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Middle to Late Holocene vegetation history of the Upper Engadine (Swiss Alps): the role of man and fire

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Abstract To reconstruct the vegetation and fire history of the Upper Engadine, two continuous sediment cores from Lej da Champfèr and Lej da San Murezzan (Upper Engadine Valley, southeastern Switzerland) were analysed for pollen, plant macrofossils, charcoal and kerogen. The chronologies of the cores are based on 38 radiocarbon dates. Pollen and macrofossil data suggest a rapid afforestation with *Betula, Pinus sylvestris, Pinus cembra,* and *Larix decidua* after the retreat of the glaciers from the lake catchments 11,000 cal years ago. This vegetation type persisted until ca. 7300 cal B.P. (5350 B.C.) when *Picea* replaced *Pinus cembra*. Pollen indicative of human impact suggests that in this high-mountain region of the central Alps strong anthropogenic activities began during the Early Bronze Age (3900 cal B.P., 1950 B.C.). Local human settlements led to vegetational changes, promoting the expansion of *Larix decidua* and *Alnus viridis*. In the case of *Larix*, continuing land use and especially grazing after fire led to the formation of *Larix* meadows. The expansion of *Alnus viridis* was directly induced by fire, as evidenced by time-series analysis. Subsequently, the process of forest conversion into open landscapes continued for millennia and reached its maximum at the end of the Middle Ages at around 500 cal B.P. (A.D. 1450).

Keywords *Larix decidua* · *Alnus viridis* · Central Alps · High-resolution palynology · Cross correlations · Human impact

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Introduction

The Upper Engadine (Engadin' Ota) valley occupies a special geographical position. The valley bottom at 1,600–1,800 m a.s.l. extends for ca. 50 km between high mountain ranges reaching to more than 4,000 m a.s.l. The high degree of sunshine (320 days with sunshine (KVSM 2003), only 51% cloud cover; data source MeteoSchweiz 2002) has attracted tourists for centuries (Hüsler 2001; KVSM 2003). Several studies focused on environmental, especially vegetational, history from bogs (e.g. Keller 1930; Kleiber 1974; Heitz et al. 1982; Punchakunnel 1983; Zoller and Brombacher 1984). Their main interest was through vegetation history to determine long-term trends, such as expansions and declines of taxa as well as climatic reconstruction. More recently, Holocene sediment cores from lakes in the Upper Engadine valley have been investigated through sediment and geochemistry studies (Ariztegui 1993; Leemann 1993; Ariztegui and Dobson 1996; Ohlendorf 1999), but none of these cores have yet been studied for the biotic aspects of palaeoecology. Palaeo-botanical studies in the Alps (e.g. Markgraf 1970; Welten 1982) had formulated several hypotheses for some of the most important vegetation changes during the Holocene (e.g. driving factors for the expansion of *Picea abies* and *Alnus viridis*), but partly because they lacked the necessary temporal resolution or because no independent proxies for vegetation disturbance (e.g. charcoal) were considered, a rigorous evaluation of these hypotheses was impossible. The present study provides the first high-resolution palaeo-botanical data for the Holocene of the Engadine. After briefly discussing human influence during the Neolithic, we focus on the Early Bronze Age, when drastic environmental changes occurred. The most spectacular feature was the strong expansion of *Alnus viridis,* which is typical for the entire Western Alps (Welten 1982; Wick 1991; Tinner et al. 1996). This change was important, since late-succession forests dominated by coniferous species (e.g. *Pinus cembra, Larix, Picea*) were widely replaced by green alder thickets. Today, large-scale expansions of

Alnus viridis occur in the Alps after forest disruptions (e.g. by fire) or where grazing or mowing of meadows is abandoned. These thickets are economically uninteresting since they are not exploitable (e.g. for timber or fodder) and they do not provide protection against avalanches (Mayer and Ott 1991). So far, the *Alnus viridis* expansion during the Bronze Age has not been regarded as typical for the Upper Engadine, since Zoller and Brombacher (1984) for example argued that the proportion of *Alnus viridis* remained always low during the Holocene (under 10% of the pollen sum). In the Upper Engadine, the *Alnus viridis* expansion was accompanied by the establishment of so-called *Larix*-meadows ("Lärchwiesen", open Larch stands with a herbaceous under-storey). Zoller and Brombacher (1984) and Zoller et al. (1996) have hypothesized that such stands resulted from agro-pastoral activities. Similarly, other authors (e.g. Welten 1982; Tinner et al. 1996) have suggested human impact for the expansion of *Juniperus* and *Alnus viridis*. The aims of this study are to investigate (1) whether in the Upper Engadine these phenomena were linked to each other and explainable by human impact alone and (2) whether fire was a driving force for the vegetational changes and thus a widely used deforestation tool in the Alps.

Research area: geology, climate and vegetation

Lej da San Murezzan (Lake St. Moritz) and Lej da Champfèr (Lake Champfèr) are situated in the Upper Engadine Valley (Rhaeto-Romansh: Engiadin'Ota), which is located in the central Alps of south-eastern Switzerland (Fig. 1). The valley is bordered by 3,000- to 4,000-m-high mountains to the northwest and southeast. The lakes Lej da Segl, Lej da Silvaplauna, Lej da Champfèr, and Lej da San Murezzan form a southwest to northeast chain, connected through the river Inn (En), which has its source 3 km west of Lej da Segl (Fig. 1). Lej da San Murezzan is located at an altitude of 1,768 m a.s.l., and has an area of 0.78 km^2. It has a maximum depth of 44 m. Lej da Champfèr is situated at 1,791 m a.s.l. with a surface area of 0.5 km^2 and is 33 m deep (Bosli-Pavoni 1971; Limnex 1994).

The Engadine represents an important fault system (Engadine line) on which the major tectonic units of the Austro alpine Nappes were displaced. The Err-Bernina, Margna-Sella, and Platta Nappes dominate the tectonics in the Upper Engadine area. The western side of the Engadine line was influenced by the Churer uplift and the corresponding tilting to the east since the early Pleistocene (Flisch 1986). Granitic rocks characterise the geology around Lej da San Murezzan and Lej da Champfèr, whereas on the eastern side of Lej da Silvaplana ophioliths (mainly basaltic rocks) dominate (Spillmann 1993; Ohlendorf 1999). Traces of Quaternary glacier activity (e.g. moraines) are very common in the Upper Engadine. During the retreat of the glaciers, the valley bottom near Punt Muragl (northeast of St. Moritz) was filled with gravel and the lake basins were formed (Glaziologische Karte Julier Bernina 1998). The origin of this chain of lakes can thus be attributed to two groups of factors, namely tectonic (fault system of the Engadine line) and glacial (glacial erosion, dead-ice blocks and melt water).

Sheltered from precipitation by high mountain chains on two sides, the Upper Engadine belongs to the so-called "inner-alpine dry valleys" like the Aosta (Italy), the Valais (Switzerland) or the Valtellina (Italy). The climate is characterised by mild summers, cold winters, low humidity and above-average sunshine (53% of relative yearly sunshine duration for Samedan, norm values 1961–1990, data source MeteoSchweiz 2002). The mean annual temperature for Samedan (1,705 m a.s.l.) is 0.5 °C, the mean July temperature is 10.6 °C, and the average precipitation is 700 mm/year with a maximum in July and a minimum in January. Segl-Maria (1,802 m a.s.l.) has a mean annual temperature of 1.4 °C, a July mean temperature of 10.8 °C, and an average of precipitation of 978 mm/year (norm values, 1961–90, MeteoSchweiz 2002). West–south-westerly air masses flowing over the

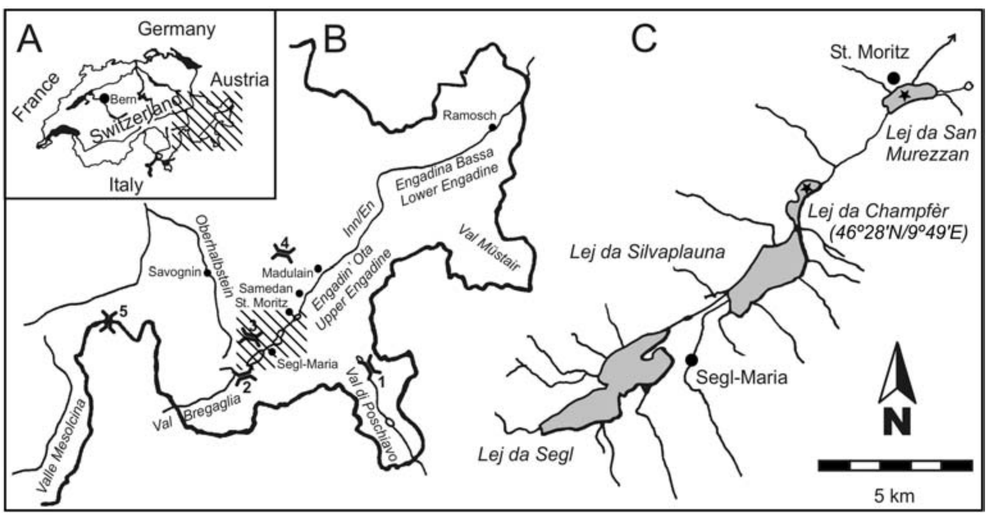


Fig. 1 Map of the study region. **A** Overview. **B** important sites and passes in Upper Engadine Valley: *1* Passo del Bernina; *2* Passo del Maloja; *3* Pass dal Güglia (Julier Pass); *4* Pass d'Alvra (Albula Pass); *5* Splügen Pass. **C** main lakes and location of pollen profiles (*) discussed. Drawing: Ch. Bigler and E. Gobet

relatively low-lying pass of Maloja (which shows a very shallow slope toward the Engadine but falls steeply toward the Val Bregaglia), producing both fair weather winds (Malojawind) and advective foul weather winds ("Malojaschlange", i.e. clouds creeping from the southwest, Gensler 1978; Gensler and Schüpp 1991).

Today, the most prominent forest tree of the Upper Engadine is larch (*Larix decidua*). Together with *Pinus cembra* it forms sub-alpine larch-stone pine forests, which are also typical for other regions of the central Alps (Zoller and Brombacher 1984; Hegg et al. 1993; Ellenberg 1996; Ozenda 2002). Today the timberline in the Upper Engadine region lies between 2,100 and 2,250 m a.s.l. (Landeskarte der Schweiz: Oberengadin 1995) and is formed by *Pinus cembra* and *Larix decidua.* The tree line (as indicated by single trees >5 m) is at 2,410 m a.s.l. In the Alps, most ecologists consider the tree line as an indicator of the uppermost limit of potential forest growth under natural conditions (potential natural timberline, e.g. Landolt 1992; Ellenberg 1996). Most *Picea abies* (spruce) is frequently present as single trees up to 2,000 m a.s.l., more commonly on shady northwest slopes between Segl-Maria and Lej da Staz (1 km east of Lej da San Murezzan, see Fig. 1; Zoller and Brombacher 1984). *Larix decidua* also forms open larch-meadows ("Lärchwiesen") characterised by old larch trees in species-rich regularly grazed meadows ("Magerwiesen", Hegg et al. 1993). The larch stands suffer periodically (ca. every 10 years) from butterfly epidemics ("Lärchenwickler", *Zeiraphera diniana)*, which can also lead to death for *Pinus cembra* (Mayer and Ott 1991). The low air humidity, the high number of sunshine days and the scarcity of fogs favour *Larix* and *Pinus cembra* in comparison with *Picea*. Around St. Moritz *Pinus mugo* ssp. *uncinata* (upright mountain pine) is frequent, whereas *Pinus sylvestris* var. *engadinensis* trees (Scots pine) occur only occasionally (Candrian 1928; Zoller and Brombacher 1984). *Alnus viridis* (green alder) grows along rivers in the sub-alpine belt but also where avalanches are frequent. Some authors consider it to be a competitive "weed" in alpine meadows (e.g. Mayer and Ott 1991).

