology to other Alpine sites is needed to check the reliability of the procedure and to improve the Alpine chronology of the Lateglacial.

All the obtained ages gave a picture of the landscape evolution and the chronology of deglaciation of the investigated area.

ACKNOWLEDGEMENTS

This research was supported by a grant from the *Stiftung für wissenschafliche Forschung* of the University of Zurich. We are indebted to I. Woodhatch, W. Schoch and B. Kägi for the support in the laboratory.

REFERENCES

Alley R.B., Meese D.A. & Shuman C.A., 1993 - Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature*, 362: 527-529.

Auer I., Böhm R., Potzmann R. & Ungersböck M., 2003 - Änderung der Frosthäufigkeit in Österreich. *Terra Nostra*, 2003/6: 25-29. Schriften der Alfred Wegener Stiftung Selbstverlag der Alfred Wegener Stiftung, Berlin.

Baldock J.A. & Skjemstad J.O., 2000 - Role of the mineral matrix and minerals in protecting organic materials against decomposition. *Organ. Geochem.*, 31: 697-710.

Bassetti M. & Angelucci D.E., 2007 - The landscape evolution of the Adige region from the Alpine Last Glacial Maximum to mid-Holocene times. 49th Annual Meeting of the Hugo Obermaier Society for Quaternary Research and Archaeology of the Stone Age, Trento, 10th-14th April, 2007. Hugo Obermaier-Gesellschaft, Erlangen.

Birkeland P.W., Burke R.M. & Shroba R.R., 1987 - Holocene Alpine soils in Gneissic Cirque Deposits, Colorado Front Range, U.S. *Geological Survey Bulletin*, 1590E: 21 pp.

Briggs C.A.D., Busacca A.J. & McDaniel P.A., 2006 - Pedogenic processes and soil-landscape relationships in North Cascades National Park, Washington. *Geoderma*, 137: 192-204.

Brimhall G.H. & Dietrich W.E., 1987 - Constitutive mass balance relations between chemical composition, volume, density, porosity, and strain in metasomatic hydrochemical sistems: results on weathering and pedogenesis. *Geochim. Cosmochim. Acta*, 51: 567-587.

Bronk Ramsey C., 1995 - Radiocarbon calibration and analysis of stratigraphy: The OxCal program. *Radiocarbon*, 37: 425-430.

Bronk Ramsey C., 2001 - Development of the radiocarbon calibration program OxCal, *Radiocarbon*, 43: 355-363.

Brown G. & Brindley G.W., 1980 - X-ray diffraction procedures for clay mineral identification. In: Brindley, G.W. & Brown G. (eds), *Crystal Structure of Clay Minerals and their X-ray Identification.* Mineralogical Society, London: 305-360.

Burga C., 1999 - Vegetation development on the glacier forefield Morteratsch (Switzerland). *Appl. Veget. Sci.*, 2: 17-24.

Carcaillet C., 2000 - Soil particles reworking evidences by AMS ^{14}C dating of charcoal. *Earth and Plan. Sci.*, 332: 21-28.

Carnicelli S., Mirabella A., Cecchini G. & Senesi G., 1997 - Weathering of chlorite to a low-charge expandable mineral in a spodosol on the Apennine mountains, Italy. *Clays and Clay Min.*, 45: 28-41.

Chadwick O.A., Brimhall G.H. & Hendricks D.M., 1990 - From a black to a gray box – a mass balance interpretation of pedogenesis. *Geomorphology*, 3: 369-390.

Egli M. & Fitze P., 2000 - Formulation of pedologic mass balance based on immobile elements: a revision. *Soil Sci.*, 165: 437-443.

Egli M., Mirabella A. & Fitze P., 2001a - Weathering and evolution of soils formed on granitic, glacial deposits: results from chronosequences of Swiss Alpine environments. *Catena*, 45: 19-47.

Egli M., Mirabella A. & Fitze P., 2001b - Clay mineral formation in soils of two different chronosequences in the Swiss Alps. *Geoderma*, 104: 145-175.

Egli M., Mirabella A., Sartori G. & Fitze P., 2003a - Weathering rates as a function of climate: results from a climosequence of the Val Genova (Trentino, Italian Alps). *Geoderma*, 111: 99-121.

Egli M., Mirabella A. & Fitze P., 2003b - Formation rates of smectite derived from two Holocene chronosequences in the Swiss Alps. *Geoderma*, 117: 81-98.

