Are Holocene wood-charcoal fragments stratified in alpine and subalpine soils? Evidence from the Alps based on AMS ^{14}C dates

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Received 5 November 1999; revised manuscript accepted 1 May 2000

A HOLOCENE RESEARCH PAPER

Abstract: The possible stratification of charcoal particles buried in well-drained soil in the subalpine and alpine belts in an inner valley of the northwestern Alps (Savoy, France) is examined. Radiocarbon dating and quantification of charcoal fragments more than 400 μm in diameter were used to analyse the soil-depth distribution of charred wood particles between 1700 and 2600 m a.s.l. in two study areas 10 km apart in the same valley. Above 2100 m a.s.l. in both study areas, charcoal concentrations are low and mainly contained in the upper horizons, and all dated charcoal fragments are older than 2300 cal. yr BP. Below 2100 m, the greatest charcoal concentration is located in the topmost 30 cm of the soil profiles, and the ^{14}C dates yield late-Holocene ages (1600 to 75 cal. yr BP). When profiles have an elevated charcoal concentration in deeper horizons the charcoal dates are mid-Holocene (6360–2770 cal. yr BP). Radiocarbon dates of charcoal fragments do not reveal an age/depth relationship, although charcoal mass concentrations suggest a coarse stratification of charcoal particles in the soils below 2100 m at forested sites. This difference may be due to the charcoal dating on a single fragment which is not representative of the charcoal assemblage containing a few tens to thousands of fragments. The lack of stratification probably results from soil bioturbation by soil fauna, soil reworking by uprooted trees, and freeze-thaw processes. At higher elevation in the alpine belt, charcoal is concentrated in the topmost soil due to a low bioturbation rate. From a pedological point of view, the ^{14}C dating and the quantification of charcoal concentration per soil level provides a time range estimate for soil-particle reworking by anecic earthworms, dung beetles and other biota. This has application in pedogenesis studies to estimate the rapidity of processes of soils dynamics. These data suggest that soils in the Alps have limited potential for palaeoecological studies based on a stratigraphic assumption but have more applications in precise spatial studies.

Key words: Charcoal analysis, soil stratification, radiocarbon dating, taphonomy, alpine, subalpine, European Alps, bioturbation, palaeoecology, pedoanthracology, pedology, Holocene.

Introduction

Soils contain pollen (Dimbleby, 1957; Iversen, 1958) and wood-charcoal particles (Iversen, 1964; Bryson *et al*., 1965). Charcoal fragments are identifiable at the family, genus or species level (Jacquiot *et al*., 1973a), and can be dated by ^{14}C measurement (Iversen, 1964; Bryson *et al*., 1965). Because the occurrence of charcoal in soil is a global feature (Payette and Gagnon, 1985; Hopkins *et al*., 1993; Vernet *et al*., 1994; Zackrisson *et al*., 1996), soil-charcoal studies could improve our knowledge of the role of fire on Holocene vegetation (Ritchie, 1995) or of the measurement of pedological processes (Boulet *et al*., 1995).

Soil-charcoal studies (pedoanthracology) allow to reconstruct, with high-spatial precision, the burned vegetation (Jacquiot *et al*., 1973a; Hopkins *et al*., 1993; Carcaillet *et al*., 1997) and of the fire-stand history (Payette and Gagnon, 1985; Carcaillet, 1998). The reconstruct of burned vegetation change is based on the assumption that charcoal fragments and other particles such as pollen are time-stratified in soil (Thinon, 1978; Aaby, 1983). The assumption of charcoal stratification is based on several studies using ^{14}C dates showing that the deeper soil horizons contain the

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 0959-6836(01)HL459RP

oldest material, and the upper the youngest (Berli *et al*., 1994; Vernet *et al*., 1994; Boulet *et al*., 1995; Carcaillet *et al*., 1997). Similar results were also exhibited using soil organic compounds (see review in Matthews, 1993). The charcoal time-stratification assumption then justifies the soil sampling according to several vertical levels to display a burned vegetation history (Thinon, 1992). Most soil-charcoal studies applied the stratification assumption without testing its reliability (Jacquiot *et al*., 1973a; Tessier *et al*., 1993; Carcaillet and Thinon, 1996) or with only sparse dating to show a rough relationship between soil depth and the age of charcoal fragments (Berli *et al*., 1994; Carcaillet *et al*., 1997; Talon *et al*., 1998).

However, data refute the assumption of the stratification of wood charcoal in soil: some old charcoal fragments were observed in upper soil horizons (Carcaillet and Talon, 1996), while modern charcoal fragments were found deep in soil profiles (Thinon, 1992: 203). Many suggest that soil are not stratified both in tropical (Hopkins *et al*., 1993), and Subarctic areas (Bryson *et al*., 1965; Payette and Gagnon, 1985). Carcaillet and Talon (1996) suggest that this inversion in charcoal dating with respect to the expected stratification is due to processes such as the ascending/descending transport of charcoal by soil fauna and the trapping of charcoal fragments by plant-root network. However, the data of Carcaillet and Talon (1996) are too isolated and based on too little dating. This interpretation needs to be improved by new dating from other soil samples.

This paper tests the relationship between the burial depth of charcoal fragments in soils and their radiocarbon ages for soils from mid- and high elevations in the northern French Alps. The charcoal dating is compared to distribution of charcoal concentration in soil. The results are discussed in the light of knowledges on natural pedoturbation from biotic or abiotic origins. Soil pedoturbation should be a central process of pedogenesis (Johnson, 1993; Paton *et al*., 1995).