The historical context

Archaeological findings from prehistoric times are rare in the Upper Engadine. Table 1 shows the chronological scheme for the Engadine suggested by Rageth (2000). First archaeological findings in the region (Tec Nev, Valle Mesolcina, Canton of Graubünden, Switzerland) are dated at 4850 B.C. (cal. 6800 cal B.P.) and testify to the presence of the nearest Mesolithic settlements (ca. 40 km away) to the Upper Engadine (Crotti 1993). For the Neolithic, single findings exist in the study region, but there is no evidence for continuous settlements (Nauli 1981; Rageth 2000b). Although the presence of Bronze Age settlements is likely, so far only a few tools have been found in the Upper Engadine (Nauli 1981; Rageth 2000b and personal communication). A massive wooden trough used to collect the water of the mineral spring of St. Moritz is dated to 1466 B.C. (3416 cal B.P., Seifert (2000). Rageth (2000a) suggests that the strong increase of settlement activities during the Bronze Age could be related to copper prospecting. The nearby Oberhalbstein (Fig. 1) has been settled at least since 2000/1900 B.C. (ca. 4000 cal B.P.) for stock and field farming, and the processing of copper (Rageth 2001; Schaer 2003). Maps of ore mineral (Schmidt 1917; Kündig and de Quervain 1953) do not show copper deposits in the Upper Engadine, but do however in the nearby Oberhalbstein (Fig. 1; Schaer 2003). During the Early Bronze Age (ca. 2000 B.C., 3950 cal B.P.), bronze ("Fahlerzbronze") was produced from copper and arsenic or antimony, which seems to have been of equal or even better quality than the copper-tin alloy used in subsequent periods (Moesta 1986; Fasnacht 1998). The very poisonous arsenic occurs naturally in copper mines, but according to Moesta (1986) it was also added artificially (Fasnacht 1998). Arsenic-rich deposits are known from close to the Bernina pass (Kündig and de Quervain 1953; Fig. 1). The Upper Engadine is situated between the above-mentioned deposits, and could thus have played a key role in the processing. There are indications for modest copper processing at least at one site near Madulain (Schweizer 1982; Rageth, personal communication; Fig. 1). Also the place name Madulain (=*metallum/metallenus*) suggests mining (Walser 1912; Bundi 1989). According to Ebeling and Birkenfeld (1970), at least 35 kg of wood were needed to smelt one kilogram of copper, so it would have been certainly easier to transport the ore instead of the wood.

Table 1 Chronology of prehistory for the Engadine (according to Rageth 2000a)

B.C.	cal B.P.	Epoch	Cultural period for the Engadine
15	1965		
			Fritzens-Sanzeno
		Iron Age	
500	2450		
800	2750		Laugen-Melaun
1200	3150		
		Bronze Age	
			Inner alpine Bronze Age
2000	3950		
2200	4150		
		Neolithic	?

Within the Iron Age (800–15 B.C.; 2700–1965 cal B.P.) no settlements are archaeologically documented in the area around the Upper Engadine lakes. However, sparse findings are known from the Oberhalbstein (Rageth 2000b, 2001). In contrast, Iron-Age settlements are known from the Lower Engadine (Engadina Bassa). According to Rageth (2000b), these findings along the Inn river reflect active trading over the passes of the Alps.

During Roman times drivable roads were built and used intensively over the Maloja and Julier passes (Conrad 1981; Nauli 1981; Planta 1986; Fig. 1). There is evidence that the Romans built their roads on already existing prehistoric pathways (Planta 1986). The strategic importance of the geographical position of the area is evident considering that four important Alpine pass routes lead to the Upper Engadine: Albula, Bernina, Julier, and Maloja (Fig. 1). This prominent role in traffic between Italy and Central Europe brought considerable benefit to this region for centuries. However, during historic times political and social conflicts are extensively documented (for example “Bündner Wirren”, A.D. 1618–1648). At the end of the 18th century the first tourist activities started (Bätzing 1991). The early onset was induced by the presence of a famous spa (Mauritius spring) near St. Moritz, recommended by Paracelsus in the 16th century (KVSM 2003). At the end of the 19th century the Upper Engadine Valley became a centre for winter sport for English tourists (Bury 1995). Soon after, the valley became easily accessible through the construction of the railway. Today, tourism is by far the most important economic factor in the area (Bury 1995).

Methods

Coring

Using a modified Kullenberg piston-corer (Kelts et al. 1986), two 12-m-long cores (5 cm diameter) were recovered from Lej da San Murezzan in July 1990 and from Lej da Champfèr in September 1994. For the youngest part, short cores were recovered and easily correlated with the long cores on the basis of prominent sediment layers. The cores Lej da San Murezzan PSM 90/3 and Lej da Champfèr PCH 94/3 were stored at ca. 4 °C prior to analysis.

Sample preparation and pollen analysis

The sediment samples were prepared for pollen analysis using standard physical and chemical methods (Moore et al. 1991) and with the addition of *Lycopodium* tablets for the estimation of pollen concentrations (Stockmarr 1971). Pollen identification was carried out at x400 or x1000 magnification. Aids to pollen identification included the pollen reference collection at the Institute of Plant Sciences, Bern, and keys by Punt et al. (1976–2003), Moore et al. (1991), Faegri and Iversen (1989), and the pollen atlases of Reille (1992, 1995, 1998). In the Holocene and Late-glacial samples, the pollen sums were at least 650 and 300, respectively. For calculations of percentages, pteridophytes, aquatics, and indeterminata were excluded from the pollen sum (arboreal pollen (AP) and non arboreal pollen (NAP)=100%).

Sample preparation and analysis of macrofossils

For the Lej da San Murezzan, core-sampling resolution for macrofossil analysis was 2 cm for the Holocene (0–650 cm) and 5 cm for the Late Glacial part (650–1,160 cm). The volume was standardised to 14.8 cm^3, the original volumes were 14.8 cm^3 between 0 and 640 cm and 36.9 cm^3 between 640 and 1,160 cm of depth. The sediment was sieved with water using a mesh width of 0.2 mm. Macrofossils were identified using a stereomicroscope at 10–40x magnification. Enumeration and/or area estimation followed standard methods as outlined in Birks (2001). For detailed analyses (wings of coniferous seeds, wood, anthers), the samples were prepared and identified at higher magnification using a light microscope. Macrofossil identifications were made using the seed reference collection at the Institute of Plant Sciences, Bern, and the keys of Trautmann (1953), Katz et al. (1965), Berggren (1969, 1981), Zoller (1981), Binz and Heitz (1990), Schoch et al. (1988) and Schweingruber (1990).

Analysis of kerogen (sedimentary organic debris) and charcoal

The kerogen and charcoal were analysed on diluted pollen slides. The particles were identified and counted under a fluorescent light microscope following Tyson (1995). Charcoal particles on pollen slides can be used as a proxy for past regional fire activities (regional −20–100 km: MacDonald et al. 1991; Tinner et al.1998; Whitlock and Larsen 2001). Charcoal identification followed Clark (1988); calculation of charcoal influx and concentration was performed using the same approach as for pollen (Stockmarr 1971), following the technique developed for the Southern Alps (Tinner et al. 1998).

Presentation of diagrams and zonation

The results for pollen, macrofossils, kerogen, and loss-on-ignition (LOI) are presented as TILIA diagrams (Grimm 1992; Figs. 3–8). Pollen diagrams were zoned by optimal partitioning using sum of squares criteria (Birks and Gordon 1985), implemented with the program ZONE (for further details see Ammann et al. 2000). The number of significant pollen zones was evaluated by comparison with the broken-stick model (Bennett 1996).

Cross correlations

Lag effects of one variable on another (e.g. charcoal particles vs. pollen) may be studied with cross correlations (e.g. Green 1981, 1982; Clark et al. 1989; Tinner et al. 1999). The analysis of such palaeoecological time series is based on two general assumptions (Green 1981): (1) the time intervals between adjacent samples are equal, and (2) the data are stationary, i.e. the series contain no significant trend (e.g. expansion or decline of a species). The sequence chosen for our cross-correlation analysis (20 cm of sediment, 3900–3570 cal B.P., 1950–1620 B.C.) has an interval sample age range of 17.5±0.2 calibrated years (span), which can be considered a nearly constant time interval. This time period presents a more or less uniform vegetation type, without pronounced persisting population trends. Therefore the variables were not transformed (de-trended or/and log-transformed). This allowed a direct comparison and verification of the pollen and charcoal diagrams (cf. Tinner et al. 1999). Because fires are single events, contiguous sampling was applied for the period from 3900–3570 cal B.P. (1950–1620 B.C.). Twenty samples were used to compute cross-correlation coefficients at ±5 lags. The 95% confidence interval of the cross-correlation coefficients is estimated by computing ±2 standard errors of the correlation coefficients (Bahrenberg et al. 1992); this corresponds to a test for a significant correlation between two variables (null hypothesis $r=0$, $\alpha=5\%$, two sided).

Radiocarbon dating

Thirty-eight samples of terrestrial plant macrofossils (needles, leaves, wood, bark, periderm) from the cores of Lej da San Murezzan (PSM 90/3) and Lej da Champfèr (PCH 94/3) were radiocarbon dated by AMS (accelerator mass spectrometry) techniques at the R.J. Van de Graff Laboratory, University of Utrecht. The ^{14}C results are reported according to Stuiver and Polach (1977, Table 2) and calibrated with the program CALIB Rev 4.1 (Stuiver et al. 1998). The calibrated radiocarbon ages were smoothed by locally weighted regression (LOWESS), and the resulting depth-age models are presented in Fig. 2a, b. LOWESS was chosen because smoothing usually gives more probable sediment accumulation-rate curves when numerous dates have to be integrated in an age-depth model (Berglund and Ralska-Jasiewiczowa 1986). Two

Table 2 AMS-radiocarbon dates from Lej da San Murezzan and Lej da Champfèr

Lab. No.	Depth (cm)	Age (uncal B.P.)	Age (cal B.P.) LOWESS	$\delta^{13}C$ (‰)	Material dated
Lej da San Murezzan					
UtC-9871	142–144	1120±30	1024	−29.3	Needles
UtC-9870	226–228	1870±40	1821	−27.5	Needles
UtC-9869	330–332	3140±40	3362	−29.1	Needles
UtC-9868	382–384	3920±60	4410	−28.7	Needles
UtC-9867	400–402	3950±40	4415	−28.3	Needles
UtC-9865	436–438	4750±50	5528	−29.4	Needles
UtC-9519	454–456	5300±50	6092	−28.0	Needles
UtC-9864	462–464	5280±50	6056	−28.8	Needles
UtC-9863	476–478	5880±50	6698	−28.5	Needles
UtC-9862	500–502	6400±50	7315	−28.1	Needles, *Betula* fruit
UtC-9861	522–524	6670±50	7529	−29.1	Needles
UtC-9860	536–538	7700±70	8440	−29.7	Needles
UtC-9859	548–550	8110±60	9030	−30.0	Needles
UtC-9858[a]	556–558	6980±60	7770	−29.0	Needles, *Betula* fruit
UtC-9526	578–580	9070±70	10220	−28.3	Needles
UtC-9525	584–586	9340±60	10560	−28.6	Fruits, needles, bark
UtC-9524	596–598	9260±130	10450	−28.0	Anthers, needles
UtC-9523[a]	675–680	9420±130	10630	−28.0	Periderm, bark, seeds, wood
UtC-9857	760–765	10200±70	11840	−28.6	Wood, leaves
UtC-9522	795–800	9660±120	11140	−29.6	Leave, wood, bark
UtC-9521	895–900	10100±100	11670	−28.0	Wood
UtC-9520	925–930	10050±90	11490	−24.1	Charcoal, leaves
Lej da Champfèr					
UtC-7718	133–137	1720±40	1658	−27.4	Needles
UtC-7719	160–162	1780±40	1707	−28.0	Needles
UtC-7720	240–242	2620±40	2750	−28.1	Needles, seed
UtC-7721	287–290	2810±40	2905	−29.0	Needles, bud scale
UtC-7722	381.5–384.5	5010±50	5735	−27.2	Needles
UtC-7723	420–421	5390±50	6197	−28.2	Needles, bark
UtC-7724	452–454	7590±60	8390	−28.9	Needles, *Betula* fruit
UtC-7725	481–482	8510±60	9530	−27.7	Needles, bark
UtC-7726	487–488	8680±60	9590	−29.2	Needles
UtC-7786	493–494	8790±130	9840	−28.0	Needles, bark
UtC-7727	497–498a	9260±60	10450	−27.7	Needles
UtC-7728	497–498b	9370±60	10570	−25.7	Wood
UtC-7787	500–503	9170±100	10320	−28.0	Needles, seed, wood
UtC-7788	530–532.5	9650±120	11120	−28.0	Twig
UtC-7789	575–585	9800±160	11200	−28.0	Bark, wood, fruit
UtC-7790[a]	624–629	9400±300	10620	−28.0	*Salix herbacea* leaves, bark
UtC-7791[a]	779–789	4920±200	5630	−28.0	Bark
UtC-7792	1035–1045	10100±500	11670	−28.0	*Juniperus* needle

[a] Dates regarded as unreliable, not used in construction of chronology

dates were obviously too young and were therefore excluded from the regression: the sample from depth 556 to 558 cm consisted of one *Pinus sylvestris* needle fragment, eight *Larix* needles and one *Betula pubescens* fruit, the dry weight was 2.4 mg and contamination was unlikely. The sample from depth 675 to 680 cm consisted of coniferous periderm, leave fragments, wood, bark, and seeds of *Potentilla* and *Saxifraga,* but the weight of dry material was only 0.8 mg, which small quantity might have caused dating problems. One age was inferred from sediment changes and concentration calculations (11000 cal B.P., indicated with an arrow in Fig. 2a; Table 2) and was added to the depth-age model.

