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COMBINATION OF NUMERICAL DATING TECHNIQUES USING ^{10}Be IN ROCK BOULDERS AND ^{14}C OF RESILIENT SOIL ORGANIC MATTER FOR RECONSTRUCTING THE CHRONOLOGY OF GLACIAL AND PERIGLACIAL PROCESSES IN A HIGH ALPINE CATCHMENT DURING THE LATE PLEISTOCENE AND EARLY HOLOCENE

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ABSTRACT. Glacier fluctuations and paleoclimatic oscillations during the Late Quaternary in Val di Rabbi (Trentino, northern Italy) were reconstructed using a combination of absolute dating techniques (^{14}C and ^{10}Be) and soil chemical characterization. Extraction and dating of the stable fraction of soil organic matter (SOM) gave valuable information about the minimum age of soil formation and contributed to the deciphering of geomorphic surface dynamics. The comparison of ^{10}Be surface exposure dating (SED) of rock surfaces with the ^{14}C ages of resilient (resistant to H_2O_2 oxidation) soil organic matter gave a fairly good agreement, but with some questionable aspects. It is concluded that, applied with adequate carefulness, dating of SOM with ^{14}C might be a useful tool in reconstructing landscape history in high Alpine areas with siliceous parent material. The combination of ^{14}C dating of SOM with SED with cosmogenic ^{10}Be (on moraines and erratic boulders) indicated that deglaciation processes in Val di Rabbi were already ongoing by around 14,000 cal BP at an altitude of 2300 m asl and that glacier oscillations might have affected the higher part of the region until about 9000 cal BP. ^{10}Be and ^{14}C ages correlate well with the altitude of the sampling sites and with the established Lateglacial chronology.

INTRODUCTION

Clear evidence of distinct climatic conditions, such as moraines and rock glaciers, make high mountain areas unique archives of past climate change effects on landscape dynamics. Since the initial work of Penck and Brückner (1901/1909) on Alpine glaciations and the structure of glacier retreat at the end of the last glaciation (the Würmian), numerous authors have worked on ice-age glacial stratigraphy (e.g. Keller and Krayss 1987, 2005; Schlüchter 1988, 2004), on the Lateglacial ice decay (e.g. Maisch 1981, 1987; Schoeneich 1999; Kerschner et al. 1999; Ivy-Ochs et al. 2004, 2006a,b, 2007), and also in detail on Holocene glacier fluctuations in the Alps (e.g. Holzhauser 1984; Hormes et al. 2001; Holzhauser et al. 2005; Joerin et al. 2006, 2008). While the general sequence and the related morphostratigraphic positions of the various stadials are quite widely accepted, reliable dating exist only for a few of them (Heitz et al. 1982; Maisch 1987; Schlüchter 1988; Kerschner et al. 1999; Ivy-Ochs et al. 2006a,b, 2007, 2008). This lack of direct dating reflects the various limitations of the applied dating methods and the rareness of optimal sampling sites (representative of the investigated site). The link between distinct moraine sequences and the absolute timescale is still highly speculative, especially in the central Eastern Alps. The timescales of the formation of the landscape reach as far back as the alpine orogeny, but mainly relate to the Lateglacial ice retreat at the end of the last Ice Age (20,000–11,500 yr BP) and include also the entire Holocene period. The Alpine area offers interesting geomorphological settings with pronounced glacial and periglacial features, such as Lateglacial moraines, erratic boulders, and rock glaciers, that give the opportunity to date the retreat stages of the glaciers and to investigate the subsequent geomorpho-

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logical modifications during the Holocene. Surface exposure dating (SED) is based on the *in situ* production and accumulation of cosmogenic nuclides (e.g. ^{10}Be, ^{26}Al, ^{36}Cl) within the first few decimeters of an exposed rock surface (Lal 1991; Gosse and Phillips 2001). This accumulation is used to determine the elapsed time since the rock surface was first exposed to cosmic rays (Nishiizumi et al. 1989; Gosse and Phillips 2001). Hence, the deposition age of boulders in various topographical situations can be measured. Several studies have shown that SED is an innovative and powerful tool for the reconstruction of glacial and climate history (e.g. Gosse et al. 1995; Ivy-Ochs et al. 2004; Briner et al. 2005; Schaefer et al. 2006). In order to compare the magnitude and timing of former glacier extents, absolute dating methods can be applied and compared to determine the age of particular glacial stages and—in combination with other approaches, i.e. by paleoglaciological reconstructions (equilibrium line altitude [ELA] depressions)—the paleoclimatic signal they represent (Kelly et al. 2004; Kerschner and Ivy-Ochs 2008).

Soils can provide useful information for the geomorphological interpretation of mountainous terrain. Their spatial distribution in Alpine areas reflects the impact of the soil-forming factors, and once their influence is known, soils can help to introduce additive aspects of landscape evolution that otherwise may be left undetected (Birkeland et al. 2003). The dating of soil organic matter (SOM) with ^{14}C is well suitable, if humified and stable substances that were produced almost at the beginning of soil formation can be found and dated, giving the possibility to elucidate soil dynamic processes (Scharpenseel and Becker-Heidmann 1992).

The main aim of the study was to test and compare signals of landscape evolution obtained from soils developed on moraines using radiocarbon ages from stable organic matter with SED obtained from rock boulders. For this purpose, we investigated 4 soils developed on morainic and glacial substrata (paragneiss) with respect to their chemical composition and to the ^{14}C ages of the most stable resilient organic material (e.g. Eusterhues et al. 2005; Mikutta et al. 2006). In the vicinity of the studied soils, we sampled 4 erratic boulders (>2 m^3, in stable position) located on lateral moraines for ^{10}Be surface exposure dating (SED). The comparison between the ^{14}C and ^{10}Be method enabled to test the validity of the dating technique using resilient SOM. The combination of ages derived from ^{10}Be and ^{14}C dating should, furthermore, give insights into the deglaciation processes and the climatic fluctuations occurring during the late Pleistocene and early Holocene in the central-eastern Alps in Italy.