Origins of natural pedoturbation in the Alps

Animal origins

Anecic earthworms play a global key role in the mixing process of soil particles (Darwin, 1881; Atkinson, 1957; Rolfsen, 1980; Stein, 1983; Johnson, 1990; Bernier, 1998; Lavelle *et al*., 1998). Charcoal fragments do not escape the vertical mixing process (Thinon, 1992), like pollen grains in temperate soils (Walch *et al*., 1970; Thinon, 1992; Davidson *et al*., 1999). In the Alps, the presence of anecic earthworms above 2000 m a.s.l. seems rare, and depends on a dry climate, on soil quality and on plant cover (Cuendet, 1986; Grossi and Brun, 1997). Their altitudinal range roughly coincides with modern forest limits (Bernier, 1996). Other invertebrates can be taken into account, e.g., ants or dung beetles that occur at high elevation in the Alps (Mani, 1968). Ants, e.g., genera *Camponotus*, *Formica* or *Myrmica*, contribute to particles reworking at high elevations. The altitudinal range of *Formica* and *Camponotus* is generally controlled by the forest limit that occurs at about 2200 m within the study area, and *Myrmica* species are frequent at higher elevations. Alpine areas, especially grazed meadows, constitute the preferred habit for dung beetles (Lumaret and Stiernet, 1990; Jay-Robert *et al*., 1997). Their size, abundance and diversity decrease with elevation, and, at similar elevation, they are less abundant and diverse in forest areas compared to meadows. Moreover, their capability to dig deeper than 20 cm is low. Consequently, we should expect a low burying depth of charcoal fragments at the highest elevations due to the limited digging capability of dung beetles, the absence of anecic earthworms and the scarcity of ants.

At high elevation above the tree-line two burrowing mammals abound: the Alpine marmot (*Marmota marmota* L.) and the snow vole (*Microtus nivalis* Martins). These species dig deep galleries in soil and contribute to mixed soil particles. The main difference between impact of invertebrates and snow vole compared with that of Alpine marmots is that the impact of the first group of soil reworkers is not patchy and generally occurs everywhere within their range limit. Indeed, Alpine marmots need deep soil for their galleries.

Other biologic and geomorphic origins

The uprooting of trees is an other cause contributing to the mixing of soil particles (Brown and Martel, 1981; Schaetzl *et al*., 1990; Bormann *et al*., 1995). This process occurs within the forest range currently located below 2200–2300 m. The uprooting is a spatially and temporally sporadic process. After a few centuries or millennia, their impact on the mixing of soil particles can occur everywhere within the forest range of trees up to few metres high. This process is often underestimated in pedogenesis (Schaetzl *et al*., 1990) and is not documented in the Alps.

Due to their adsorption capacity, charcoal particles attract roots (Carcaillet and Talon, 1996; Zackrisson *et al*., 1996), which find many nutrients at the surface and in the charcoal porosity. Consequently fine and dense herb-root mats trap charcoal in the upper horizons more than thick tree roots, which do not abound in upper horizons of forest soils. The role of herb-root mats is in opposition to that of dung beetles, anecic earthworms and other soil reworkers.

At high elevations, the soil freezing increases. Where the plant cover is low, the formation of head ice contributes to the upward movement of clay and silt to the soil surface (van Vliet-Lanoë, 1988). This process partially mimics the burial role of anecic earthworms. However, the charcoal fragmentation is probably the main impact of freeze-thaw processes on charcoal (Carcaillet and Talon, 1996).

Biologic and geomorphic processes participate together over centuries and millennia in the burial of wood charcoal in soil. At middle elevations (below 2000–2100 m a.s.l.) bioturbation is the main mechanism, while at higher elevations the geomorphic mechanisms are more important. This transition with increasing elevation mainly results from the vegetation change (opening of forest and diminished size of trees), and from the decrease of diversity and abundance of invertebrates. At high elevation above 2100 m, charcoal should be mainly in the upper horizons because animal reworkers are few and vegetation mainly composed of herbs.

Study area

Location and climate

The two study localities, Aussois (45°15′ N; 6°45′ E) and Saint-Michel-de-Maurienne (45°15′ N; 6°30′ E), are located 10 km apart in the upper Maurienne valley (Savoy's Alps, France). The valley delimits the southern portion of the Vanoise massif in the northern French Alps (Figure 1). Climatic data were obtained from weather stations located in Saint-Michel-de-Maurienne (1360 m a.s.l.) and Aussois (1490 m a.s.l.), both with southern exposure (Fournier, 1985). Mean annual air temperatures are 7.0 and 6.2°C in Saint-Michel-de-Maurienne and Aussois, respectively. The mean temperature for the coldest (January) and the warmest month (July) are –0.7 and 15.0°C at Saint-Michel-de-Maurienne and –3.2 and 15.2°C at Aussois. Snow covers the ground for 3–4 months per year at 1400 m a.s.l. on southern slopes. Mean monthly precipitation is 79 (±14) and 59 (±10) mm at Saint-Michel-de-Maurienne and Aussois, respectively. The High Maurienne valley is one of the driest in the Alps; precipitation and temperature, their intra-annual variability and mean