Results and interpretation

Sediment and dating

The cored sections (Lej da San Murezzan and Lej da Champfèr) consist of a gyttia between 0 - ca. 620 and 0–500 cm respectively. The lower part the Late-Glacial sediments include minerogenic, mainly silty, material (Ariztegui 1993; Ohlendorf 1999; Figs. 3 and 4). The radiocarbon dating from Lej da San Murezzan and at Lej da Champfèr gives two very similar depth-age-models (Figs. 2a, b; Table 2), indicating that both basins were influenced by similar sedimentation processes and rates. In addition, the sediment of Lej da Champfèr was dated in a former study (Ohlendorf 1999); three dated terrestrial plant material samples are given in Fig. 2b.

Biostratigraphy

At Lej da San Murezzan a total of 300 different fossil pollen, spores, kerogen and macrofossil types were identified in 700 samples. Our comparison between the two sites is based on the chronology as established by radiocarbon dates (Table 2; Figs. 2, 3, 4). Pollen

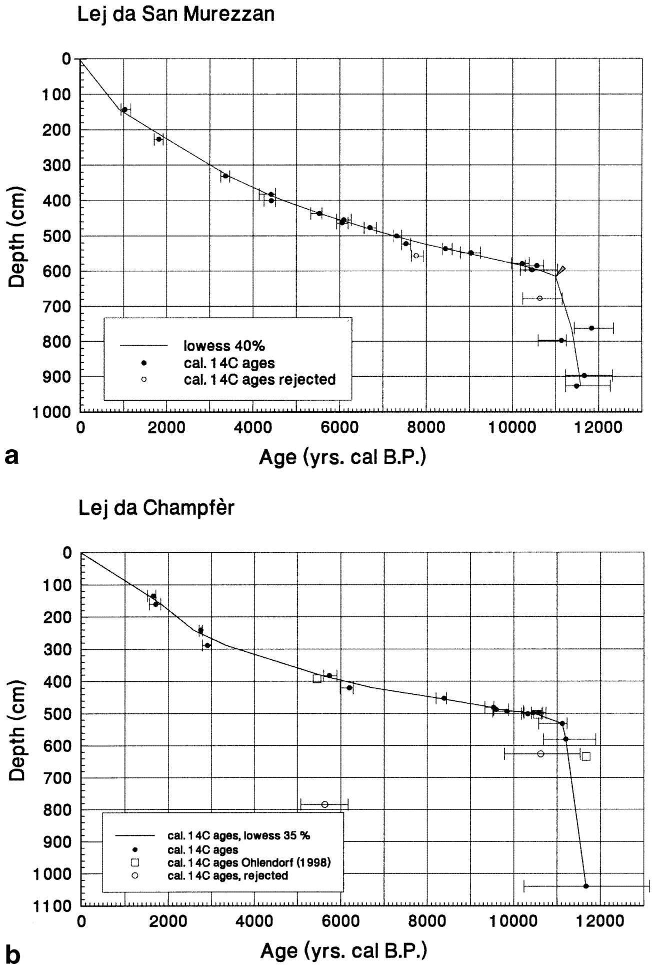


Fig. 2 **a** Radiocarbon dating of sediments from Lej da San Murezzan. *Arrow* indicates an artificial date added because of change in sediment and concentrations. *Error bars* show 2 σ span of cal age ranges. **b** radiocarbon dating of sediments from Lej da Champfèr. *Unbroken line* indicates curve fitted by locally weighted regression. *Error bars* show 2 σ span of cal age ranges

concentration values of selected types are plotted for comparison with pollen percentages (Fig. 5). In general, pollen concentrations are similar to influx values (data not shown).

Pollen

Five local pollen assemblage zones (LPAZ) are statistically significant for Lej da San Murezzan and four for Lej da Champfèr (Tables 3a, b; Figs. 3 and 4). Two important zone boundaries delimited by ZONE for Lej da Champfèr (CH-2a/2b and CH-4a/4b) were statistically not significant and are indicated as sub-zones for better comparison with Lej da San Murezzan (Fig. 4). For the time period 6150 to 1500 cal B.P. we plotted a more detailed diagram for Lej da San Murezzan (Fig. 6) to show the transition from a stable, mainly natural system to periods showing increasing prehistoric human impact (Neolithic to Roman Times). Since *Larix* pollen are poorly dispersed and thus underrepresented, the *Larix decidua* pollen percentage curve was tentatively corrected, only in the main pollen diagram of Fig. 6, using the correction factors of Lang (1994).

The pollen stratigraphy of Lej da San Murezzan can be summarised as follows: In LPAZ SM-1 (1,160–625 cm, 11800–11000 cal B.P., 9850–9050 B.C.) *Pinus* (probably *P. sylvestris* and/or *P. mugo*) pollen dominates. Other important pollen types are Poaceae, *Artemisia* and Chenopodiaceae. The end of the zone is characterised by the increasing importance of *Juniperus* and *Hippophaë.* In SM-2 (625–501 cm, 11000–7300 cal B.P., 9050–5350 B.C.) arboreal pollen (AP, sum of tree and shrub pollen) reaches maximum percentage values of over 95% and is dominated by *Pinus, Pinus cembra,* and to a minor degree *Betula* and *Larix*. Subsequently *Picea* was the most important pollen type in zone SM-3 (501–359 cm, 7300–3900 cal B.P., 1950–5350 B.C.). In addition to *Picea, Pinus, Pinus cembra, Alnus viridis,* and *Abies alba* also showed considerable values. During SM-4 (359–145 cm, 3900–1100 cal B.P., 1950 B.C.–A.D. 850) tree pollen (mainly *Picea, Pinus, Pinus cembra* and *Larix*) reaches average values of only 60%, whereas *Alnus viridis* as the most important shrub reaches maximum values of over 50%. Poaceae, monolete fern spores (up to 12%), and other pollen indicative of anthropogenic activities increase. During the youngest section (LPAZ SM-5, -40–1100 cal B.P., 1990–A.D. 850), non-arboreal pollen (NAP) reaches values of over 50%, whereas *Alnus viridis* percentages were lower than in the former zone, reaching about 15%. Poaceae pollen increases to over 30% and the pollen of other herbaceous taxa such as Cichorioideae and *Plantago alpina* reach their peak in this zone. The monolete fern spores decrease markedly but still reach average values of 2.5%.

The pollen stratigraphical characteristics of Lej da Champfèr are similar to those of Lej da San Murezzan. During LPAZ CH-1 (1,150–545 cm, 11800–11150 cal B.P., 9850–9200 B.C., Fig. 4) the non-arboreal pollen (NAP, dominated by *Artemisia* and Poaceae) reaches values >35%. *Pinus* pollen is dominant and the *Juniperus* percentage values fluctuated around 5%. The sub-zone LPAZ CH-2a (545–502 cm, 11150–10600 cal B.P., 9200–8650 B.C.) shows a prominent peak in *Hippophaë* pollen and can be considered as transitional between LPAZ CH-1 and LPAZ CH-2b (10600–8800 cal B.P., 8650–6850 B.C.), when Poaceae, *Artemisia* and *Juniperus* percentages strongly decreased. The high percentages of tree pollen (95%) decreases towards the end of zone CH-3 (465–380 cm, 8800–5500 cal B.P., 6850–3550 B.C.) in favour of *Alnus viridis. Picea* also increases, reaching values up to 25%, whereas *Pinus cembra* pollen decreases. In LPAZ CH-4a (380–100 cm, 5500–1200 cal B.P., 3550 B.C.–A.D. 750) the pollen of *Picea, Pinus* and *Alnus viridis* is still important, although NAP increases considerably. During the past 1,200 years corresponding to zone CH-4b, NAP increases and reaches maximum values of ca. 40% after A.D. 1200.

Table 3 Local Pollen Assemblages Zones: Lej da San Murezzan

LPAZ	Depth (cm)	Age cal B.P. (A.D./B.C.)	Main curves (estimated averages)	Important subalpine pollen and spore taxa	Important macrofossil	Important kerogen
SM-5	1–145	−40–1100 cal B.P. (A.D. 1990–850)	35% trees, 15% shrubs, 50% herbs	Poaceae, *Alnus viridis, Pinus, Picea, Pinus cembra t.,* Cichorioideae, *Plantago alpina, Larix, monolete spores*	*Larix decidua* needles, wood (area), charcoal (area)	Non-woody plant material, wood fragments, charcoal, fungi (spores, fruit bodies)
SM-4	145–359	1100–3900 cal B.P. (A.D. 850–1950 B.C.)	60% trees, 25% shrubs, 15% herbs	*Picea, Alnus viridis, Pinus, Pinus cembra t.,* Poaceae, Monolete fern spores, *Larix*	*Larix decidua* needles, periderm and wood (area), charcoal (area)	Non-woody plant material, wood fragments, fungi (spores, fruit bodies), charcoal particles
SM-3	359–501	3900–7300 cal B.P. (1950–5350 B.C.)	90% trees, 5% shrubs, 5% herbs	*Picea, Pinus, Pinus cembra t., Alnus viridis, Abies alba*	*Larix decidua* needles, *Picea abies* (needles, seeds, anthers), leaves and leave fragments, periderm and wood (area), charcoal (area)	Non-woody plant material, wood fragments, fungi (spores, fruit bodies), charcoal particles
SM-2	501–625	7300–11000 cal B.P. (5350–9050 B.C.)	95% trees, 5 % herbs	*Pinus, Pinus cembra t., Betula, Larix*	*Larix decidua* and *Pinus cemba* needles, *Pinus sylvestris and Pinus mugo* (needls, seeds, short sprouts), periderm and wood (area), *Betula* (seeds, fruit scales)	Non-woody plant material, algae cysts, wood fragments, fungi, pollen
SM-1	625–1160	11000–11800 cal B.P. (9050–9850 B.C.)	55% trees , 5% shrubs, 40% herbs	*Pinus,* Poaceae, *Artemisia, Juniperus,* Chenopodiaceae	Leaves and herbs	Charcoal, pollen

Macrofossils

Our continuous macrofossil record of Lej da San Murezzan attains a mean sample resolution of ca. 30 years. Since for macrofossils it is usually possible to reach higher taxonomic resolutions than for pollen, they provide a valuable insight into the local vegetation history around the site. In this paper, we focus on the period 6100–1500 cal B.P. (4150 B.C. to A.D. 450). Macrofossils of *Larix decidua, Pinus cembra* and *Picea abies* were frequent around 6000 cal B.P. (>20 needles/14.8 cm^3). Around 5500 cal B.P. (3550 B.C.) *Larix* needle concentrations decreased to a minimum, whereas in the following samples periderm and wood remains, macroscopic charcoal, leaf remains, and *Picea abies* needles increased strongly. During and after this change, *Larix* needle concentrations increased again, with the exception of the sample at 4700 cal B.P. (2750 B.C.) where they failed to reach their former values. At 4800–4650 cal B.P. (2850–2700 B.C.) charcoal, charred plant material (*Larix* needles), periderm, wood and leaves also showed distinct peaks. During LPAZ SM-3 (7300–3900 cal B.P., 5350–1950 B.C.) *Picea* needles reached maximum values, whereas only single needles were present in zone SM-4 (3900–1100 cal B.P., 1950 B.C.–A.D. 850). In contrast *Larix* needle concentrations did not decrease between 4700 cal B.P. (2700 B.C.) and 1000 cal B.P. (A.D. 950). Macroscopic charcoal particles reached high values at 5400 and 4700 cal. B.P. (3450–2750 B.C.). Between 4500 cal B.P. (2550 B.C.) to 3700 cal B.P. (1750 B.C.) macroscopic charcoal was deposited virtually continuously into the lake sediments, reaching a transient maximum between 4100 and 4000 cal B.P. (2150–2050 B.C.). Other charcoal maxima occurred at ca. 2800 cal B.P. (850 B.C.) and around 2000 cal B.P. (50 B.C.; Fig. 7).

Kerogen

The kerogen data (Fig. 8) support and strengthen the pollen and macrofossil results, although their resolution is generally much lower. The results presented here cover the time period 6200–1500 cal B.P. (4250 B.C.–A.D. 450, LPAZ SM-3 and SM-4 partially). Wood, fungi, and charcoal concentrations showed several peaks between 5500–5200 cal B.P. (3550–3250 B.C.), at around 4500 cal B.P. (2550 B.C.), 3800 cal B.P. (1850 B.C.), between 3000–2700 cal B.P. (1050–750 B.C.) and at around 1900 cal B.P. (A.D. 50).