SITE DESCRIPTION

The investigation area is located in Val di Rabbi, in a small side cirque within a lateral valley of Val di Sole, Trentino, in the southern Alpine belt of northern Italy (Figure 1). The climate of the valley ranges from temperate to alpine (above the timberline). Mean annual temperatures range from 8.2 °C (valley floor, at ~800 m asl) to around 0 °C (at 2400 m asl) and mean annual precipitation approximately from 800 to 1300 mm/yr (Servizio Idrografico 1959). The timberline is close to 2100–2200 m asl and the forests are dominated by the conifers *Larix decidua* and *Picea abies* (Pedrotti et al. 1974). Areas above 2300 m are covered with rocks, boulders, and short-grass meadows dominated by *Carex curvula* and *Nardus stricta*.

The 4 investigated soils and boulders (Figure 1; Tables 1 and 2) are located between 2100 and 2456 m asl, hence, close to the timberline and in the high alpine zone (Figure 1, Tables 1 and 2). The soil types were Entic Podzol and Haplic Podzol at lower altitudes (between 2000 and 2200 m asl) and Protospodic Leptosol and Brunic Regosol developed at around 2300 m asl according to the WRB (IUSS Working Group 2006). According to the soil taxonomy (Soil Survey Staff 2006), the soil moisture regime is udic (humid conditions, <90 days/yr with a dry soil) at all sites and the soil

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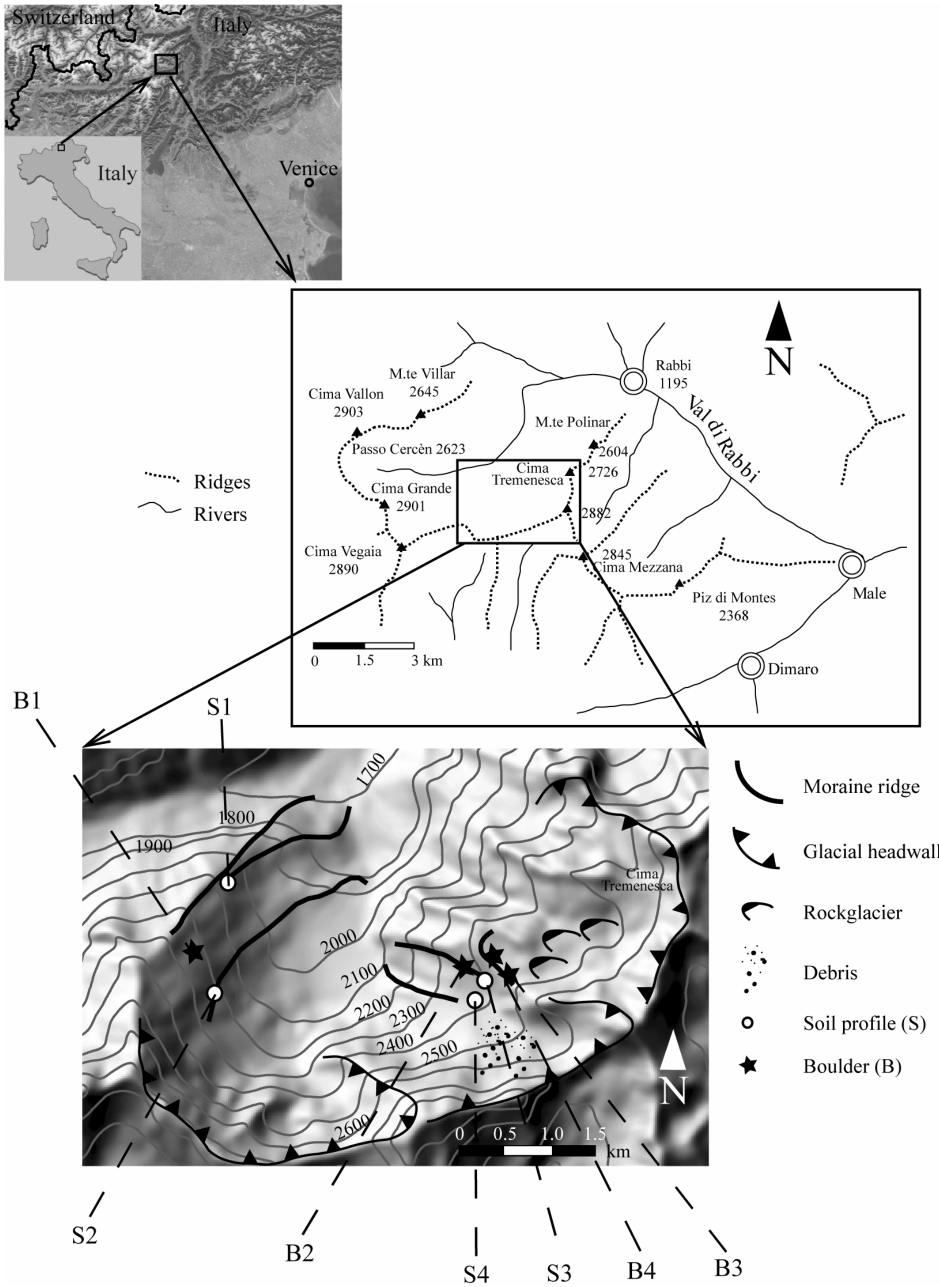

Figure 1 Location of the investigation site, soil profiles, rock boulders (S = soil profile; B = boulder) and main geomorphologic features.

temperature regime is cryic (mean annual temperature <8 °C, without permafrost). Soil material was collected from excavated pits, and undisturbed soil samples were taken, where possible, down to the BC or C horizon (parent material). Two to 4 kg of soil material were collected per soil horizon from the 4 soil pits (Hitz et al. 2002). The landscape near the investigation sites was strongly influenced by former glaciers and the sampled soils developed on moraines or on rock glaciers (paragneiss)

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Table 1 Characteristics of the investigated soils.