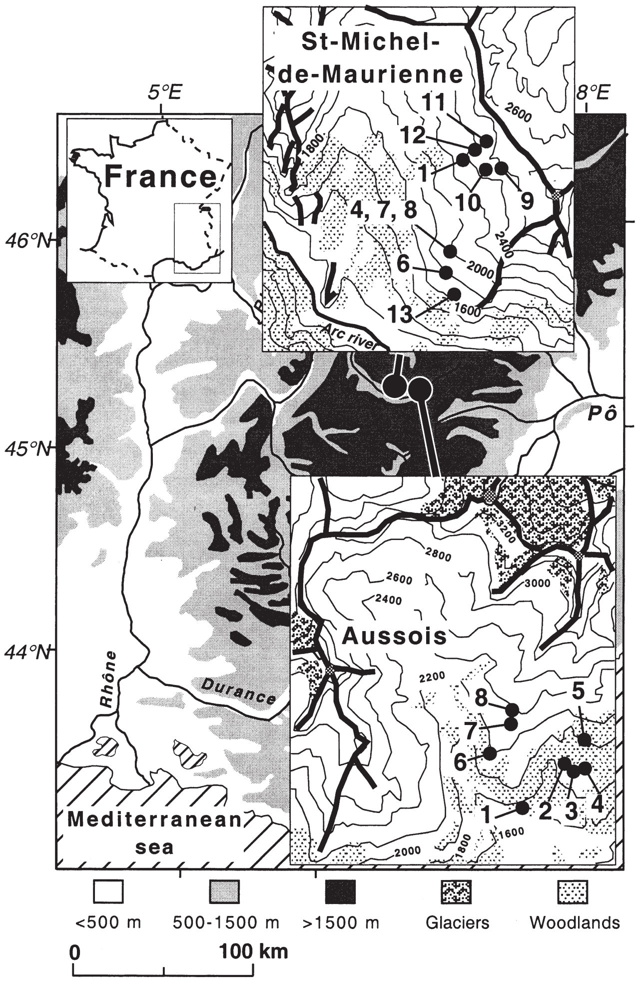

Figure 1 Map of the study area. Numbers at Saint-Michel-de-Maurienne and Aussois correspond to site numbers named MAUR and AUSSOIS, respectively.

annual amplitude are similar to those of European continental climate (Fournier, 1985).

Vegetation

Above 1500 m a.s.l. on the southern exposure of the Vanoise massif, the vegetation consists of coniferous woodlands up to the tree-line, which occur at about 2350 m a.s.l. (Bartoli, 1966). The zone between 1500 and 1900 m a.s.l. is in the range of *Pinus sylvestris* L. and *Picea abies* [L.] Karst., and between 1900 and 2300 m a.s.l. is a patchy woodland mosaic of *Pinus cembra* L., *P. uncinata* Mill., *Larix decidua* Mill., heathlands composed of *Arctostaphylos uva-ursi* (L.) Spreng, *Juniperus communis* L., *Rhododendron ferrugineum* L., *Vaccinium myrtillus* L., *V. uliginosum* L. and *V. vitis-idaea* L., and pastures for cattle summer grazing. Areas above 2300 m a.s.l. consist of boulders and short-grasslands dominated by *Carex curvula* All. and *Nardus stricta*. Glaciers occur in some places at elevations above 2800 m (Figure 1).

At the beginning of the Holocene (8000–5000 years BP), a mixed vegetation of *Abies alba*, *Acer*, *Betula*, *Pinus cembra* and *Pinus sylvestris* occurred below 1900 m a.s.l., and communities were dominated by *Pinus cembra* above 1900 m a.s.l. (David, 1995; Carcaillet and Thinon, 1996; Talon *et al*., 1998). Between 4300 and 3000 years BP the upper tree-line was located at about 2700 m a.s.l. and was composed mainly of *Pinus cembra*, *Ericaceae* and *Juniperus* (Carcaillet *et al*., 1998).

Soils in subalpine and alpine belts

The classification of soils follows the French nomenclature (AFES, 1992, for soil; and Brethes *et al*., 1995, for humus). The spatial distribution of soils is closely related to vegetation type (woodland or grassland) and composition (*Larix*, *Picea*, *Pinus*), bedrock (acid, calcic, carbonate-rich), and slopes. On steep slopes thin soils occur that are often composed of a single organic-matter-rich horizon (A horizon): ranker on acid substrate and rendzina on carbonate-rich bedrock. Brunisol composed of O, A, B and S horizons are formed when the slope allows for more developed soils. On south exposures, acid brunisols are widespread on acid bedrock which are covered by more active humus even under spruces and pines. Under *Pinus uncinata* covering carbonate-rich moraines, the humus is a thick dry calcic dysmull produced by pine needles and heathland twigs and leaves. In this environment, soils are carbonated brunisol. In the grassland areas, both in the subalpine and alpine belts, soils are brunisolic with a micro-crumb rhyzogenous structure, and the humus belongs to the eumull.

Methods

Soil sampling

Eight soil profiles were sampled along an altitudinal transect at Aussois; 10 profiles were sampled at Saint-Michel-de-Maurienne (Figures 1 and 2). Some soil profiles up to 2680 m a.s.l. contain buried charcoal (Carcaillet *et al*., 1998), but the small size of fragments above 2400 m a.s.l. does not allow ^{14}C measurements by AMS in each profiles. Soil sampling was avoided when soils were obviously disturbed by human activities, were located at the foot of steep or long slopes, or were eroded or hydromorphic (Carcaillet and Thinon, 1996). Profiles were taken in a trench dug down to the bedrock whenever possible. Soil material was sampled by cutting soil blocks from the face of a vertical soil profile. Blocks were collected at different depths from the bottom to the surface to avoid particles falling from the upper horizons (Carcaillet and Thinon, 1996). Block limits correspond to horizon limits. However, horizons have been separated in several levels when the horizon height was higher than 20 cm. About 10–15 l of dry fine material was sampled per levels of *c*. 20 cm. Dried material from profiles weighed 30 to 100 kg, depending on the number of sampled levels, the depth of the profiles and the organic and sand content of the horizons.