Charcoal stratigraphy and cross-correlations

Charcoal concentration and charcoal influx values show very similar trends, except for the Late Glacial part (Fig. 5b). In the Holocene, charcoal influx values are not affected by calculation artefacts, whereas for the Late-

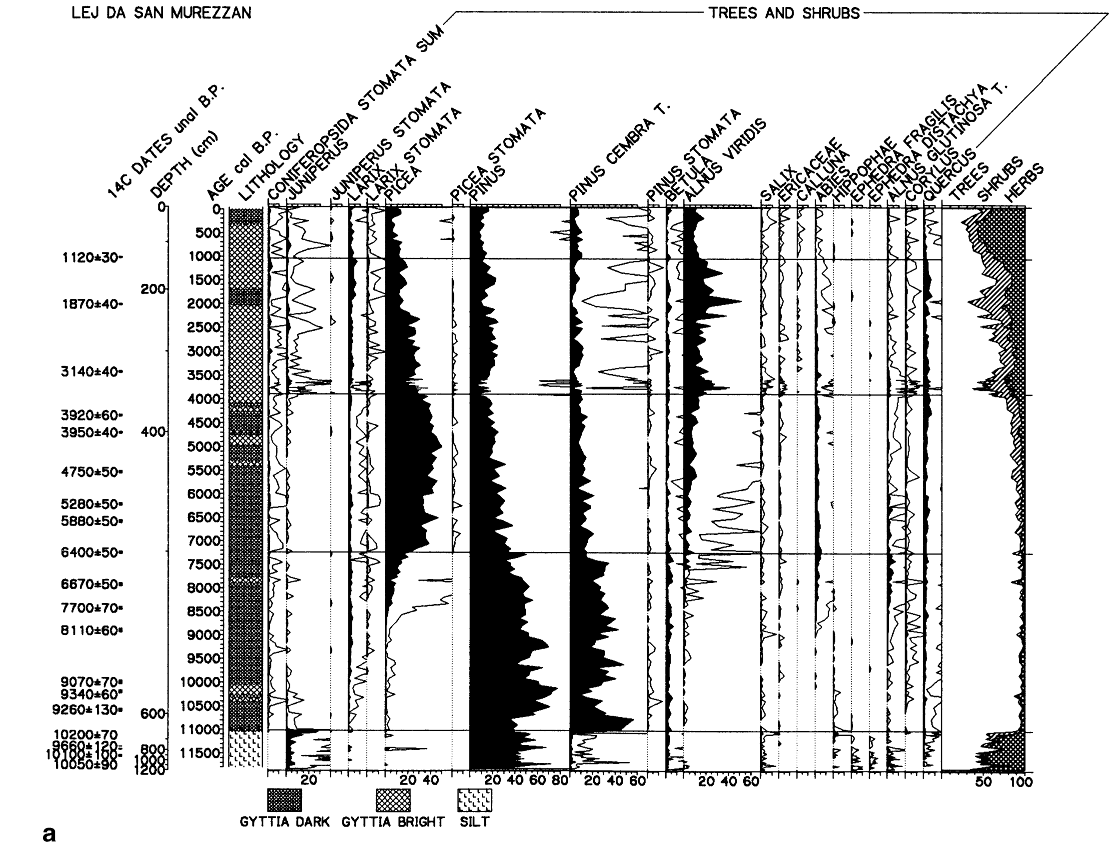


Fig. 3 Percentage diagram from Lej da San Murezzan (selected taxa). Exaggeration (x10) is indicated by *line*. Analysts: E. Gobet; between 3900 and 3570 cal B.P. E. Gobet and J.F.N. van Leeuwen

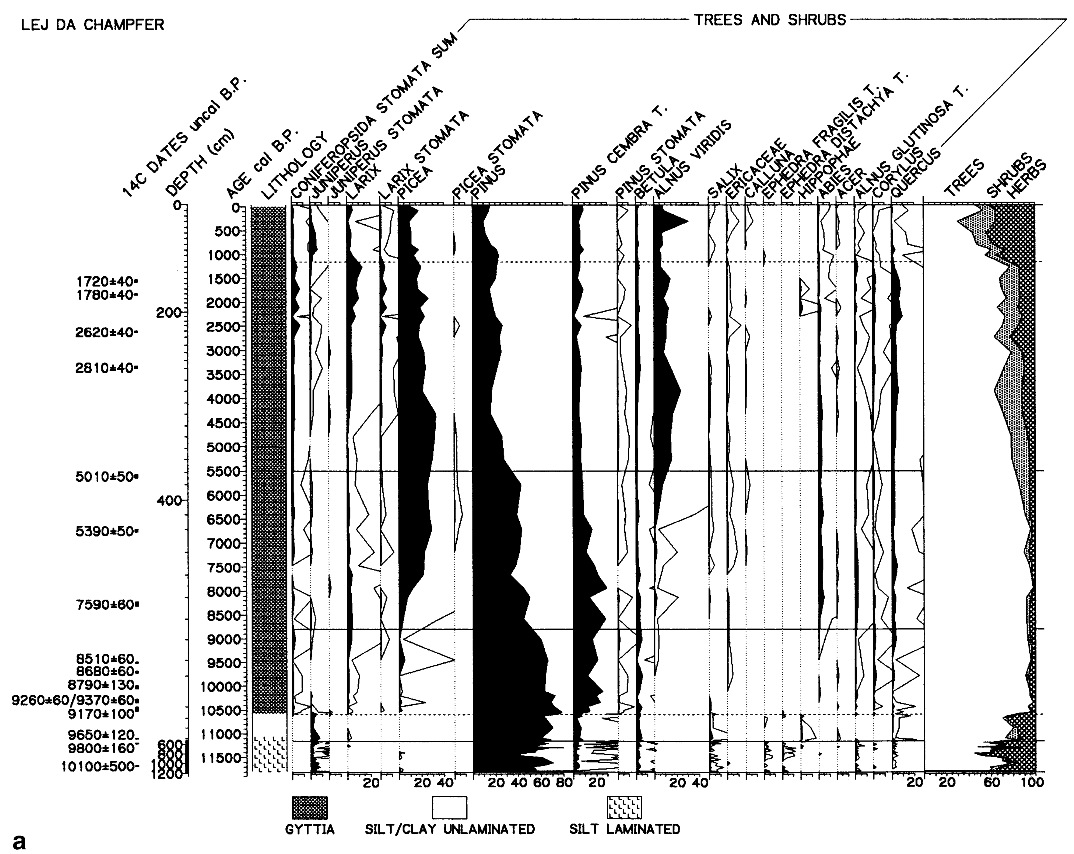
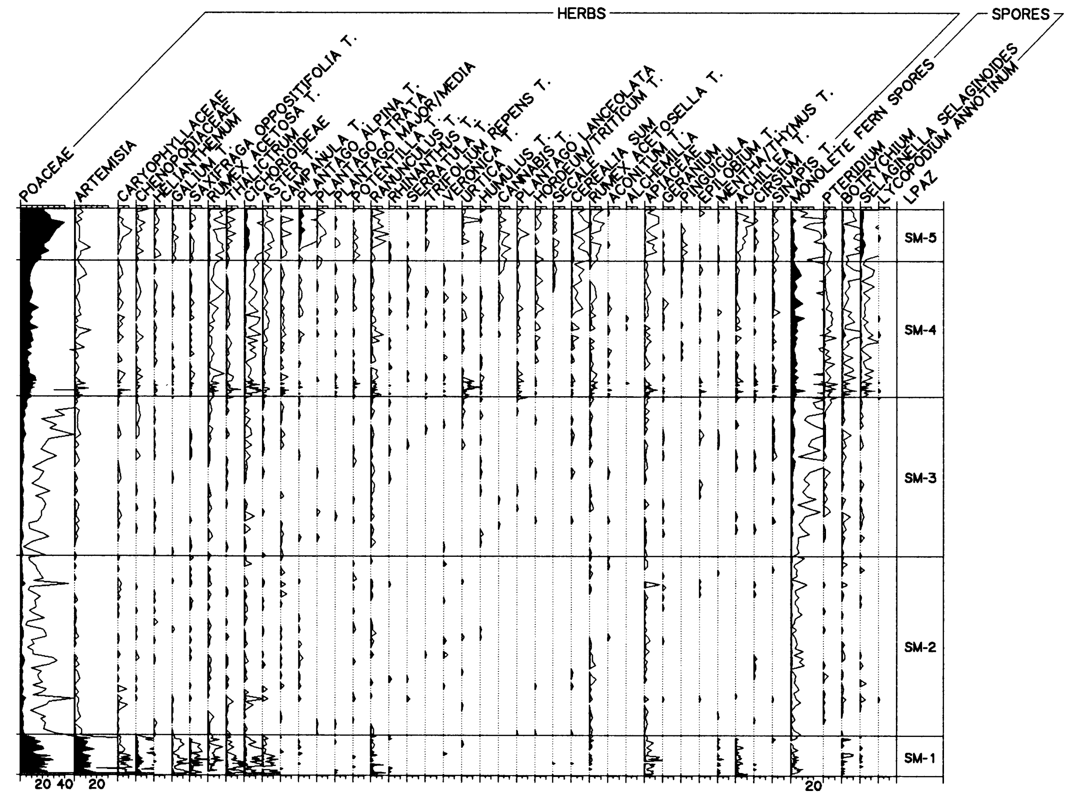
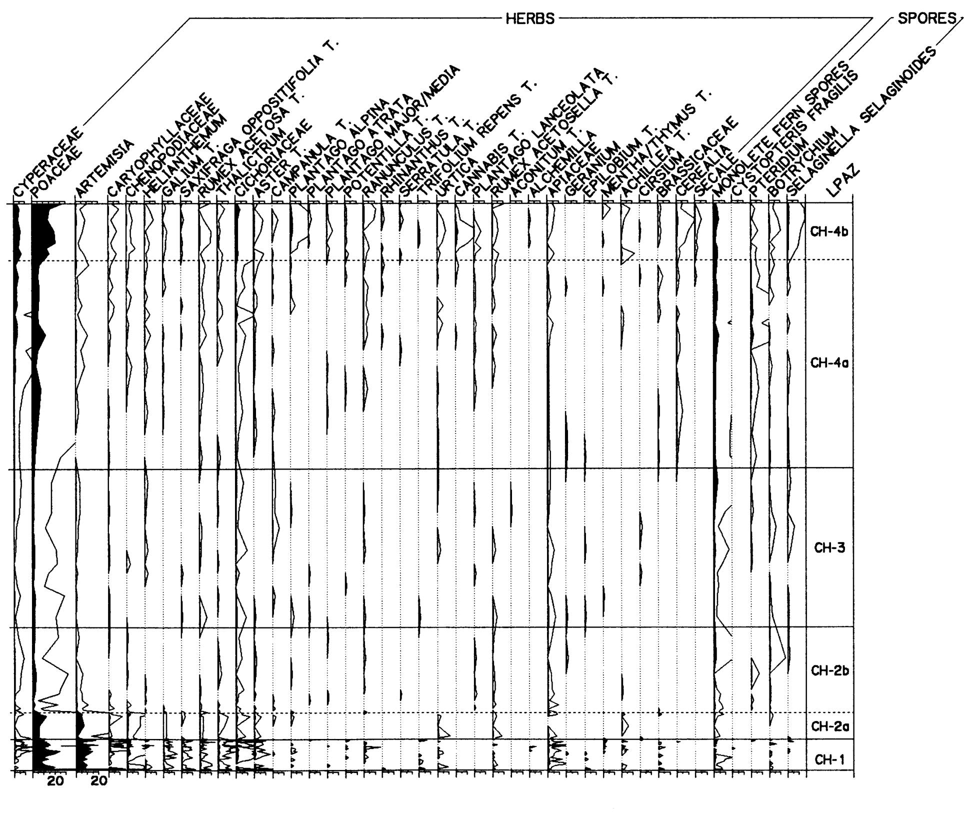


Fig. 4 Percentage diagram from Lej da Champfèr (selected taxa). Exaggeration (x10) is indicated by *line*. Analyst: E. Gobet