Profile	Elevation (m asl)	Aspect (°N)	Slope (%)	Parent material	Vegetation	WRB (IUSS Working Group 2006)
S1	2100	60	32	Paragneiss morainic material	*Larix decidua*/*Juniperus communis*	Entic Podzol
S2	2230	70	55	Paragneiss morainic material	*Rhododendro-vaccinietum extrasilvaticum*	Haplic Podzol
S3	2380	320	5	Paragneiss morainic material	*Carex curvula*/*Nardus stricta*	Protospodic Leptosol
S4	2370	300	10	Paragneiss, inactive rock glacier/solifluction	*Carex curvula*/*Nardus stricta*	Brunic Regosol

being inactive today. According to the geomorphological studies of Baroni and Carton (1990) and Filippi et al. (2007), surface ages were estimated to 14,000–16,000 yr. Large lateral moraines extend down to 1700–2000 m asl and glacial deposits, such as erratic boulders, can be found up to 2600 m asl. Big boulders (>2 m^3) with prominent quartz veins in flat and stable positions are widespread throughout the investigated area.

METHODS

Soil Chemistry and Physics

The soil samples were air-dried; large aggregates were gently broken by hand and sieved to <2 mm. Total C and N contents of the soil were measured with a C/H/N analyzer (Elementar Vario EL, Elementar Analysensysteme GmbH) using oven-dried (105 °C) and ball-milled fine earth. Total C corresponds in our case to organic C due to the absence of any carbonates in the soil. Soil pH (in 0.01M $CaCl_2$) was determined on air-dried samples of the fine earth fraction using a soil solution ratio of 1:2.5. After a pretreatment of the samples with H_2O_2 (3%), particle size distribution of the soils was measured by a combined method consisting of sieving the coarser particles (2000–32 µm) and measurement of the finer particles (<32 µm) by means of an X-ray sedimentometer (SediGraph 5100). 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 analyzed by AAS (atomic absorption spectrometry—AAnalyst 700, PerkinElmer, USA)

Extraction of the Stable Organic Matter (SOM)

Acting on the assumption that chemical oxidation mimics natural oxidative processes, we treated the soils with 10% H_2O_2 to eliminate the more labile organic material from the more refractory organic matter (Plante et al. 2004; Eusterhues et al. 2005; Mikutta et al. 2006; Helfrich et al. 2007). The stable fraction that remained at the end of the treatment was supposed to be part of the first organic matter formed in the sediment after glacier retreat (Favilli et al. 2008) and to provide minimum ages of deposition of the moraines and of deglaciation. One gram of air-dried soil was wetted for 10 min with a few mL of distilled water in a 150-mL beaker. Afterwards, 90 mL of 10% H_2O_2 were added. The procedure was run at a minimum temperature of 50 °C throughout the treatment period. The beakers were closed with 2 layers of parafilm to avoid evaporation of the reagent. Peroxide treatments were performed for 168 hr (7 days). At the end of the treatment, the samples were washed 3 times with 40 mL deionized water, freeze-dried, weighed, analyzed for total C and N, and ^{14}C dated.

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Radiocarbon Dating

The CO_2 of the combusted samples was catalytically reduced over cobalt powder at 550 °C to elemental carbon (graphite). After the reduction, this mixture was pressed into a target and the ratios ^{14}C:^{12}C (for ^{14}C age) were measured by accelerator mass spectrometry (AMS) using the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology Zürich (ETHZ). The calendar ages were obtained using the OxCal 4.0.5 calibration program (Bronk Ramsey 1995, 2001) based on the IntCal04 calibration curve (Reimer et al. 2004). Calibrated ages are given in the 2-σ range (minimum and maximum value).

Exposure Dating

Four large boulders on top of moraines with volumes >2 m^3 were sampled for exposure dating. The assumption is that boulders were transported by glaciers during the last glaciation and were, since the time of the last glacier retreat, exposed to cosmic rays without being moved from their present position. Gosse et al. (1995) demonstrated that on a single alpine moraine the cosmogenic nuclide ages reflect the timing of deposition. According to the position of the selected boulders in the investigation area, it is not likely that they were pre-exposed to cosmic rays before being deposited by the glacier. Similarly, based on results from numerous sites in the Alps, we consider pre-exposure extremely unlikely (Ivy-Ochs et al. 2007). These boulders were chosen for dating in order to exclude any long-term effects from slope-movement processes (Table 2). Rock samples were crushed, sieved, and leached in order to obtain pure quartz following Kohl and Nishiizumi (1992) and Ivy-Ochs (1996). ^9Be solution was added to the dried quartz, which was then dissolved in 40% HF. Be was isolated using anion and cation exchange columns followed by selective pH precipitation techniques (Ivy-Ochs 1996). $^{10}Be/^9Be$ ratios were measured at the ETH AMS facility. The surface exposure ages listed in Table 2 were calculated using a sea-level high-latitude production rate of 5.1 ± 0.3 (^{10}Be atoms/g SiO_2/yr) with 2.2% production due to negative muon capture (Stone 2000). This production rate was scaled for latitude (geographic) and altitude (Stone 2000) and corrected for sample thickness assuming an exponential depth profile, a rock density of 2.65 g cm^{-2} (quartz veins), and an effective collimated radiation attenuation length of 155 g cm^{-2} (Gosse and Phillips 2001). Topographic shielding was based on a zenith angle dependence of $(\sin\theta)^{2.3}$ (Dunne et al. 1999). The errors given for each boulder age reflect the analytical uncertainties of the AMS measurement parameters. The exposure age was corrected for mean snow cover (Gosse and Phillips 2001) with an assumed snow density of 0.3 g cm^{-3}. The duration of the snow cover (6 months, Table 2) was estimated according to Auer et al. (2003) from 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 the exposure ages significantly. A geomagnetic field correction (Pigati and Lifton 2004) was omitted because its possible effect is small (1–2%).