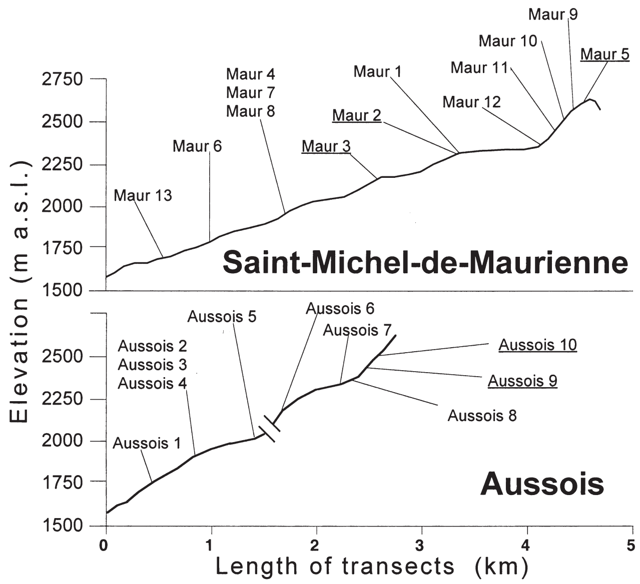

Figure 2 Location of the 23 soil profiles along two altitudinal transects. Underlined profile names did not provide enough amount of charcoal for ^{14}C dating.

Description of soil profiles

For all profiles, we described in the field the horizons, the depth, skeletal content, colours and structure. pH was measured in all horizons of soils laying on carbonaceous bedrock. Texture was estimated in the field and at the laboratory. A brief soil description per horizon based on field observation is summarized in Tables 1 (Aussois) and 2 (Saint-Michel-de-Maurienne). The presence of earthworms (individual and cocoons) was recorded either in the field or in the laboratory (Table 3).

Charcoal extraction and identification

Charcoal was extracted from soil by flotation (Carcaillet and Thinon, 1996). Dry wood charcoal fragments have low density, so flotation, with or without an ascending water flow, together with water sieving and manual sorting under a binocular microscope allowed the separation of charcoal fragments from other soil particles. Charcoal particles were identified with an incident light microscope equipped with an interference contrast (× 200, × 500, × 1000), and were compared with descriptions of wood anatomy (Greguss, 1959; Jacquiot, 1955; Jacquiot *et al*., 1973b; Schweingruber, 1990; Queiroz and van der Burgh, 1989) and with a charred-wood reference collection.

AMS ^{14}C measurements

I tried to obtain two radiocarbon dates per soil profile. However, only one dating was performed in profiles with too little or too small fragments. Totally, 34 ^{14}C datings were carried out only on plant shoot material (Tables 4 and 5). Because charcoal fragments from soil are very small, AMS (accelerator mass spectrometry) ^{14}C measurements were used. This method allows the dating of

Table 1 Thickness and main features of horizons from Aussois soil profiles

Horizon	Litter – O	OA or A	Bh or AB	B	BC	C
AUSSOIS 1 (1750 m)	10 cm thick Pine needles, roots, twigs and leaves of Ericaceae	0–10 cm Brown-back calcic dry fibrous dysmull micro-crumb structure	10–40 cm Light ochre-brown, crumby, sandy, carbonated, organic-rich	40–90 cm Light ochre-grey, very sandy-stony, compact	<95 cm No roots, stony (ϕ 10–30 cm), very compact	Calcareous moraine
AUSSOIS 2 (1890 m)	10–15 cm thick Pine needles, roots, twigs and leaves of Ericaceae	0–10 cm Black calcic dry fibrous dysmull micro-crumb structure	10–50 cm Ochre-brown, crumby, sandy and stony, carbonated organic-rich tree roots pH 7.6 at 20 cm and 8.3 at 40 cm	50–90 cm Ochre-yellow, very stony-sandy, compact tree roots pH 8.0 at 60 cm	90–150 cm Light ochre-yellow stony and gravelous, compact	Calcareous moraine
AUSSOIS 3 (1890 m)	10–15 cm thick Pine needles, roots, twigs and leaves of Ericaceae	0–10 cm Black calcic dry fibrous dysmull micro-crumb structure	10–50 cm Ochre-brown, crumby, sandy and stony, carbonated, organic-rich little roots pH 7.3 at 20 cm	50–90 cm Ochre-yellow, very stony-sandy, compact pH 8.1 at 60 cm	90–140 cm Light ochre-yellow, stony and gravelous, compact	Calcareous moraine
AUSSOIS 4 (1890 m)	10 cm thick Pine needles, roots, twigs and leaves of Ericaceae	0–10 cm Black calcic dry fibrous dysmull micro-crumb structure	10–50 cm Ochre-brown, crumby, sandy and stony, carbonated, organic-rich, little roots pH 7.8 at 20 cm and 7.9 at 40 cm	50–90 cm Ochre-yellow, very stony-sandy, compact pH 8.1 at 60 cm	90–115 cm Light ochre-yellow, stony and gravelous, compact	Calcareous moraine
AUSSOIS 5 (2050 m)	5–10 thick Pine neeldes, roots, twigs and leaves of Ericaceae	0–12 cm Black calcic dry fibrous eumoder, mycogenous	12–55 cm Ochre-brown, crumby, sandy and stony, carbonated, organic-rich, root-rich	55–85 cm Light ochre-yellow, very stony-sandy, compact, root-poor	<85 cm Light ochre-yellow, stony and gravelous, compact	Calcareous moraine
AUSSOIS 6 (2180 m)	Acid eumull	0–15 cm Brown-black, sandy, rhyzogenous structure	15 40 cm Brown-ochre, many roots loamy	40–75 cm Ochre, loamy-sandy, root-poor	80–90 cm Stony	Schist
AUSSOIS 7 (2340 m)	Calcic eumull	0–25 cm Light brown micro-crumb and rhyzogenous structure	25–40 cm Brown-ochre, sandy, roots limit at 35 cm	40–70 cm Light brown-ochre, sandy	60–90 cm Yellow-ochre, stony, Fe oxydes, mottles	Gypsum
AUSSOIS 8 (2380 m)	Hemimoder	0–15 cm Dark grey-brown, sandy, rhyzogenous structure	15–25 cm Dark brown-ochre, sandy and stony, rhyzogenic structure	25–100 cm Brown-ochre to light yellow-ochre, sandy		Limestone