HERBS
SPORES
POACEAE
ARTEMISIA
CARYOPHYLLACEAE
CHENOPODIACEAE
HELIANTHEMUM
GALIUM T.
SAXIFRAGA OPPOSITIFOLIA T.
RUMEX ACETOSA T.
THALICTRUM
CICHORIOIDEAE
ASTER T.
CAMPANULA T.
PLANTAGO ALPINA T.
PLANTAGO ATRATA
PLANTAGO MAJOR/MEDIA
POTENTILLA T.
RANUNCULUS T.
RHINANTHUS T.
SERRATULA T.
TRIFOLIUM REPENS T.
VERONICA T.
URTICA
HUMULUS T.
CANNABIS T.
PLANTAGO LANCEOLATA
HORDEUM/TRITICUM T.
SECALE
CEREALIA SUM
RUMEX ACETOSELLA T.
ACONITUM T.
ALCHEMILLA
APIACEAE
GERANIUM
PINGUICULA
EPILOBIUM T.
MENTHA/THYMUS T.
ACHILLEA T.
CIRSIUM
SINAPIS T.
MONOLETE FERN SPORES
PTERIDIUM
BOTRYCHIUM
SELAGINELLA SELAGINOIDES
LYCOPODIUM ANNOTINUM
LPAZ
SM-5
SM-4
SM-3
SM-2
SM-1
20 40
20
20

b


HERBS
SPORES
CYPERACEAE
POACEAE
ARTEMISIA
CARYOPHYLLACEAE
CHENOPODIACEAE
HELIANTHEMUM
GALIUM T.
SAXIFRAGA OPPOSITIFOLIA T.
RUMEX ACETOSA T.
THALICTRUM
CICHORIACEAE
ASTER T.
CAMPANULA T.
PLANTAGO ALPINA
PLANTAGO ATRATA
PLANTAGO MAJOR/MEDIA
POTENTILLA T.
RANUNCULUS T.
RHINANTHUS T.
SERRATULA T.
TRIFOLIUM REPENS T.
URTICA
CANNABIS T.
PLANTAGO LANCEOLATA
RUMEX ACETOSELLA T.
ACONITUM T.
ALCHEMILLA
APIACEAE
GERANIUM
EPILOBIUM T.
MENTHA/THYMUS T.
ACHILLEA T.
CIRSIUM
BRASSICACEAE
CEREALIA
SECALE
MONOLETE FERN SPORES
CYSTOPTERIS FRAGILIS
PTERIDIUM
BOTRYCHIUM
SELAGINELLA SELAGINOIDES
LPAZ
CH-4b
CH-4a
CH-3
CH-2b
CH-2a
CH-1
20
20

b

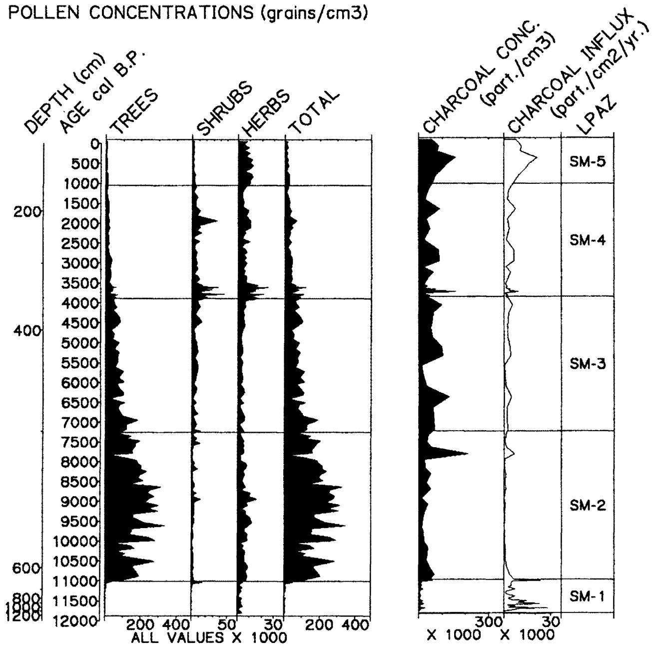


Fig. 5 Pollen concentrations of trees, shrubs and herbs (grains/cm^3), charcoal particle concentrations (particles/cm^3) and influx (particles/cm^2/year) from Lej da San Murezzan. All values x1000. Charcoal analysts: E. Gobet and W. Tinner

Glacial sections high sedimentation rates bias the calculations. A first marked increase of charcoal influx occurred at 5500–5400 cal B.P. (3550–3450 B.C.). After this rise, the charcoal influx values never fell back to the level of before 5500 cal B.P. (3550 B.C.). Five major charcoal influx peaks were dated at ca. 5350–5150, 4100, 3750, 3000–2700, and 1700 cal B.P. (3400–3200, 2150, 1800, and 1050–750 B.C., and A.D. 250) with the absolute maximum reached at c. 3750 cal B.P. (1800 B.C.). In comparison with sites in the nearby southern Alps the charcoal peak values seem rather low at ca. 4000–9000 particles cm^{-2} yr^{-1}, corresponding to ca. 1.5–3.0 mm^2 cm^{-2} yr^{-1}, according to the regression equation defined in Tinner et al. (1998). We performed a cross-correlation analysis for the time period between 3900 and 3570 cal B.P. (1950–1620 B.C., Figs. 9, 10). The results can be summarised as follows: a first group of taxa (e.g. *Larix, Betula, Pinus cembra,* Coniferopsida stomata, see Fig. 9, Nr. 1–4) shows significant negative correlations between charcoal and pollen with a maximum at lag 0. Cichorioideae and *Helianthemum* show significant positive correlation at time lag 1(Fig. 9, No. 5–6). A third group (e.g. *Alnus viridis*, monolete fern spores, *Botrychium*, *Selaginella selaginoides*, Caryophyllaceae, Fig. 9, No. 7–11) is characterised by significant positive correlations with a maximum at lag 0. The next group shows significant positive correlations after lag 0 (e.g. *Aconitum, Aster* t., *Epilobium, Thalictrum*, Apiaceae, *Cercophora* spores at lags +1 to +2, *Urtica* at lag +4, Fig. 9, No. 12–18). Finally, a last group of pollen taxa (e.g. *Picea abies* and *Pinus sylvestris,* Fig. 9 No. 19–20) shows no significant correlations with charcoal. This group also includes Cerealia, *Juniperus, Plantago lanceolata*, *P. alpina, P. atrata, P, major, Pteridium* and *Rumex acetosella.*

Pollen and macrofossil-inferred vegetation history

The biostratigraphic record of Lej da San Murezzan suggests the presence of an open pioneer vegetation formed by grasses, *Artemisia,* Chenopodiaceae and other herbs (local pollen assemblage zone LPAZ (SM1, 11800–11000 cal B.P., 9850–9050 B.C., Figs. 3, 6). After this pioneer phase, successional processes culminated in afforestation around the site at 11000 cal B.P. Pollen data suggest that this process included the population expansions of the shrubs *Juniperus, Hippophaë,* and *Salix* (Fig. 7), although only one *Juniperus communis* ssp. *alpina* needle was found. *Betula alba* type fruits and fruit scales were found at around this time, indicating that this taxon was also involved in afforestation. *Pinus sylvestris* t. arrived at this time, since needles were found around 10950 cal B.P. Forest development is also indicated together with peaks in macrofossil wood and periderm fragments (Tables 3 and 4). In agreement with the pollen

Table 4 Local Pollen Assemblages Zones: Lej da Champfèr

LPAZ	Depth (cm)	Age cal B.P. (A.D./B.C.)	Main Curves (estimated averages)	Important sub alpine pollen taxa
CH-4b[a]	1–100	–40–1200 cal B.P. (A.D. 1990–750)	45% trees 20% shrubs 35% herbs	Poaceae, *Pinus, Picea, Alnus viridis, Juniperus,* Cyperaceae, *Larix, Betula*
CH-4a[a]	100–380	1200–5500 cal B.P. (A.D. 750–3550 B.C.)	75% trees 15% shrubs 10% herbs	*Picea, Pinus, Alnus viridis, Pinus cemba t.,* Poaceae, *Larix*
CH-3	380–465	5500–8800 cal B.P. (3550–6850 B.C.)	90% trees 5% shrubs 5% herbs	*Pinus, Picea, Pinus cembra t., Larix, Abies, Alnus viridis*
CH-2b[a]	465–502	8800–10600 cal B.P. (6850–8650 B.C.)	95% trees 5% herbs	*Pinus, Pinus cembra t., Betula*
CH-2a[a]	502–545	10600–11150 cal B.P. (8650 B.C.–9200 B.C.)	75% trees 5% shrubs 20% herbs	*Pinus, Pinus cembra t.,* Poaceae, *Artemisia, Juniperus, Betula*
CH-1	545–1150	11150–11800 cal B.P. (9200–9850 B.C.)	60% trees 5% shrubs 35% herbs	*Pinus,* Poaceae, *Artemisia, Juniperus, Pinus cembra t.*

[a] Zones statistically not significant

record, first needles of *Larix decidua* indicate the arrival of this species at around 10650 cal B.P., whereas the expansion of *Pinus cembra* seems somewhat delayed according to the needles (10400 cal B.P.) but not to the pollen (10950 cal B.P.). Between 10400 and 7300 cal B.P. (8450–5350 B.C., SM-2), dense *Pinus cembra* and larch forests occurred around the lake as indicated by AP percentages >90%. Based on the pollen record it is likely that *Abies alba* and *Alnus glutinosa* t. were regionally present at least at 8500 cal B.P. (6550 B.C.). However, local presence of *Abies alba* in the surroundings of the lake is not documented by stomata or macrofossils. The Holocene population expansion of *Picea abies* occurred at about the same time (Fig. 3), although its local presence is documented only 1,300 years later by stomata and needles at around 7200 cal B.P. (5250 B.C.). *Alnus viridis* was probably present in the region from about 8200 cal B.P. (continuous curve, Fig. 3), but its expansion was lagged and covered several millennia (most of zone SM-3, Fig. 3). During SM-3 (7200–3900 cal B.P., 5250–1950 B.C.) the vegetation was characterised by forests dominated by *Picea* and *Larix,* whereas *Pinus cembra* trees were less frequent than before. Towards the end of this period (3900 cal B.P., 1950 B.C.) *Alnus viridis* thickets became more common and the first meadows were established, as indicated by elevated NAP values (especially grasses). Some habitats were probably anthropogenically disturbed, as indicated by the increase of monolete fern spores, *Botrychium*, *Selaginella* and *Pteridium*. The pollen record during the subsequent period (3900–1100 cal B.P., 1950 B.C.–A.D. 850) shows that *Picea abies* and *Pinus cembra* became rarer, whereas other trees and shrubs such as *Larix, Juniperus,* and *Alnus viridis* were more common. More frequent findings of Cerealia, *Rumex acetosella, Plantago lanceolata, Urtica,* Cichorioideae and many other herbaceous taxa (Fig. 3) point to a marked increase in human activities after 3900 cal B.P. (1950 B.C.). These trends to a more open landscape and an increased anthropogenic impact continued between 1100 and −40 cal B.P. (A.D. 850–1990, SM-5), although the last 100–150 years were characterised by the beginning of reforestation.

In general, the vegetation histories of Lej da San Murezzan and Lej da Champfèr are very similar. Open pioneer vegetation was present at ca. 11800 cal B.P. (9850 B.C., CH-1; Figs. 4 and 8) at the end of the Late Glacial. The first unambiguous evidence of afforestation is dated at around 10500 cal B.P. These early sub-alpine forests were formed by *Larix* (pollen, stomata and needles), *Pinus cembra* (pollen and needles) and *Betula alba* (pollen and fruits). Closed forests persisted until 5500 cal year B.P. (3550 B.C., LPAZ CH-2 to LPAZ CH-3). *Picea abies* expanded at 8000 cal B.P. at the latest, but the local presence of the taxon is documented only at ca. 7000 cal B.P. (5050 B.C.) with stomata findings. Vegetation was more open after 5500 cal B.P. (3550 B.C., an increase in NAP, coinciding with a significant zone change, Fig. 4). The pollen record suggests that with the exception of *Picea* all coniferous trees declined. Subsequently sub-alpine forests were dominated by *Picea abies*, whereas the more open habitats were occupied by *Alnus viridis* thickets. At ca. 4300 cal B.P. *Larix* trees, *Juniperus* shrubs, and herbaceous taxa (e.g. Poaceae, *Artemisia*, Cichorioideae) growing in meadows became more abundant. Around 1100 cal B.P. (A.D. 850) the remaining arboreal vegetation was drastically reduced, whereas species of open habitats and meadows expanded strongly.

Kerogen-based interpretation of environmental history

Most peaks of the kerogen types, wood, fungi, and charcoal concentrations (5500–5200 cal B.P., 3550–3250 B.C.; 4500 cal B.P., 2550 B.C.; 3800 cal B.P., 1850 B.C.; 3000–2700 cal B.P., 1050–750 B.C., and at around 1900 cal B.P., A.D. 50) coincided with cultural periods, as documented by pollen indicative of anthropogenic activities. The shape of the kerogen curves suggests that kerogen deposited in the lake sediments documents phases of increased human impact. Microscopic wood and fungi accumulations could be interpreted as dead biomass accumulations of wood in a more open landscape that was susceptible to soil erosion through human activities.