RESULTS

Chemical Composition and Physical Characteristics of the Soils

The investigated soils are characterized by a high proportion of rock fragments ranging from 0 up to 60% of the total weight (Table 3). These are typical values for alpine soils on a moraine type substratum (Egli et al. 2001). All investigated soils have a sandy to silty-sandy texture. The proportion of sand decreased towards the soil surface, and correspondingly silt and clay increased (Table 3). The decrease of the grain sizes from the bottom to the top of the soil profile is a clear effect of weathering. Due to the siliceous parent material, the soils show pronounced acidification (Table 4). Eluviation and illuviation of Fe and Al is typical for the podzolized soils (S1 and S2). A distinct increase

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Table 2 List of samples for surface exposure dating, elevation and latitude of the sample sites, thickness of sample, dip (angle from horizontal) of the surface sample, amount of quartz retrieved from the sample that was used for the measurement of ^{10}Be, correction factor for topography, production rate, ^{10}Be measured concentration in the sample, measurement error, and ^{10}Be date.

Sample	Elevation (m asl)	Lat. (°N)	Long. (°E)	Sample thickness (cm)	Surface dip (°)	Direction of dip (°)	Shielding corr.	Depth corr.	Snow cover[a] (m)	Local prod. rate (at g^{-1} yr^{-1})	^{10}Be[b] (at g^{-1} [1E+5])	Error[c] (%)	^{10}Be date (yr)	^{10}Be date (snow corr.) (yr)
B1 (W67)	2247	46.3763	10.7697	3	30	270	0.931	0.975	1.3	27.70	3.23	10.1	11,680 ± 1180	13,230 ± 1340
B2 (W70)	2360	46.3736	10.7883	5	38	270	0.927	0.958	0.7	29.27	3.24	8.5	11,110 ± 940	11,620 ± 990
B3 (W72)	2456	46.3747	10.7911	5	30	220	0.961	0.958	0.3	32.34	3.15	7.9	9780 ± 770	9920 ± 780
B4 (W73)	2446	46.3750	10.7902	5	16	240	0.982	0.958	0.3	32.84	2.85	7.8	8710 ± 680	8840 ± 690

[a]Average value of snow cover during 6 months.
[b]Using ETH AMS standard S555 ($^{10}Be/^{9}Be$ = 95.5 10^{-12} nominal) with a ^{10}Be half-life of 1.51 Myr.
[c]Estimated total error including measurement error and the effects of altitude, latitude and topography/depth scaling.

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of dithionite and oxalate iron and aluminium is observed in all spodic horizons (Table 4). The soil S3 is rather shallow but showed the typical characteristics of a developing Podzol (Al, Fe, and organic C translocation within the soil profile and formation of a Bhs horizon). In the soil profile S4, no clear translocation of Fe and Al forms is detectable due to a lower stage of soil development. This soil developed in an area with former solifluidal activity. The soil has a polygenetic horizon sequence due to the accumulation of younger material on top of a former surface (Figure 2). The concentration of organic C in the profile shows a strong increase in the Ab horizon, thus confirming the macromorphological observation (Table 4).

Table 3 Physical characteristics of the investigated soils.

Site	Horizon	Depth (cm)	Munsell color (moist)	Skeleton[a] (%)	Sand (g/kg)	Silt (g/kg)	Clay (g/kg)
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	nd	nd	nd
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 1.7/1	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

[a]Size fractions: skeleton = >2 mm; sand = 2000–62 µm; silt = 62–2 µm; clay = <2 µm; nd = not determined.

Table 4 Chemical characterization of the investigated soils.

Site	Horizons	pH ($CaCl_2$)	Org. C (%)	Total N (%)	C/N	Al_o (g/kg)	Fe_o (g/kg)	Al_d (g/kg)	Fe_d (g/kg)
S1									
	AE	3.7	10.37	0.57	18	1.73	5.57	2.50	15.90
	BE	3.6	6.10	0.29	21	1.91	6.06	2.80	20.50
	Bs1	4.1	3.94	0.18	22	10.27	19.62	14.70	44.10
	Bs2	4.4	1.70	0.07	24	5.84	9.37	7.30	21.40
	BC	4.5	0.75	0.06	12	4.04	1.67	5.60	6.90
S2									
	AE	3.4	18.46	0.88	21	2.78	5.67	3.94	14.53
	Bhs	3.7	6.38	0.27	24	6.31	24.90	5.96	45.33
	Bs	4.15	2.54	0.12	21	6.41	8.81	10.65	30.13
S3									
	AE1	3.4	12.49	0.68	18	2.03	2.47	2.80	8.50
	AE2	3.55	4.80	0.22	22	2.48	4.33	3.20	11.00
	Bhs	3.85	7.14	0.31	23	8.30	13.76	14.20	27.10

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Table 4 Chemical characterization of the investigated soils. *(Continued)*

Site	Horizons	pH ($CaCl_2$)	Org. C (%)	Total N (%)	C/N	Al_o (g/kg)	Fe_o (g/kg)	Al_d (g/kg)	Fe_d (g/kg)
S4									
	A	3.85	5.53	0.38	15	3.05	7.05	5.40	21.90
	Bw1	4.00	2.07	0.15	14	2.47	9.61	5.00	30.80
	Bw2	4.1	1.95	0.13	15	1.58	4.21	3.30	20.60
	Ab	3.95	6.20	0.39	16	4.39	6.52	7.50	23.10
	Bbw	4.25	0.91	0.05	18	1.57	3.70	2.70	15.30

(A)

(B)