Table 2 Thickness and main features of horizons from Saint-Michel-de-Maurienne soil profiles

Horizons	OA or A	Bh or AB	B	BC	C
MAUR 13 (1700 m)	0–5 cm Acidic eumull, micro-crumb structure	5–35 cm Rhyzogenic structure, micro-crumby, herb root rich	35–130 cm Brown, sandy and stony below 90–100 cm	<130 cm Dark grey, sandy and stony	Schists and sandstones
MAUR 6 (1770 m)	0–5 cm Acidic eumull, micro-crumb structure	5–40 cm Rhyzogenic and micro-crumby structure, herb root rich	40–85 Stony (ϕ 5 cm) and sandy, very compact	85–120 cm Stony (ϕ 10–20 cm) and sandy, very compact	Schists and sandstones
MAUR 4 (1960 m)	0–10 cm Acidic eumeull, micro-crumb structure	10–25 cm Micro-crumby, herb root rich, few stones	25–75 cm Sone layer at 55–60 cm	75–95 cm Stony and gravelous (stones ϕ 5 cm)	Schists and sandstones
MAUR 7 (1960 m)	0–10 cm Acidic eumull, micro-crumb structure	10–25 cm Micro-crumby, herb root rich	25–75 cm Few roots, stone layer at 70–75 cm	75–95 cm No roots, sandy and gravelous (stones ϕ 5 cm)	Schists and sandstones
MAUR 8 (1960 m)	0–10 cm Acidic eumull, micro-crumb structure	10–25 cm Micro-crumby, herb root rich	25–75 cm Few roots, stone layer at 55–65 cm	75–95 cm No roots, sandy and gravelous (stones ϕ 5 cm)	Schists and sandstones
MAUR 1 (2360 m)	0–12 cm Herb root and organic matter rich, micro-crumb and rhyzogenous structure	12–30 cm Poorly structured, root rich	–	30–50 cm Weathered bedrock	Schists and sandstones
MAUR 12 (2400 m)	0–25 cm Dark brown herb root and organic matter rich, sandy	Very gradual transition between A and B	25–50 cm Brown-ochre, loamy and stony	50–70 cm Dark grey, few roots, very stone	Schists and sandstones
MAUR 11 (2450 m)	0–30 cm Brown-black, organic and herb root-rich, crumby, sandy-loamy	30–45 cm Gradual transition between A and B	45–70 cm Dark brown, loamy-sandy, stony, roots limit at 70 cm	70–120 cm Dark grey, few roots, weathered bedrock	Schists and sandstones
MAUR 10 (2510 m)	0–15 cm Black-brown, organic and herb root rich	15–45 cm Dark brown-ochre, organic and herb root rich	–	45–67 cm Dark grey, few roots, weathered bedrock	Schists and sandstones
MAUR 9 (2580 m)	0–15 cm Black-brown organic and herb root rich	15–45 cm Dark grey-ochre, organic and herb root rich	–	45–67 cm Dark grey, few roots, weathered bedrock	Schists and sandstones

Table 3 Presence and depth of earthworms and worm cocoons in soil profiles

Soil profiles	Altitude (m a.s.l.)	Earthworms	Cocoons
AUSSOIS 2	1890	90–120 cm	70–90 cm
AUSSOIS 3	1890	–	70–90 cm
AUSSOIS 6	2180	60–75 cm	–
MAUR 4	1960	20–40 cm	–
MAUR 6	1770	40–60 cm	–
MAUR 7	1960	20–40 cm	–
MAUR 8	1960	10–25 cm	–

fragments weighing as little as 1 mg. Three times, two and three fragments were pooled to reach the minimum required mass for AMS measurements (Table 5). The ^{14}C datings were carried out at the NSF Arizona Facility Laboratory (Tucson, Arizona, USA) and at the Centre de Datation par le Radiocarbone (Lyon, France) and labelled AA-xxxx and Lyon (OxA)-xxxx, respectively.

Prior to AMS dating, charcoal fragments were cleaned under binocular lenses ($\times 40$) in order to remove the small roots, the fungi hyphae and the mineral particles that could rejuvenate or age the charcoal. The external surfaces of charcoal fragments were delicately cleaned using an ultrasonic wave generator such as that used by dentists (Carcaillet and Thinon, 1996). Further, each fragments were treated during 24h with a solution of $Na_4P_2O_7$ or NaP_2O_4 to extract the organic compounds adsorbed in the charcoal

Table 4 Radiocarbon dates of soil wood charocal fragments from Aussois in the Vanoise massif (north French Alps). Calibrated dating was computed using the calibration program CALIB (Stuiver and Reimer, 1993). Reported as intercept midpoint with 2 σ range in parentheses