Egli M., Sartori G., Mirabella A., Favilli F., Giaccai D. & Delbos E., 2009 - Effect of north and south exposure on organic matter in high Alpine soils. *Geoderma*, 149: 124-136.

Eusterhues K., Runpel C. & Kögel-Knabner I., 2005 - Stabilization of soil organic matter isolated via oxidative degradation. *Org. Geochem.*, 36: 1567-1575.

FAO (Food and Agriculture Organization of the United Nations) 1998 - *World Reference Base for Soil Resources. WRB*. World Soil Resources Reports 84, FAO, Rome.

Favilli F., Egli M., Cherubini P., Sartori G. & Haeberli W., 2008a - Comparison of different methods of obtaining a resilient organic matter fraction in Alpine soils. *Geoderma*, 145: 355-369.

Favilli F., Egli M., Cherubini P., Mirabella A., Sartori G. & Giaccai D., 2008b - High Alpine landscape evolution in Val di Sole (Trentino, Italy) during the Holocene based on charcoal, soil chemistry and mineralogy. In: *Klimaveränderungen auf der Spur*. Europäisches Tourismus Institut, Samedan: 18-37.

Favilli F., Egli M., Brandova D., Ivy-Ochs S., Kubik P.W., Maisch M., Cherubini P. & Haeberli W., (2008c) - Combination of numerical dating techniques using ^{10}Be in rock boulders and ^{14}C in resilient soil organic matter for reconstructing glacial and periglacial processes in a high alpine catchment during the late Pleistocene and early Holocene. *Radiocarbon* (in press).

Favilli F., Egli M., Brandova D., Ivy-Ochs S., Kubik P.W., Cherubini P., Mirabella A., Sartori G., Giaccai D. & Haeberli, W., (submitted) - Combined use of relative and absolute dating techniques for detecting signals of Alpine landscape evolution during the late Pleistocene and early Holocene. *Geomorphology*.

Gosse J.C., Klein J., Evenson E.B., Lawn B. & Middleton R., 1995 - Beryllium-10 dating of the duration and retreat of the last Pinedale glacial sequence. *Science*, 268: 1329-1333.

Gosse J.C. & Phillips F.M., 2001 - Terrestrial in situ cosmogenic nuclides: theory and application. *Quat. Sci. Rev.*, 20: 1475-1560.

Helfrich M., Flessa H., Mikutta R., Dreves A. & Ludwig B., 2007 - Comparison of chemical fractionations methods for isolating stable soil organic carbon pools. *Eur. J. Soil Sci.*, 58: 1316-1329.

Ivy-Ochs S., 1996 - *The dating of rock surfaces using in situ produced ^{10}Be, ^{26}Al and ^{36}Cl, with examples from Antarctica and the Swiss Alps.* Ph.D. Thesis, Universität Zürich: 196 pp.

Ivy-Ochs S.D., Schäfer J., Kubik P.W., Synal H.A. & Schlüchter C., 2004 - Timing of deglaciation on the northern Alpine foreland (Switzerland). *Eclogae geol. Helv.*, 97: 47-55.

Ivy-Ochs S., Kerschner H. & Schlücter C., 2007 - Cosmogenic nuclides and the dating of Lateglacial and Early Holocene glacier variations: the Alpine perspective. *Quat. Int.*, 164: 53-63.

Ivy-Ochs S., Kerschner H., Reuther A., Preusser F., Heine K., Maisch M., Kubik P.W. & Schlüchter C., 2008 - Chronology of the last glacial cycle in the European Alps. *J. Quat. Sci.*, 23: 559-573.

Kelly M.D., Kubik P.W., Von Blackenburg F. & Schlüchter C., 2004 - Surface exposure dating of the Great Aletsch Glacier Egesen moraine system, western Swiss Alps, using the cosmogenic nuclide ^{10}Be. *J. Quat. Sci.*, 19: 431-441.

Kerschner H., Ivy-Ochs S. & Schlüchter C., 1999 - Paleoclimatic interpretation of the early late-glacial glacier in the Gschnitz valley, central Alps, Austria. *Ann. Glaciol.*, 28: 135-140.

Krull E.S., Baldock J.A. & Skjemstad J.O., 2003 - Importance of mechanisms and processes of the stabilization of soil organic matter for modeling carbon turnover. *Funct. Plant Biol.*, 30: 207-222.

Lundström U.S., van Breemen V. & Bain D., 2000 - The podzolization process. A review. *Geoderma*, 94: 91-107.