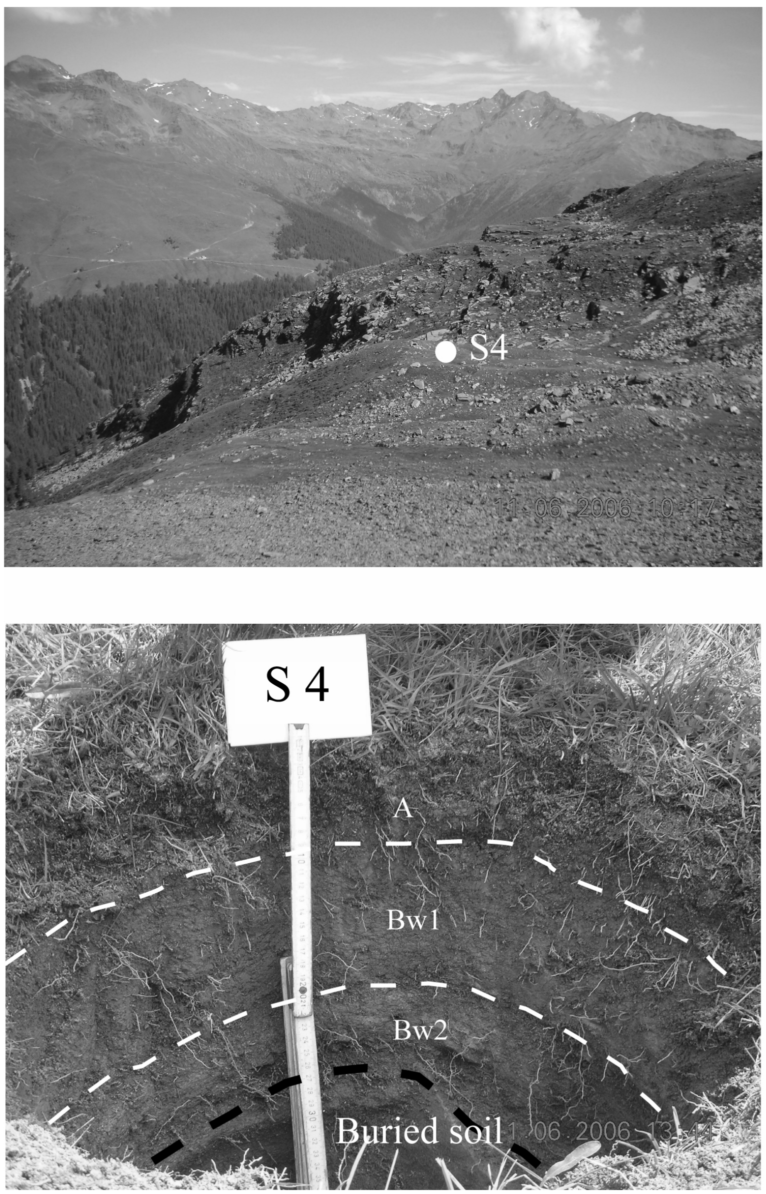

Figure 2 A) Location of the soil profile S4; B) Soil profile S4 with horizons and buried soil

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Radiocarbon Age of Soil Organic Matter and ^{10}Be Age of Boulders

The ages of SOM varied considerably within all soil profiles (Table 5). The highest age of the H_2O_2-treated samples was usually measured in the E or B horizon (Bs or Bhs) and gives an indication about the start of soil formation. H_2O_2 is a strong reagent to oxidize all labile organic matter in soils (Favilli et al. 2008).

Table 5 Measured and calibrated ^{14}C ages of untreated and H_2O_2-treated soil samples. Calibrated ^{14}C ages are given in the 2-σ range.[a]

Site	Soil type, depth (cm)	Soil horizon	ETH # untreated	Uncal ^{14}C untreated	Cal ^{14}C untreated	ETH # H_2O_2-treated	Uncal ^{14}C H_2O_2-treated	Cal ^{14}C H_2O_2-treated
S1	**Entic Podzol**							
	0–4	AE	-33323	–650 ± 40	Modern	-33508	12,470 ± 90	14,160–14,964
	4–8	BE	-33324	–30 ± 40	Modern	-33509	14,410 ± 110	16,782–17,839
	8–20	Bs1	-33325	780 ± 40	666–772	-33510	10,060 ± 85	11,274–11,972
	20–45	Bs2	-33326	2815 ± 45	2794–3064	-33511	9735 ± 75	10,786–11,270
	45–60	BC	—	—	—	—	—	—
S2	**Haplic Podzol**							
	0–9	AE	—	—	—	-33972	2360 ± 50	2207–2699
	9–20	Bhs	—	—	—	—	—	—
	20–40	Bs	—	—	—	-33973	9775 ± 70	10,825–11,386
S3	**Protospodic Leptosol**							
	0–4	AE1	—	—	—	-33976	5115 ± 55	5729–5989
	4–12	AE2	—	—	—	—	—	—
	12–20	Bhs	-34208	650 ± 50	546–676	-33977	9425 ± 75	10435–11073
S4	**Brunic Regosol**							
	0–8	A	—	—	—	-33974	7655 ± 65	8370–8585
	8–20	Bw1	—	—	—	—	—	—
	20–32	Bw2	—	—	—	-35573	8025 ± 60	8647–9073
	32–35	Ab	-33978	2505 ± 50	2366–2743	-33975	11,920 ± 85	13,596–13,991
	35–40	Bbw	—	—	—	—	—	—

[a] — = not determined.

The measured lower ages in the AE horizon of profile S2 and the AE1 horizon of profile S3, compared to those of the subsoil, are most probably due to the very high C content and, therefore, either to the incapability of H_2O_2 to oxidize all young OM or to young OM, which was able to expel older C. The untreated soil organic matter from the whole top- and subsoil of site S3 (Table 5, Bhs horizon) seems to have in general a very young age. Strong leaching conditions, due to the very low pH, have caused the downward migration of soluble young-aged organic material compounds with soil percolating water into the subsoil. The H_2O_2 treatment, performed on the sample from the Bhs horizon, gave an age of 10,435–11,073 cal BP of the resilient OM fraction.

The ^{14}C results show that the site S4 has a polygenetic soil. Soil formation in the initial layer started around 13,596–13,991 cal BP and ended, due to the accumulation of eroded material (probably slope deposits), between 2366–2743 cal BP (Table 5). This burial event was inferred from dating root remains in the Ab horizon. The accumulation was probably due to periglacial activity/processes (solifluction) during a colder period around 2500 yr BP. This periglacial period would fit with the Göschener I cold phase, which occurred around 3.0–2.3 kyr (Zoller et al. 1966; Maisch et al. 1999; Figure 4). Preweathered sediments containing already organic material (having an age between 8370–9073 cal BP) were deposited on top of the original soil (horizon A/Bw2; Figure 2).