Profiles	Taxa	Mass (mg)	Sample codes	^{14}C years BP	Calibrated years BP
AUSSOIS 1	*Abies alba*	1.9	AA-20464	1025 ± 100	939 [1009–803]
AUSSOIS 1	*Pinus sylvestris/uncinata*	1.0	AA-20465	210 ± 100	283 [319–61]
AUSSOIS 2	*Pinus sylvestris/uncinata*	23.7	Lyon-298(OxA)	1230 ± 50	1130 [1261–1009]
AUSSOIS 2	*Pinus sylvestris/uncinata*	3.3	AA-20466	1095 ± 100	977 [1077–931]
AUSSOIS 3	*Pinus sylvestris/uncinata*	21.1	Lyon-299(OxA)	1700 ± 50	1580 [1704–1469]
AUSSOIS 3	*Juniperus* sp.	3.7	AA-16493	1730 ± 50	1662 [1806–1530]
AUSSOIS 4	cf. *Picea abies*	2.5	AA-20467	75 ± 55	60 [104–0]
AUSSOIS 4	*Pinus sylvestris/uncinata*	3.0	AA-20468	405 ± 55	483 [507–465]
AUSSOIS 5	*Pinus sylvestris/uncinata*	118.3	Lyon-300(OxA)	4665 ± 60	5340 [5562–5137]
AUSSOIS 5	*Pinus sylvestris/unicinata*	11.2	Lyon-301(OxA)	4530 ± 60	5255 [5322–4944]
AUSSOIS 6	*Erica herbacea*	2.0	AA-20469	3170 ± 115	3377 [3487–3256]
AUSSOIS 6	Angiosperm	5.2	AA-20470	2330 ± 110	2341 [2435–2180]
AUSSOIS 7	*Arctostaphyllos uva-ursi*	8.4	AA-20471	3845 ± 75	4248 [4358–4123]
AUSSOIS 7	*Pinus sylvestris/uncinata*	2.4	AA-20472	3340 ± 65	3568 [3643–3487]
AUSSOIS 8	*Pinus cembra*	2.4	AA-20473	3605 ± 65	3882 [3950–3833]
AUSSOIS 8	*Pinus cembra*	1.3	AA-20474	4175 ± 105	4740 [4849–4541]

Table 5 Radiocarbon dates of soil wood charcoal fragments from Saint-Michel-de-Maurienne in the Vanoise massif (north French Alps). Calibrated dating were computed using the calibration program CALIB (Stuiver and Reimer, 1993). * and # indicate measurements on two and three fragments respectively. Reported as intercept midpoint with 2σ range in parentheses

Profiles	Taxa	Mass (mg)	Sample codes	^{14}C years BP	Calibrated years BP
MAUR 1	*Pinus cembra*	1.6	AA-12483	*3415 ± 85	3687 [3889–3469]
MAUR 1	*Pinus cembra*	3.7	AA-12484	3745 ± 75	4113 [4406–3899]
MAUR 4	*Pinus cembra*	6.8	AA-12487	#4975 ± 70	5730 [5919–5589]
MAUR 4	*Pinus cembra*	74.2	AA-12486	3885 ± 70	4369 [4524–4092]
MAUR 6	*Pinus sylvestris/uncinata*	12.1	AA-14775	4980 ± 85	5730 [5939–5495]
MAUR 6	*Abies alba*	7.9	AA-14776	5590 ± 65	6360 [6604–6358]
MAUR 7	*Alnus viridis*	1.3	AA-16496	2670 ± 55	2772 [2869–2739]
MAUR 7	*Pinus cembra*	33.4	AA-16497	5125 ± 50	5920 [5984–5737]
MAUR 8	*Pinus cembra*	89.5	AA-16495	3970 ± 45	4432 [4537–4346]
MAUR 8	*Pinus cembra*	3.2	AA-16494	4495 ± 55	5114 [5309–4879]
MAUR 9	Bark	1.0	AA-19115	5115 ± 245	5781 [6509–5319]
MAUR 10	*Pinus cembra*	3.8	AA-19116	3680 ± 95	4029 [4400–3730]
MAUR 11	*Pinus cembra*	11.7	AA-19117	3280 ± 80	3485 [3699–3359]
MAUR 12	*Arctostaphyllos uva-ursi*	1.8	AA-19118	6715 ± 95	7574 [7699–7377]
MAUR 12	*Pinus cembra*	18.6	AA-19119	3245 ± 80	3469 [3685–3349]
MAUR 13	*Rhododendron* sp.	2.6	AA-20475	*3995 ± 65	4420 [4464–4335]
MAUR 13	*Albies alba*	42.8	Lyon-302(OxA)	3580 ± 65	3865 [4059–3698]
MAUR 13	*Abies alba*	6.4	AA-20476	3800 ± 65	4171 [5260–4085]

porosity. The solution was daily changed up to the release end of organic compounds by charcoal. Generally, five to seven days were sufficient to chemically clean the charcoal fragments.

The AMS ^{14}C measurements were calibrated against dendrochronological years using the CALIB 3.0 program (Stuiver and Reimer, 1993) and are labelled cal. yr BP. Six dates were initially obtained to establish the methodology (Carcaillet and Thinon, 1996) and to verify the lack of disturbance to stratification (Carcaillet and Talon, 1996). All 34 dates have been applied to the reconstruction of past fire chronologies on Aussois and Saint-Michel-de-Maurienne (Carcaillet, 1998).

Soil-charcoal concentration

The soil-charcoal concentration permits the study of the vertical distribution of charcoal at different levels in a given soil profile and the comparison of different profiles. Concentration is expressed as mg charcoal per kg of dry soil particles less than 2 cm in diameter in one particular soil level. The amount of charcoal fragments smaller than 400 μm in diameter was negligible in many soils, such as those from African savannahs, the Mediterranean, or European temperate mountain (Thinon, 1992; Ouedraogo, 1995). Thus only charcoal fragments larger than 400 μm were quantified.

Results

Soil profiles

The sampled sites are mesic or xero-mesic and were located far from humid zones (peat, pond and riverside). All soils from Saint-Michel-de-Maurienne (MAUR 1, 4, 6–13) and those above 2100 m a.s.l. from Aussois (AUSSOIS 6–8) are brown acidic on Permo-Carboniferous schist and sandstone with an acidic eumull. Below 2100 m a.s.l. at Aussois the soils are calcareous with a thick litter of pine needles and Ericaceae fragments and covered by a calcic dry dysmull (Table 1). They are situated on moraines containing gypsum and hard limestone particles. Soil depths vary between 60 and 140 cm above bedrock, and decrease with increasing slope gradient and with the thickness of moraine deposits, but not with altitude.