Maisch M., 1987 - Zur Gletschergeschichte des alpinen Spätglazials: Analyse und Interpretation von Schneegrenzdaten. *Geogr. Helv.*, 42: 63-71.

Maisch M., Wipf A., Denneler B. Battaglia J. & Benz C., 1999 - Die Gletscher der Schweizer Alpen. Gletscherhochstand 1850, aktuelle Vergletscherung, Gletscherschwund-Szenarien. *Schlussbericht NFP 31 Projekt. Eidgenössische Technische Hochschule,* Zürich.

McKeague J.A., Brydon J.E. & Miles N.M., 1971 - Differentiation of forms of extractable iron and aluminium in soils. *Soil Sci. Soc. Am. Proc.*, 35: 33-38.

Mikutta R., Kleber M., Torn M.S. & Jahn R., 2006 - Stabilization of organic matter: association with minerals or chemical recalcitrance? *Biogeochemistry*, 77: 25-56.

Mirabella A. & Sartori G., 1998 - The effect of climate on the mineralogical properties of soils from the Val Genova valley – Trentino (Italy). *Fres. Env. Bull.*, 7: 478-483.

Moore D.M. & Reynolds R.C., 1997 - *X-ray Diffraction and the Identification and Analysis of Clay Minerals*. 2nd ed. Oxford Univ. Press, New York.

Phillips J.D., Turkington A.V. & Marion D.A., 2008 - Weathering and vegetation effects in early stages of soil formation. *Catena*, 72: 21-28.

Plante A.F., Chenu C., Balabane M., Mariotti A. & Righi D., 2004 - Peroxide oxidation of clay-associated organic matter in a cultivation chronosequence. *Eur. J. Soil Sci.*, 55: 471-478.

Poirer N., Derenne S., Balesdent J., Mariotti A., Massiot D. & Largeau C., 2003 - Isolation and analysis of the non-hydrolysable fraction of a forest soil and an arable soil (Lacadée, southwest France). *Eur. J. Soil Sci.*, 54: 243-255.

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 G., Manning S., Bronk Ramsey C., 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, 0-26 cal kyr BP. *Radiocarbon*, 46: 1029-1058.

Rethemeyer J., Grootes P.M., Bruhn F., Andersen N., Nadeau M.J., Kramer C. & Gleixner G., 2004 - Age heterogeneity of soil organic matter. *Nuc. Instr. Meth. in Phys. Res.*, *B*, 223-224: 521-527.

Righi D., Huber K. & Keller C., 1999 - Clay formation and podzol development from post glacial moraines in Switzerland. *Clay Min.*, 34: 319-332.

Sartori G. & Mancabelli A., 2009 - *Carta dei suoli del Trentino (scala 1:250.000).* Museo Tridentino di Scienze Naturali, Trento.

Scharpenseel H.W. & Becker-Heidmann P., 1992 - Twenty-five years of radiocarbon dating soils: paradigm of erring and learning. *Radiocarbon*, 34: 541-549.

Schaub M., Büntgen U., Kaiser K.F., Kromer B., Talamo S., Andersen K.K. & Rasmussen S.O., 2008 - Lateglacial environmental variability from Swiss tree rings. *Quat. Sci. Rev.*, 27, 29-41.

Schoch W., 1986 - *Wood and charcoal analysis*. In: Berglund B.E. (ed.), *Handbook of Holocene, Palaeoecology and Palaeohydrology.* JohnWiley and Sons Ltd, Chichester, UK: 619-626 pp.

Schweingruber FH., 1990. *Anatomie europäischer Hölzer. - Anatomy of European woods.* Verlag, Bern - Stuttgart: 800 pp.

Strahler A.N. & Strahler A.H., 1987 - *Modern Physical Geography.* 3rd Edition. John Wiley and Sons, New York: 544 pp.

Wang Y. & Amundson R., 1996 - Radiocarbon Dating of Soil Organic Matter. *Quat. Res.*, 45: 282-288.

Wiseman C.L.S. & Püttmann W., 2006 - Interactions between mineral phases in the preservation of soil organic matter. *Geoderma*, 134: 109-118.

Zech W., Glaser B., Abrammowski U. Dittmar C. & Kubik P.W., 2003 - Reconstruction of the Late Quaternary Glaciation of the Macha Khola valley (Gorkha Himal, Nepal) using relative and absolute (^{14}C, ^{10}Be, dendrochronology) dating techniques. *Quat. Sci. Rev.*, 22: 2253-2265.