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The ^{10}Be dates from the sampled boulders range from 13,230 to 8840 yr (Table 2). The ^{10}Be ages decrease with increasing altitude, which is in agreement with the general direction of retreat of the glaciers after the LGM (Last Glacial Maximum). The position of the boulders in the investigation area supports the calculated ages (Figures 1 and 5). If exposure ages and ^{14}C ages (start of soil formation) are plotted versus elevation, a significant (r^2 = 0.68; p = 0.0115), linear relationship is obtained (Figure 3).

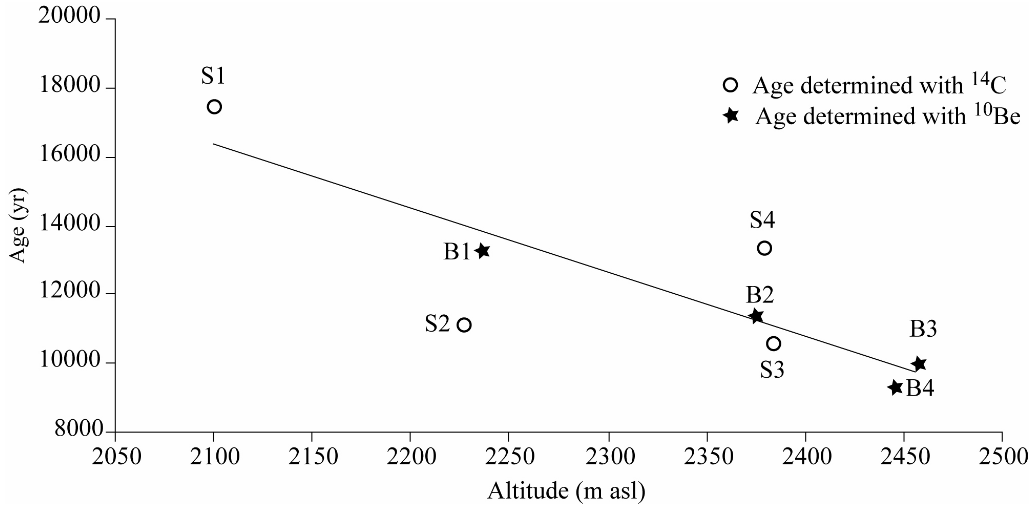

Figure 3 Relationship between the obtained ages (^{14}C [calibrated age] and ^{10}Be) and the elevation of the dated objects

The ^{14}C age of stable organic matter extracted from soil S1 implies that the oldest moraine (at an altitude of 2100 m asl) had already been deposited by around 16,782–17,839 cal BP (Figure 4, Table 5). The soil S4 at 2370 m asl started to develop 13,596–13,991 cal BP. More or less simultaneously, the boulder B1, located at 2247 m asl, was deposited on a moraine. Around 11,700 yr ago, the site B2 at 2360 m asl was affected by the re-advance of a small glacier tongue, most probably during the late Egesen glacial stage (Younger Dryas) or the early Preboreal (Ivy-Ochs et al. 2006a, 2008) with the deposition of new material (Figure 5). The soil S3, located a short distance from B2, started its evolution shortly after the deposition of the moraine. The chemical and morphological evolution of the soil profile S3 confirms that this soil has had an undisturbed development during the last 10,000 yr—a time span that leads to well-developed Podzols (e.g. Starr 1991; Barett and Schaetzl 1992; Lundström et al. 2000). The following period, the Holocene, was characterized by higher temperatures (Clapperton 1995), which finally caused the total disappearance of the glaciers in the investigation area. Periglacial activity (solifluction) was, however, traceable at the site S4 until around 2366–2743 cal BP. This soil profile is polygenetic and strongly influenced by solifluction (accumulation of soil material because of slope deposits, burial of a former soil) around that period.

DISCUSSION

The moraines in the study area are characterized by sharp crests and numerous large boulders (cf. Ivy-Ochs et al. 2006, 2008). The investigated soils are well developed and show the typical characteristics of podzolization, with the formation of an eluvial and a illuvial horizon. The oxidation of SOM with H_2O_2 left behind intrinsically resistant soil organic matter (Theng et al. 1992; Cuypers et al. 2002; Favilli et al. 2008). Humic compounds may form close and strong associations with the