Profiles AUSSOIS 1, 2, 3, 4 and 5 were dug between 1750 and 2050 m a.s.l. within a forest growing on calcareous moraine. AUSSOIS 1 and 5 sites are located on slopes 10–15° steep, while sites 2, 3 and 4 are on the top of a moraine. AUSSOIS 5 is the shallowest soil (*c*. 85 cm) while 2, 3 and 4 are more than 100 cm deep (Figure 3). Sharp boundaries separate O, OA, Bh and B horizons. The horizons are evidenced by colour, organic-matter content, and the amounts of coarse particles ($\phi > 2$ cm), which increase regularly from the top to the bottom. Profiles AUSSOIS 6, 7 and 8 were sampled between 2180 and 2380 m a.s.l. in a pasture located above the modern tree-line and occupied since the Neolithic (Carcaillet, 1998). These profiles are about 100 cm deep and show horizons whose limits are difficult to identify. The transition between the OA (top) and the B horizon is diffuse. The rhizogenic structure of the upper horizons is due to herb roots associated with the alpine and subalpine meadow vegetation. Small, horizontally disposed schist fragments abound at depth in these profiles (Figure 3). They are located on a ridge separating two pastures with south and west exposures, respectively. The ridge location of AUSSOIS 6–8 and AUSSOIS 2–4 excludes accumulation of charcoal by mass movement, but this process is not totally excluded for the other two profiles, AUSSOIS 1 and 5.

Soil profiles from Saint-Michel-de-Maurienne were dug in pastures as a result of deforestation by human occupation over the last 6000 years (Carcaillet, 1998). Profiles MAUR 9, 10, 11 and 12 were on the top of slopes while MAUR 1 is located at the foot of a slope 100 m long and 15° steep. This profile could trap charcoal fragments from an area of less than about 1 ha upslope. MAUR 4, 7 and 8 were located within the same site. They are 30 m apart. Although MAUR 4, 7 and 8 are located on a small plateau (5° steep), they are at the foot of a slope 1 km long inclined at 10°. Accumulation from higher elevations cannot be excluded. MAUR 6 and 13 were dug along a 20–30° slope. These two profiles and MAUR 4, 7 and 8 are at sites most susceptible to the accumulation of charcoal originating from higher elevations. Just as with the Aussois profiles under pastures, the horizonation at Saint-Michel-de-Maurienne depends on the rhizogenic structure of the soil, with diffuse transitions from the OA to the BC horizons (Figure 4; Table 2).

^{14}C dating and burial depth of charcoal fragments

The 34 dates cover the last 7500 cal. yr (Tables 4 and 5). At Aussois radiocarbon measurements below 2000 m a.s.l. are younger than 1600 cal. yr BP (Figure 3; Table 4), while those above 2000 m a.s.l. at Aussois and all those at Saint-Michel-de-Maurienne are dated between 7000 and 2300 cal. yr BP (Figures 3 and 4; Tables 4 and 5). Most soil profiles having two or three dates do not present the distribution that would be expected from