Long-term fire ecology as indicated by cross-correlation analysis

The calculation of cross-correlations for the period 3900–3570 cal B.P. (1950–1620 B.C.) indicates that tree taxa such as *Larix*, *Betula*, and *Pinus cembra* declined in response to increased fire occurrence. Conversely, *Alnus viridis* and some herbaceous taxa (Caryophyllaceae, monolete ferns, *Botrychium*, *Selaginella selaginoides*) took advantage of the increased fire disturbance immediately (within the sample resolution of 0–17 years). Other taxa, most of them upland herbs (e.g. *Aconitum, Epilobium, Thalictrum*, Apiaceae) and *Cercophora* at lags +1, expanded only with a delay of ca. 17–35 years, *Aster* t. 35–52, and *Urtica* 68–85 years after the fire increase. These patterns are similar to those observed in the lowlands of the Southern Alps, where in response to fire, shrub and herbaceous species could expand at the cost of coniferous and deciduous late-successional tree species (Tinner et al. 1999). As for the Southern Alps, the most likely interpretation is that the local Bronze Age settlers set fire to the forests to gain open space for agricultural purposes. This interpretation is sustained by the general increase of pollen indicative of anthropogenic activities at the beginning of zone SM-4 (3900 cal B.P., 1950 B.C.). The first environmental response to fire (the increase of agriculturally less attractive opportunists such as ferns and *Alnus viridis*) was probably not intended by man. Our results indicate that only decades after the fire a new environment better adapted to human needs was formed. In fact, some of the taxa that followed some decades after

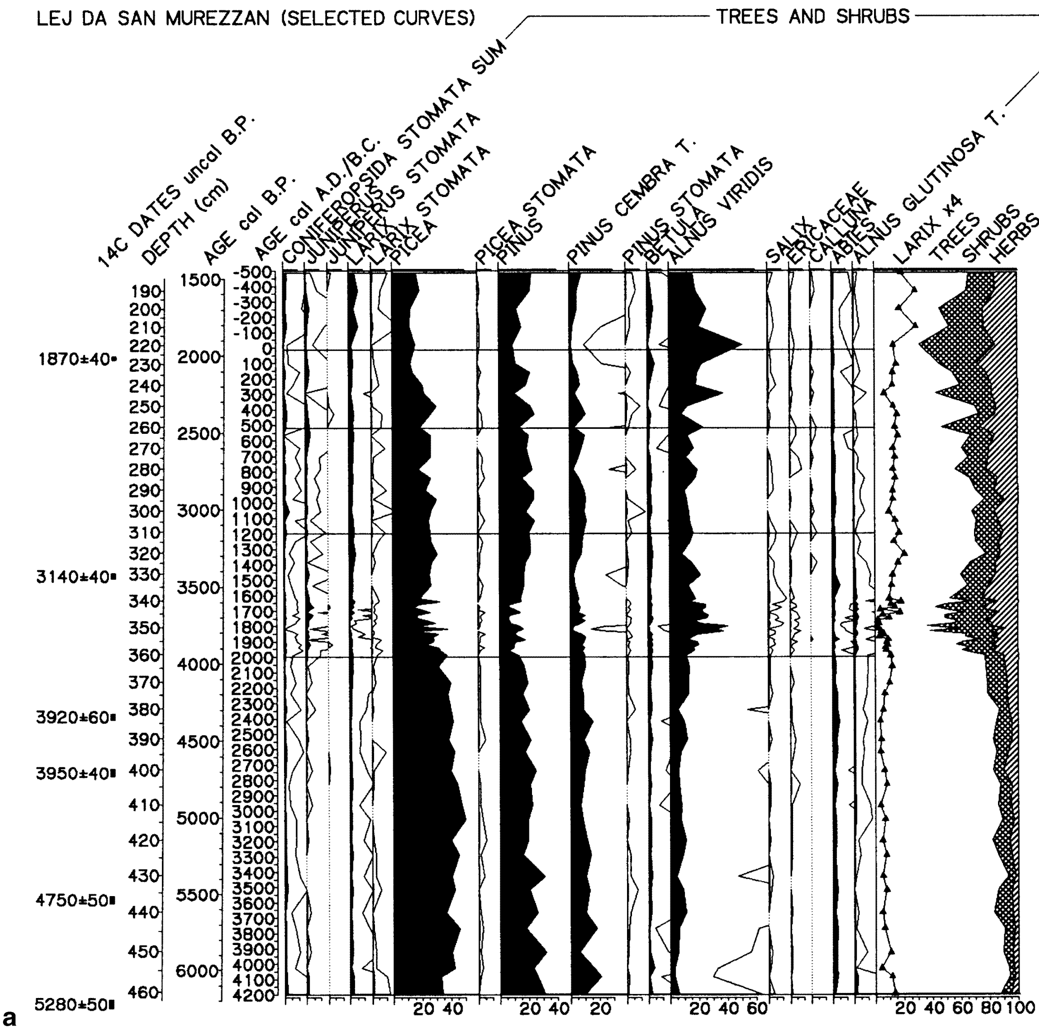


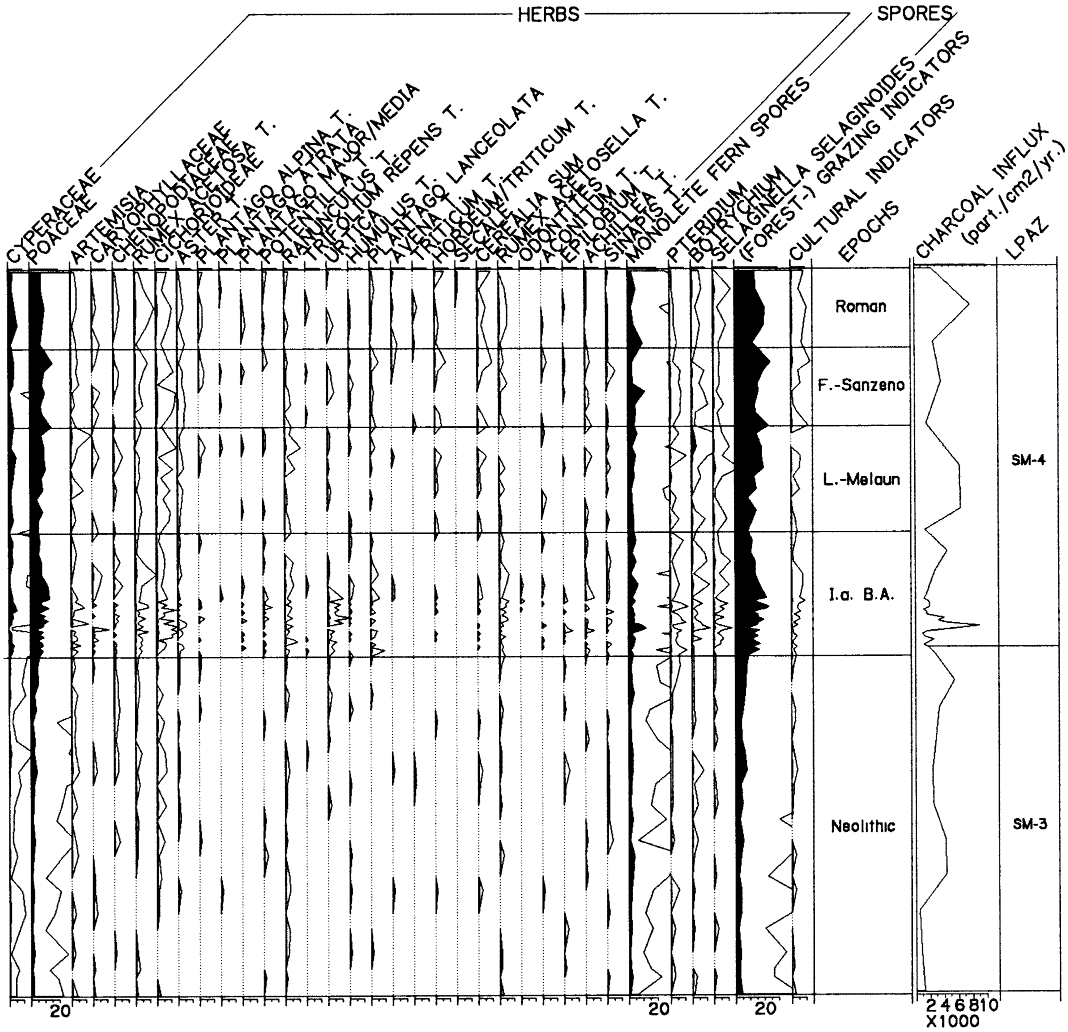
Fig. 6a, b Percentage diagram from Lej da San Murezzan (selected taxa), time window 6100 to 1500 cal B.P. Exaggeration (x10) is indicated by *line*. *Larix* curve (*Larix* x4) in main pollen percentage diagram is corrected by correction factor as suggested by Lang (1994) before percentage calculations. (Forest-) grazing indicators according to Lang (1994), cultural indicators: cereals and field weeds according to Lang (1994) and Burga (1998). Epochs from 15 to 2000 B.C. according to the chronological scheme for the Engadine (Rageth 2000a): *F. Sanzeno* Fritzens-Sanzeno, *L.-Melaun* Laugen-Melaun, *I.a. B.A.* Inner alpine Bronze Age

fire are of great pastoral interest (e.g. meadow species *Aster* t., *Thalictrum*, Apiaceae). Cichorioideae and *Helianthemum* show correlations before the fire (17–35 years), possibly indicating early human presence in the area prior to increased fire occurrence.

Discussion

Pre-Bronze Age signal of human influence in the Upper Engadine

During the period before 5500 cal B.P. (3550 B.C.) there is no unambiguous evidence of human activities around the lakes. It is likely that the first human-induced changes to the vegetation started ca. 5500 cal B.P. (3550 B.C.) as documented by openings in the forest. These forest disruptions took place during a period with relatively warm climate (between CE-5 to CE-6, 5600–5300 cal B.P., 3650–3350 B.C.; Haas et al. 1998) and are reflected at both study sites, though only at Lej da Champfèr they led to a statistically significant LPAZ boundary (CH-3 to CH-4a). The expansion of *Alnus viridis* shrubs (one *Alnus viridis* leaf found at 5450 cal B.P., 3500 B.C.) and grasses coincides with microscopic and macroscopic charcoal increases (Figs. 7 and 8), as well as the appearance of single Cerealia pollen grains. These findings are in agreement with timberline studies in the Alps at Lago Basso (Italy) and Gouillé Rion (western Switzerland, Wick and Tinner 1997), where the expansion of *Alnus viridis* was explained by Neolithic human impact (as documented for example by increasing charcoal values). Simultaneously, between 5700 and 5100 cal B.P., anthropogenic fires and agricultural activities led to large



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changes in vegetation in the lowlands of the Southern Alps such as the extinction of *Abies alba* (Tinner et al. 1999, 2000). Moreover, during this period the "Iceman Ötzi" passed over the Alps, indicating human use of subalpine and alpine environments (Rom et al. 1999). Thus it is likely that increasing anthropogenic activities in the nearby southern lowlands of the Alps coincided with a warm period. This combination of favourable climatic and economic conditions promoted an extension in land use to the Upper Engadine lake region. Although archaeological findings for the Neolithic period in the Upper Engadine are rather sparse and permanent settlements are not indicated by archaeological remains (Nauli 1981; Rageth 2000b), it seems very likely that Neolithic people were interested in this region for several reasons, including grazing, hunting, fishing, and trade over the Alpine passes (Curdy et al. 1998). On the basis of our results, it even seems likely that this favourable period saw the onset of a permanent landnam in the Upper Engadine.

The early Bronze Age: a transition from quasi-natural forest ecosystems to a cultural landscape dominated by anthropogenic *Larix* meadows and *Alnus viridis* maquis

Around 3900 cal B.P. (1950 B.C.) a marked change in vegetation occurred in the Upper Engadine lake region coinciding with the beginning of the Bronze Age (Table 2, Rageth 2000a). A general economic upturn and a persistent regional population growth at around 3900 cal B.P. (1950 B.C., Bätzing 1991) probably led to an intensified land use and to a denser settlement in the climatically favoured inner-alpine dry valleys. The importance of copper deposits in the Alps was also important for settlement activities (Rageth 2000a; Bätzing 1991). The nearby Oberhalbstein was settled from at least 3900 cal B.P. for stock and field farming, and the processing of copper (Rageth 2001). Until now only one outcrop of copper processing has been found in the Upper Engadine region, near Madulain (Fig. 1, Schweizer 1982 and Rageth, personal communication). Similarly, no archaeological evidence for settlement in the Upper Engadine during the Early Bronze Age has been found

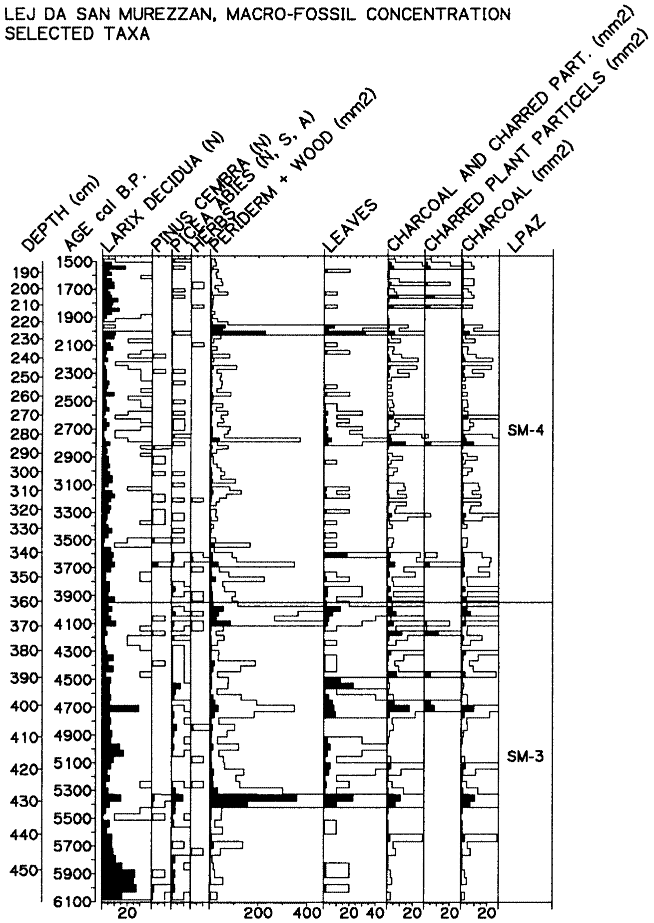

Fig. 7 Macrofossil concentrations (selected taxa) from Lej da San Murezzan. Time window 6100 to 1500 B.P. cal. Analyst: E. Gobet

till now (Nauli 1981; Rageth 2000b), but single findings date back to the this period (Conrad 1981).