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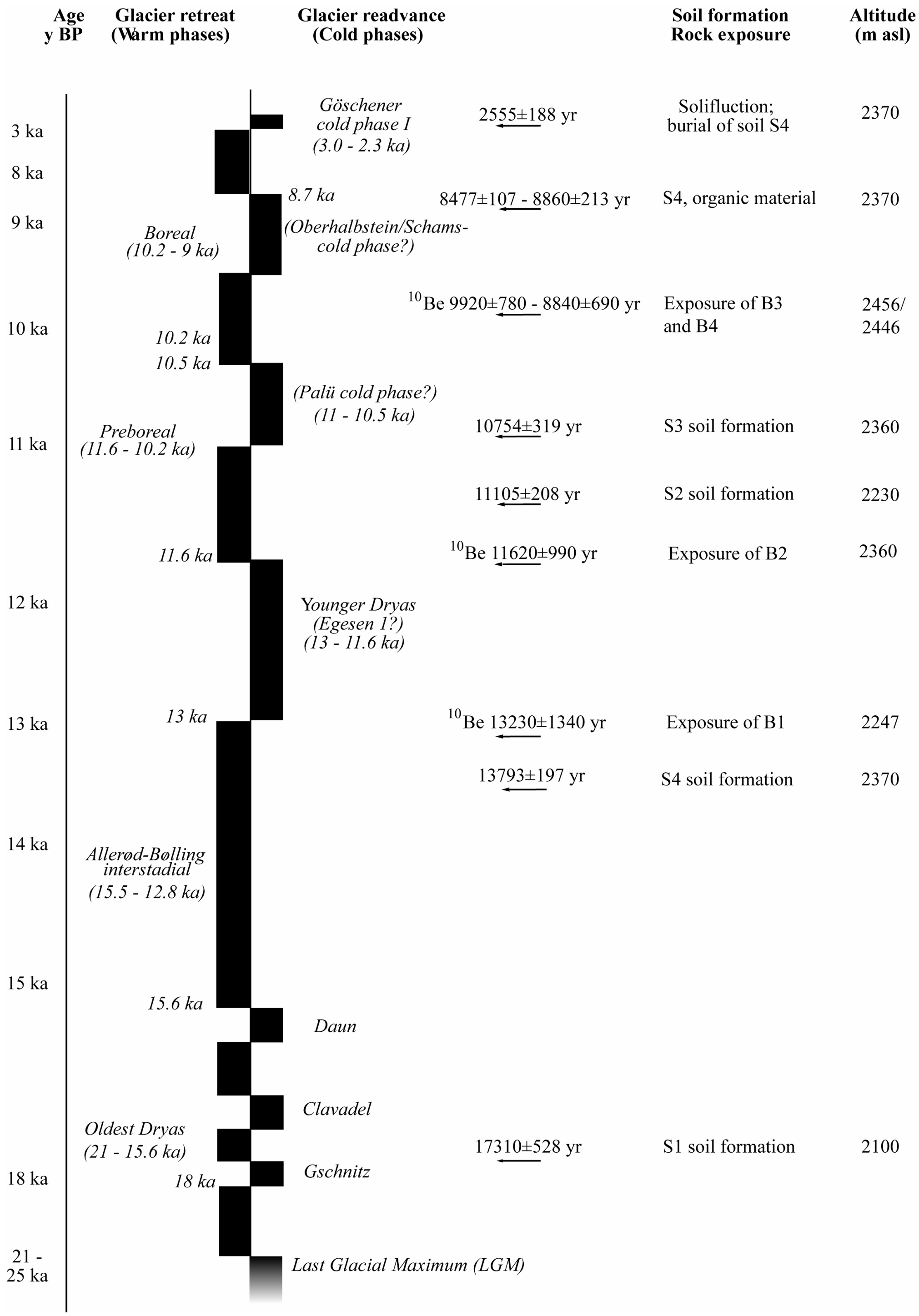

Figure 4 Ages of the investigated sites (^{14}C calibrated age and ^{10}Be) related to the chronology of the Lateglacial and Holocene glacier and climate variations (according to several authors, e.g. Maisch 1987; Maisch et al. 1999; Kerschner et al. 1999; Ivy-Ochs et al. 2004).

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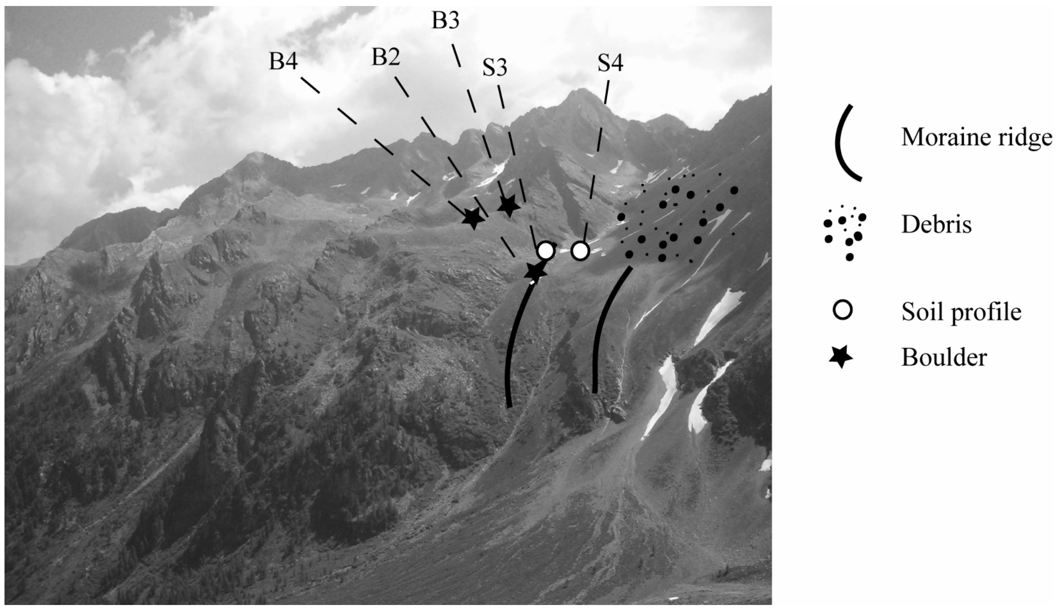

Figure 5 Location and geomorphic details in the surroundings of the profiles S3, S4 and of the boulders B2, B3, and B4

mineral phase, especially with clay minerals (Righi and Meunier 1995). Clay organic complexes, once formed, do not easily exchange the organic component with infiltrated younger humus components (Scharpenseel and Becker-Heidmann 1992). A higher ^{14}C age in the topsoil or near the surface should be the theoretical expectance since soil formation starts at the surface and proceeds with time into greater depths. Organic matter from plants and animals is incorporated into soil material and mixed with the mineral part. Because the investigated soils are podzols and consequently have a low biological activity and no earthworms, the highest ages of the stable SOM should be found in the topsoil. Such a typical trend is found in profile S1. Biological activity is low in these soils. Hence, mixing of organic material into greater depth takes a rather long time. Bioturbation is, however, not the only process of downward movement of organic matter. Due to podzolization, organic matter has been translocated into greater soil depths. In contrast to the H_2O_2-treated samples, the untreated samples show an increase of age with soil depth. This is explained by a continuous rejuvenation of SOM from the soil surface. Most of modern carbon is <100 yr old and decreases exponentially with increasing depth, leading to an increase of the percentage of old carbon present (O'Brien and Stout 1978; Mikutta et al. 2006). Hence, the ratio young SOM:old SOM should be higher in the topsoil than in the subsoil. The ratio of the H_2O_2-resistant C (old C) to total C was in the subsoil usually between 20–30% and in the topsoil in most cases <10%. On one hand, it seems that at least a part of the oldest fraction is still present in the top- and subsoil and that the treatment with hydrogen peroxide is able to detect some of the initially formed OM. On the other hand, it does not seem that in every case the oldest organic material can be found in the topsoil. This means that the top- and subsoil material has to be dated to obtain the oldest SOM fraction. ^{14}C ages prove the late Pleistocene and Holocene age of the surfaces. The ^{14}C ages of resilient SOM fit well to the ^{10}Be ages of rock boulders. ^{14}C dating of stable organic matter therefore seems to be a promising tool for dating Holocene- and late Pleistocene-aged soils. The significant linear correlation found between the ^{14}C and ^{10}Be ages and the altitude of the investigated sites enables hypotheses about the chronology of glacial and periglacial processes that occurred in the investigated area. Therefore, the combination of these 2 dating techniques helps to decipher landscape history of high Alpine regions on siliceous parent material in the late Pleistocene/Holocene.

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The investigation area experienced deglaciation between 18,000 and 9000 cal BP. The ages of the soils and of the exposed boulders reflect quite clearly the movement and the timing of the glacier retreat and—in a general sense—the dynamics of Alpine landscape geomorphology. The ages of the soils and of the exposed rocks correspond quite well with the general chronology of the Lateglacial and the Holocene period, even if some aspects remain open. Deglaciation from the LGM occurred worldwide during the 3 millennia 18–15 kyr BP, documented by ice cores (e.g. Johnsen et al. 1992, 2001) and global sea-level records (e.g. Yokoyama et al. 2000). Studies from the Upper Engadine (Switzerland) indicate that retreat of the main valley glacier was substantially progressed already at 16 kyr (Studer 2005). This fits well with the ^{14}C age of stable organic matter extracted from the soil S1 having an age of around 17,000 cal BP.

The overall trend of deglaciation continued after ~15 kyr but was interrupted by extensive glacier re-advance around 16,000 to 17,000 yr ago (Gschnitz stadial; Ivy-Ochs et al. 2006b and references therein) and reflects an ELA 650–700 m below that of the Little Ice Age reference ELA (Ivy-Ochs et al. 2006b). Similarly, the age of 14,160–14,964 cal BP in the topsoil of profile S1 could point to a re-advance of local glaciers and deposition of moraine material in the Oldest Dryas. In this case, profile S1 would be polygenetic (burial of a pre-existing soil surface with the start of a new soil development). A polygenetic soil is, however, rather improbable as no signs of accumulation and burial were visible and measurable, e.g. by a distinct increase of rock fragments (material >2 mm) near the surface (see Table 3). Until the end of the Gschnitz stadial the oscillations of the glaciers occurred down to an altitude of around 1700 m asl. The period between about 15.5 and 12.8 kyr has been recognized as the Bølling-Allerød interstadial (Alley et al. 1993; Maisch et al. 1999; Schaub et al. 2008). ^{14}C dates with varve counting indicated that the Upper Engadine lakes became ice-free prior to approximately 13.5 kyr (around 16,000 cal BP) (Ohlendorf 1998). During this period of warming, Val di Rabbi also experienced a further retreat of its glaciers in a relatively short period of time compared to the overall deglaciation. After the "Younger Dryas" (about 13.0–11.6 kyr; e.g. Mangerud et al. 1974; Lundqvist 1986; Maisch et al. 1999), soils started to develop also at higher altitudes (e.g. profile S2).

The 2 boulders on the highest elevation moraine have ^{10}Be exposure ages of 8840 ± 690 and 9920 ± 780 yr. Their average age points to around 9500 yr. They may have been deposited during a re-advance phase in the Boreal (Oberhalbstein/Schams cold phase?). Periglacial activity measured probably increased around 2366–2743 cal BP (profile S4). This would fit with the "Göschener I" cold phase, which occurred between 3.0–2.3 kyr (Zoller et al. 1966) (Figure 4). Preweathered sediments containing already organic material (having an age between 8370–9073 cal BP) were deposited on top of the original soil (Figure 2, Table 5). According to previous studies (Egli et al. 2001), the formation and development of podzolization features at this altitude takes at least 1000–3000 yr. Typical podzolization features did not develop in these 2600-yr-old slope deposits. Some 2600 yr of soil evolution were obviously not a sufficiently long time for the development of podzolic characteristics.

CONCLUSIONS

We compared and combined ^{14}C ages of stable organic matter in 4 soil profiles with the ^{10}Be exposure ages of erratic boulders in order to reconstruct the timing of deglaciation at the transition of the Pleistocene/Holocene in Val di Rabbi. We obtained the following principle findings:

- The ^{14}C data of the resilient organic matter in soils fit quite well to and can be combined with the ^{10}Be age sequence obtained from boulders.

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- Extraction and dating of stable organic matter from alpine soils gives a numerical value for an ice-free minimum age for deglaciation of land surfaces and the beginning of soil formation. More research is, however, needed to confirm these results.
- Dating of resilient organic matter in soils offers new perspectives in deciphering landscape history, but has to be critically evaluated and discussed.
- ^{10}Be and ^{14}C ages correlated with elevation of the investigated site and with the chronology of the Lateglacial/early Holocene re-advance and retreat phases of glaciers.
- The combination of ^{10}Be and ^{14}C dating techniques, applied in relatively small catchments in Alpine environments, despite the limited number of samples, seems to be a promising tool for a better understanding of the geomorphology and paleoclimate.
- Obtained ages reveal the chronology of the glacial and periglacial processes that occurred in Val di Rabbi between 18,000 and 9000 yr ago.

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