According to Magny et al. (1998) and Haas et al. (1998), climatic conditions during the Early Bronze Age were favourable for agriculture (warm and dry, between the cold periods CE-6 and CE-7). This phase of positive climatic conditions in the Alps and the surrounding lowlands as well as the geological resources (copper-bearing rocks) and the introduction of copper/bronze tools might have induced an increase of human activities in the study region, although archaeological evidence for settlements does not yet exist. In fact, only permanent and noticeable agricultural activities could explain the large-scale anthropogenic reshaping of vegetation observed at the boundary of LPAZ SM-3 to SM-4. Tinner et al. (2003) proposed several climatically driven phases of agricultural intensification during the Bronze Age, the Iron Age and the Roman period. Most of these phases and especially those of the Bronze Age are also clearly documented in the Engadine (Table 5; 2100–1900 B.C., 1750–1650 B.C., 1450–1250 B.C., 50 B.C.–A.D. 100; for correlation with palaeoclimatic proxies such as Alpine dendroclimatic records and oxygen isotopes see Tinner et al. 2003).

Table 5 Prehistoric farming periods in relation to climate. Number of + corresponds to the number of localities

B.C.	cal B.P.	NA, SA	LE	UE
			*	+ (1)
100	1850	++++	+	+ (1)
		++++	*	+ (1)
0	1950	++++	*	+ (1)
		++++	+	+ (1)
100	2050			++ (2)
200	2150		*	
300	2250			+ (3)
			++	
400	2350		++ **	
		++++	++	
500	2450	++++	++	+ (4)
		++++	++ *	
600	2550	++++	++ *	
		++++	++	
700	2650		++	+ (2)
			++ *	+ (2)
800	2750	(+++)	**	++ (5)
900	2850			
1000	2950			
			*	
1100	3050		+	
			+	
1200	3150		+	
		++++	+	
1300	3250	++++	+++	+ (6)
		++++	++ *	
1400	3350	++++	++	+ (7)
		++++	++	+ (8)
1500	3450		++ *	
			++	
1600	3550		++ *	+ (2)
		++	++ *	+ (2)
1700	3650	++	+ **	+ (4)
		++	+	+ (4)
1800	3750		+	+ (9)
1900	3850	+++		++ (10)
		+++		+ (10)
2000	3950	+++	+	
		+++	+	
2100		+++	+	
			+ **	
2200	4150			

NA and *SA* Warm-dry phases corresponding to agricultural activity increases north (NA) and south of the Alps (SA) according to Tinner et al. (2003). *LE* agricultural phases in the Lower Engadine after Zoller et al. (1996, Fig. 4); number of * indicates dated charcoals in different localities (according to Raba 1996). *UE* farming phases in the Upper Engadine (this study), defined by the increases / peaks of the groups: *1 Alnus viridis,* monolete fern spores; *2* grazing indicators (GI), cultural indicators (CI); *3 Alnus viridis,* monolete fern spores, Cichorioideae; *4 Alnus viridis,* GI, CI; *5* CI, GI, charcoal; *6* charcoal; *7 Alnus viridis,* monolete Spores, *Ranunculus* t., GI; *8 Alnus viridis, Rumex acetosa*, *Ranunculus* t., CI; *9 Alnus viridis,* GI, spore plants, charcoal; *10* defined by a significant zone boundary. Vertical dashes indicate phases at lake St. Moritz with tree values over 65% (see Fig. 6)

The significance of the vegetational change is underscored by a statistically significant zone boundary at Lej da San Murezzan (LPAZ SM-3/SM-4, Fig. 6), which is accompanied by a strong peak in microscopic charcoal

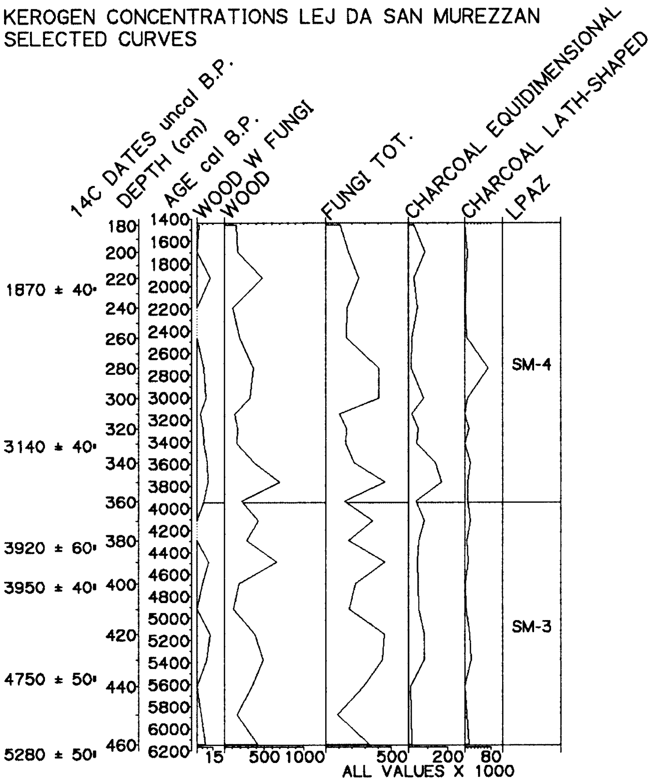

Fig. 8 Kerogen particle concentrations from Lej da San Murezzan (selected taxa, analyst E. Gobet). Time window 6100 to 1500 cal B.P.

influx. Most of these charcoals are equidimensional (Tyson 1995), most likely indicating burned wood (Umbanhowar and McGrath 1998). Tallying with this, the presence of charred needles of *Picea abies* and *Larix decidua* (Fig. 7) suggest local forest fires at ca. 4200 to 4000 and 3700 cal B.P. The corresponding peak in wood and fungi particles (Fig. 8) may be interpreted as due to forest disturbances and subsequent soil erosion. One major force driving this ecosystem reorganisation was fire. The strong vegetational reactions (as documented by significant negative and positive cross-correlation values for the period 3900–3570 cal B.P., 1950–1620 B.C.) point to fire as the main tool of anthropogenic deforestation.

On the basis of our data we argue that the formation of *Larix*-meadows starts at the beginning of the early Bronze Age in the Upper Engadine. In contrast, Punchakunnel (1983) and Zoller and Brombacher (1984) suggested that the expansion of *Larix*-meadows as indicated by the strong expansion of *Larix* and the decrease of *Picea* took place during the Late Bronze Age. However, 1,500 years before, during the Neolithic, the same land use was established in the Lower Engadine (Zoller et al. 1996). At Alpe Palü (Passo del Bernina; Fig. 1) the use of *Larix*-dominated areas as pasture begins in the middle Bronze Age (Zoller et al. 1998). This vegetation type is most likely man made and ecologically corresponds to a savanna with scattered trees in meadows (Rackham 1998). It is likely that the rapid growth of the heliophilous *Larix* after forest fire (Schönenberger and Wasem 1997) aided the rapid development of this land-use type based on animal farming. In fact grazing is very important to maintain the open larch forests (Hegg et al. 1993). Schönenberger and Wasem (1997) studied vegetation responses after a forest fire at an altitude of 1,800 to 2,200 m a.s.l. in the nearby Val Müstair. Herbaceous taxa (grasses and *Epilobium angustifolium)* followed soon after the forest fire. Within 12 years, shrubs and broadleaved trees were re-established, whereas coniferous trees, except for *Larix,* recovered only rarely (Schönenberger and Wasem 1997). Interestingly, Zoller (1960) notes large increases in *Epilobium angustifolium* and other herbaceous taxa in pollen assemblages related to charcoal layers, and thus to past wildland fires in southern Switzerland. Küchli (2000) also mentions the importance of deforestation and fire as the driving factor for the expansion of *Larix* in Engadine during the 19th century. These fire-ecological and historical results are in agreement with our pollen-inferred interpretation of fire-induced vegetational changes during the Bronze Age (increase of e.g. *Epilobium*, monolete spores of ferns, Caryophyllaceae, *Selaginella selaginoides*, Apiaceae, *Aconitum,* and *Helianthemum* at lag 0; Fig. 9). However, the cross-correlation results indicate that *Larix* first suffered under forest fires, although this heliophilous tree (Ellenberg et al. 1992) may have benefited from forest clearings, which affected important late-successional species such as *Pinus cembra* and *Picea abies.* To test this hypothesis a longer time period should be analysed by continuous sampling to allow the detection of more long-lasting successional dynamics.

Different hypotheses have been established about competition between *Picea* and *Pinus cembra* (e.g. Zoller and Brombacher 1984; Oeggl and Wahlmüller 1994). Based on the cross-correlation results it is likely that the decline of *Pinus cembra* forests was closely related to fire. These results indicate that under natural conditions the species was able to occupy habitats as low as 1,800 m a.s.l. in the Upper Engadine, in agreement with similar findings from the Valais (Tinner 1994). In contrast, *Picea* seems not to be affected by fire directly. Indeed not all coniferous trees were thus affected by fire, which could be related to different species-inherent fire adaptations or to differently fire-prone habitats (e.g. *Picea* on more humid soils or north-facing slopes). However, our finding could possibly have resulted from different pollen productivities and dispersals. *Larix decidua* is strongly underrepresented in pollen diagrams, whereas *Pinus cembra* is normally represented. *Pinus* non-*cembra* and *Picea* are higher pollen producers and tend to be overrepresented in pollen diagrams (Lang 1994). In the case of a forest fire, local coniferous taxa including *Picea* and *Pinus* non-*cembra* would be affected similarly to *Larix* and *Pinus cembra.* However, we hypothesize that pollen of *Picea* and *Pinus* non-*cembra* coming from regional sources would compensate at least in part for any local losses, thus obscuring the post-fire response of these taxa.

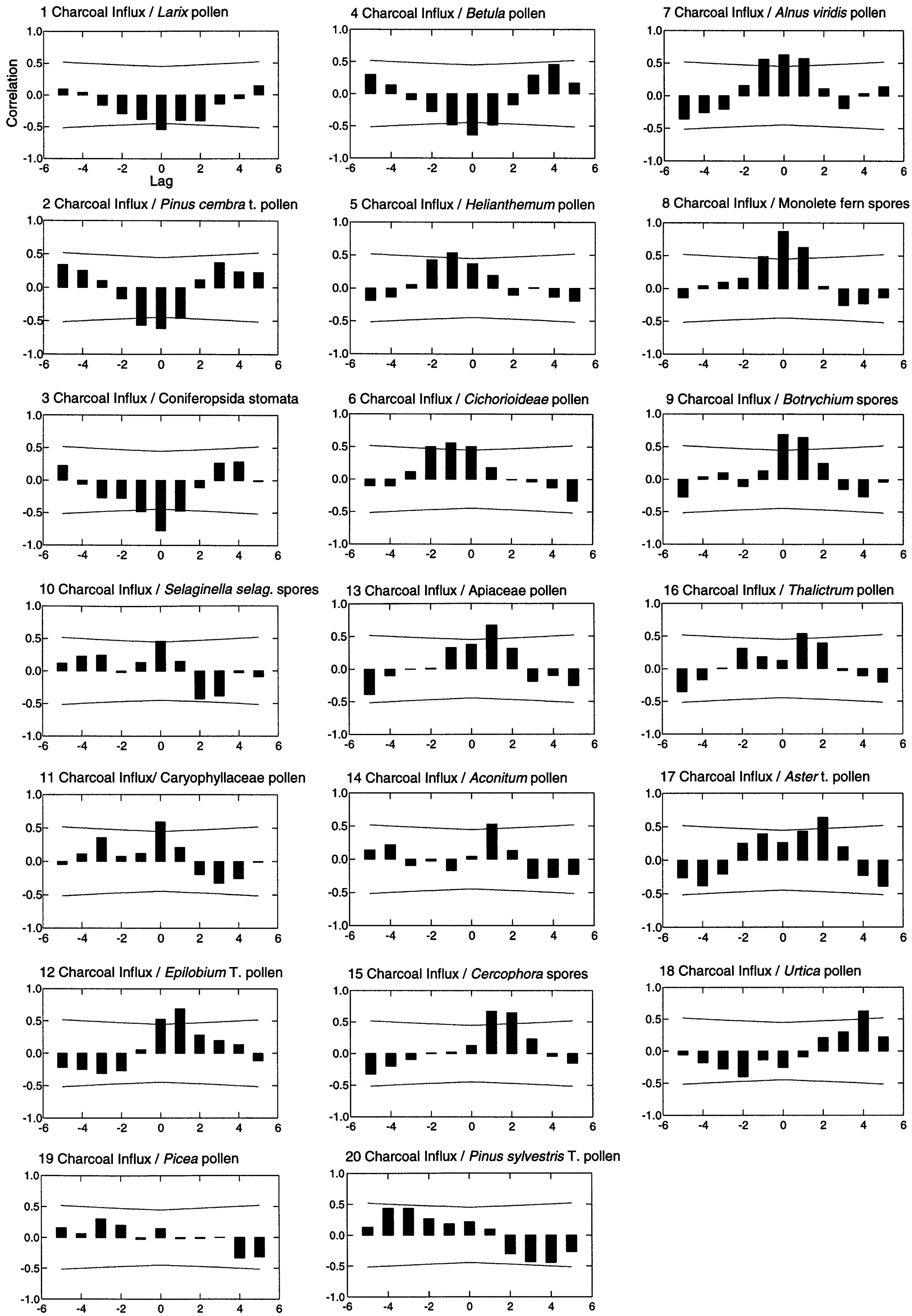

Fig. 9 Selected cross-correlation plots for Lej da San Murezzan, time period 3900–3570 cal B.P., charcoal influx versus pollen/spore/stomata percentages. Significance levels indicated by *horizontal lines*: only correlations reaching or crossing these lines are statistically significant. *1–4* negative correlated, *5–6* positive correlated, time lag 1; *7–11* positive correlated, time lag 0; *12–18* positive correlated, time lags 1–4; *19–20* not correlated

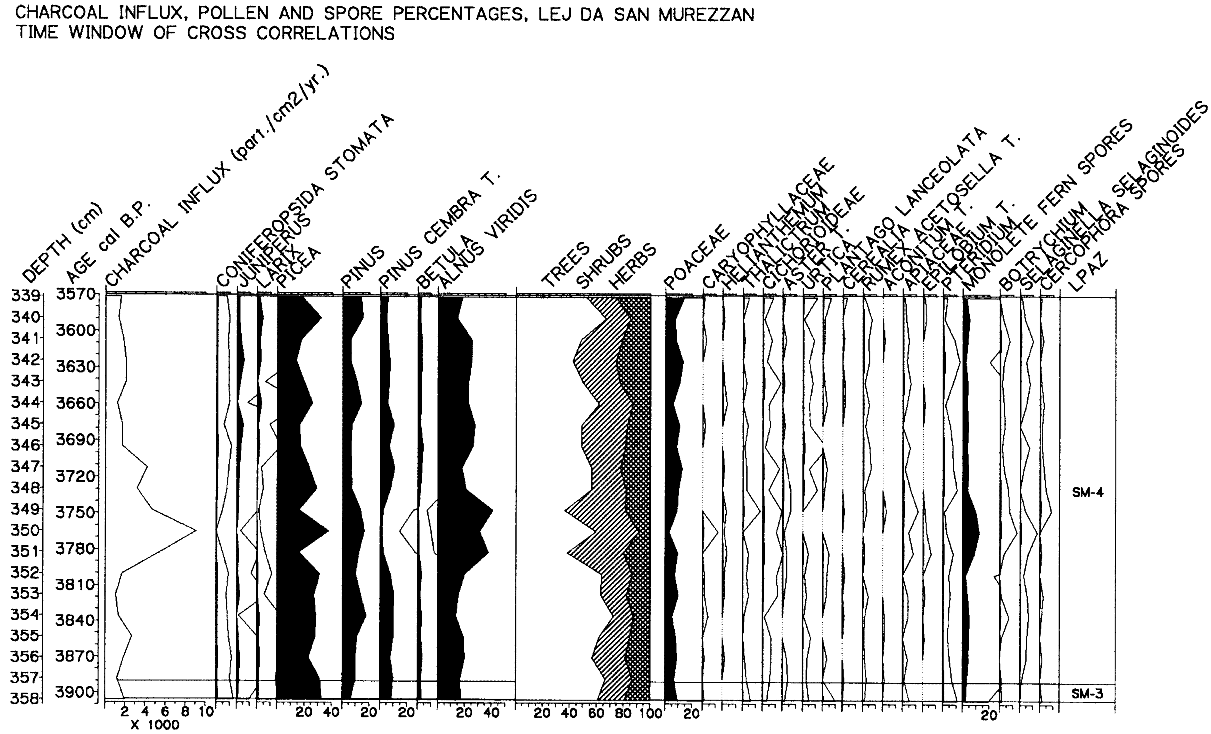

Fig. 10 Selected pollen percentage and charcoal influx diagram for Lej da San Murezzan for the time window 3900–3570 cal B.P. Exaggeration (x10) is indicated by *line*

Cross-correlations suggest that fire was a main determinant for the expansion of *Alnus viridis* (Fig. 9). Wick and Tinner (1997) argue that climate change and human impact were the main reasons for the expansion of *Alnus viridis* near the timberline. Welten (1982) mentions that alder shrubs could have been used as winter fodder and were therefore likely to be coppiced. He also hypothesised that forest clearing by fires could have favoured *Alnus viridis* and disadvantaged *Pinus cembra*. Wick (1994) showed that at Pian dei Cavalli (Splügen Pass area; Fig. 1) the increase of *Alnus viridis* was accompanied by an increase in charcoal particles. However, the closely related American green alder (*Alnus viridis* subsp. *crispa*) is well adapted to fire: it does not burn easily and it sprouts from the root crown after fire damage (FEIS 2003). Additionally, wind-dispersed seeds quickly colonise bare mineral soils exposed by fire. The sprouting response is usually immediate and generally results in an increased number of plant individuals. American green alder is abundant in areas with frequent fires (FEIS 2003). The positive correlation of *Alnus viridis* in our cross-corellograms with microscopic charcoal (Fig. 9) is a strong indication for a fire-driven expansion of *Alnus viridis* in the Early Bronze Age. *Alnus viridis* colonisation on secondary succession takes place through sexual reproduction, whereas temporal persistence of dense stands is thought to require layering, which is hypothesised to inhibit arboreal coniferous species (Anthelme et al. 2002). However, it is likely that stands of uniform age would decline within some decades if human influence did not persist. Today's ecological observations suggest that only on (spatially constricted) regularly disturbed avalanche slopes is *Alnus viridis* able to form persistent stands. Thus it appears that the continuously high *Alnus viridis* representation in the landscape was caused by persistent human disturbances including fire. This progressive vegetational degradation can be compared to the formation of maquis and garigues in the Mediterranean, where fire is considered to play the most important role in the transformation from forest to small-height thickets (Pignatti 1997; Frey and Lösch 1998; Pignatti et al. 2002).

In autarky-based agricultural systems field farming was necessary to sustain continuous settlement. Candrian (1928) mentioned remains of field terraces up to the region of Segl-Maria (1,809 m a.s.l., Fig. 1). Mathieu (1992) described that according to historical documents cereals were planted in the Upper Engadine region almost everywhere on terraces in the past (though it is not clear how old these terraces are). Bundi (1989) mentions that during the 13th century cereals were planted in the Upper Engadine and cereal cultivation was so successful that corn taxes (Kornzehnten) had to be paid to the parish of St. Luzi in Zuoz (Upper Engadine). In the Lower Engadine Cerealia cultivation starting at 4200 to 4000 cal B.P. was inferred from palaeo data (Raba 1996; Zoller et al. 1996; Abderhalden-Raba and Bischoff 1998). In agreement with this, the older layers in the settlement of Savognin-Padnal (Oberhalbstein) are dated to the Early Bronze Age (2000–1900 B.C., 3950–3850 cal B.P., Rageth 2001). The Cerealia macrofossils found in these layers belong mostly to the *Hordeum-Triticum* type and were dated to 1800–1600 B.C. (3750–3550 cal B.P., Jacomet et al. 1999). Schellenberg (1900) mentions that *Hordeum distichum* is the most abundant cereal in the mountain valleys of this region, due to the short growing season of 90 to 100 days, and that *H. distichum* was planted near Celerina (next to St. Moritz) and Segl-Maria at 1,800 m a.s.l., but did not mature every year. Our diagrams document the occurrence of regular Cerealia pollen findings in the Upper Engadine since the beginning of the Early Bronze Age. The pollen grains found around 3900 cal B.P. belong to the *Hordeum-Triticum* type. Cerealia pollen is accompanied by peaks in pollen of field weeds (e.g. *Rumex acetosella,* Behre 1981) supporting our interpretation of a significant agricultural impact on the prehistoric landscape. It is interesting that historical documents mention the importance of larch needle litter in stables, which can be subsequently used as fertiliser, making it possible for the farmers to successfully cultivate cereals (Kasthofer 1828, cited in Küchli 2000).

Conclusions

Human impact began during the Neolithic, at the latest around 5400 cal B.P. (3500 cal B.C.). Marked vegetational changes induced by anthropogenic activities are documented from 4000 cal B.P. (1900 B.C.), when a special vegetation type developed after forest clearance by burning and the subsequent influence of extensive livestock grazing (larch-meadows). Continuous prehistoric agriculture is indicated by increased values in pollen indicative of anthropogenically enhanced forest grazing and regular findings of Cerealia pollen grains (3900 cal B.P., 1950 B.C.)

Though our percentage values are too low to prove unambiguously the cultivation of Cerealia (*Hordeum vulgare*), it seems likely that since the Neolithic, but at the latest during the Bronze Age, field crops were cultivated for self-sufficiency in this high-mountain area. In the lower Engadine (Ramosch, Zoller et al. 1996) and Savognin (Oberhalbstein, Jacomet et al. 1999) Early Bronze Age Cerealia cultivation is unambiguously documented in small mires and cultivation layers. The large size of our lakes may have diluted the pollen signal, rendering it less clear than in the Lower Engadine. Our interpretation that permanent settlements in the Upper Engadine started during the Early Bronze Age at the latest is sustained by the statistically significant zone boundary SM-3/SM-4, which includes many anthropogenic pollen indicators as well as higher levels of charcoal influx. The only archaeological evidence for continuous settlement is a spring holder dated to 1466 B.C. (ca. 3400 cal B.P., Seifert 2000). In the light of our data it seems likely that the lack of archaeological evidence for Bronze Age settlements in the Upper Engadine is due to the special geomorphic conditions (steep slopes etc.) preventing the preservation of settlement traces, and/or to the lack of systematic surveys. Possibly more settlement remains will be found in future. However, it is likely that changes to a dry and warm climate favoured more intensive land use and settlement phases in the Upper Engadine, as shown by synchronous increases of cultural indicators in and around the Alps. Our data provide the first quantitative evidence for the prominent role of fire in sub-alpine environments of the Alps. In particular we conclude that high fire disturbance was the main determinant for the strong expansion of *Alnus viridis* and the decline of *Pinus cembra.* In this context, the establishment of the first important meadows in the sub-alpine belt (400 to 500 m below the timberline) was also closely related to fire increase. The expansions of *Juniperus* and *Larix* after 4000 cal B.P. (2000 B.C.) were not primarily due to fire. Instead as heliophilous taxa they could probably benefit from the more open conditions created after fires through their tolerance of human land use, especially grazing. Thus it seems that the expansions of *Alnus viridis, Juniperus*, and *Larix* after 4000 cal B.P. (2000 B.C.) were not directly linked to each other, but are explainable by human impacts of different origin (e.g. fire, grazing, clear felling). However this topic would be better addressed through the analysis of longer time-series covering the full range of successional processes (i.e. at least 200 years). Additional disturbance and environmental proxies, such as the distribution of particulate organic matter (kerogen) can provide further useful information. This tool, which had not been used previously in Alpine palaeo-studies, proved very helpful in the detection of soil-inwash events as recorded by deposition increases in fungi and wood debris.

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