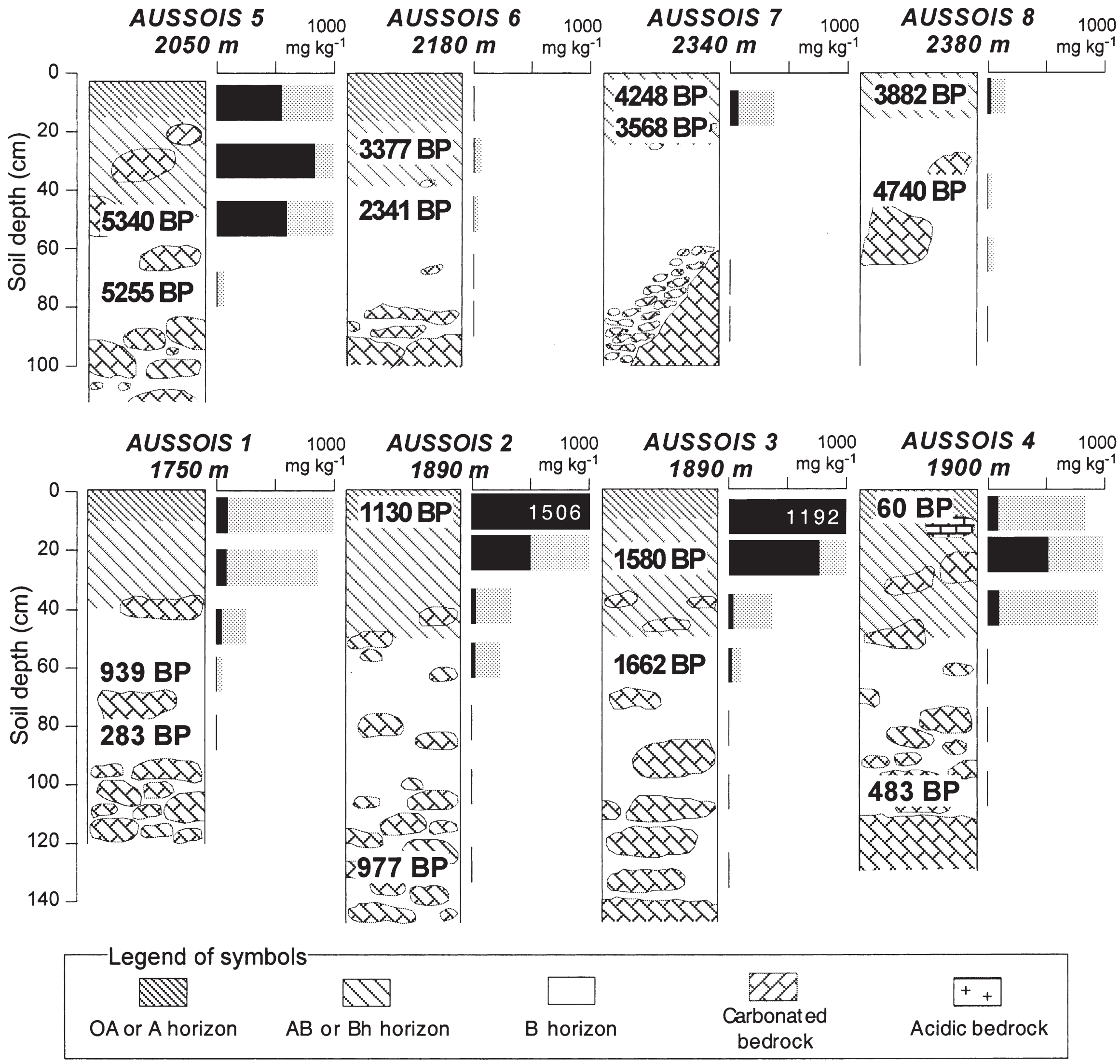

Figure 3 Soil profiles from Aussois. They are located on calcareous bedrock. The black bar is the charcoal mass concentration per level (mg kg^{-1}). The grey bars correspond to a $\times 10$ exaggeration of the concentration. Dates are expressed in calibrated years before present (details in Table 4).

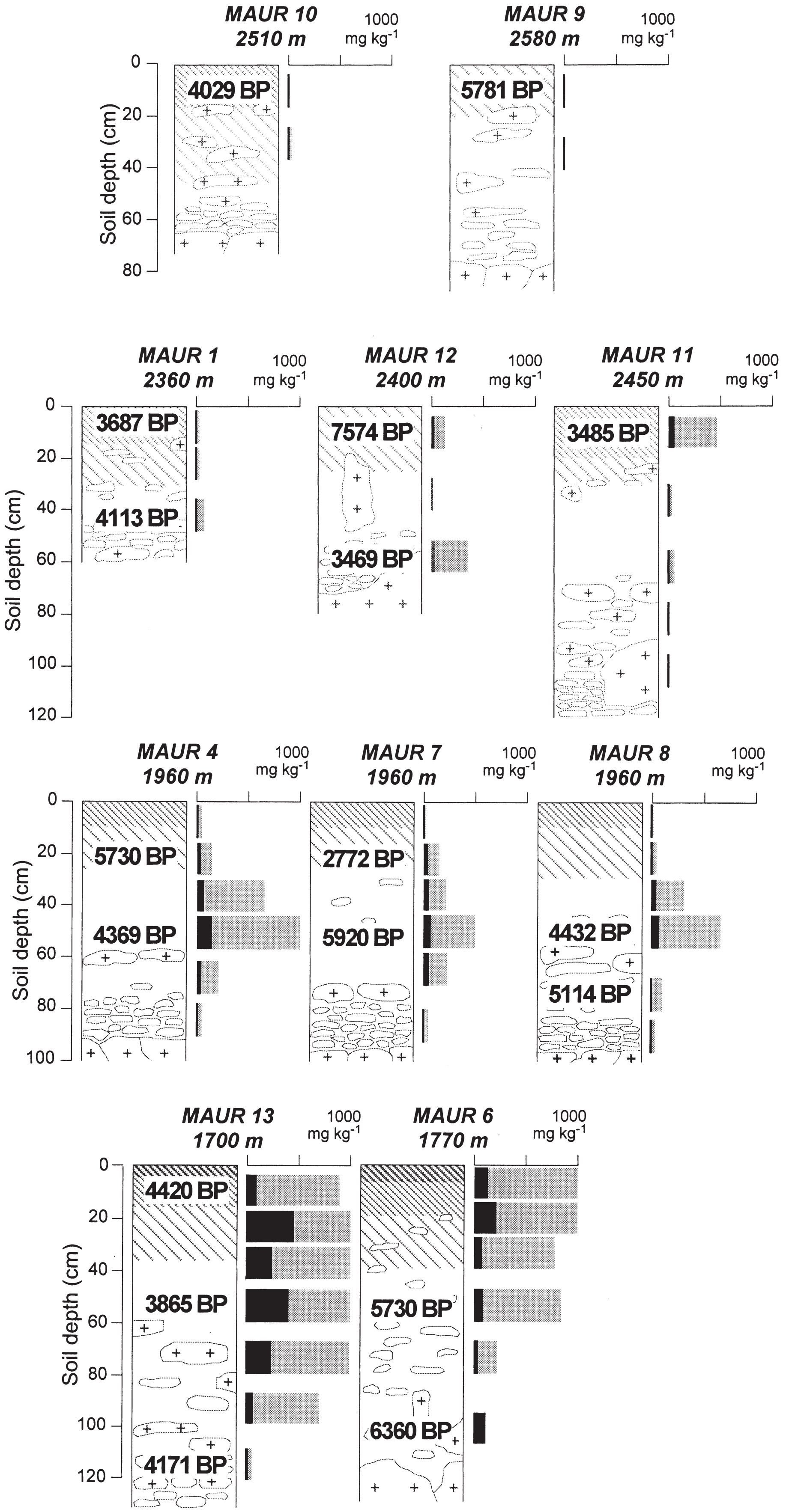

Figure 4 Soil profiles from Saint-Michel-de-Maurienne. They are located on acidic bedrock. The black bar is the charcoal mass concentration per level (mg kg^{-1}). The grey bars correspond to a $\times 10$ exaggeration of the concentration. Dates are expressed in calibrated years before present. For the symbol legend, see Figure 3 (details in Table 5).

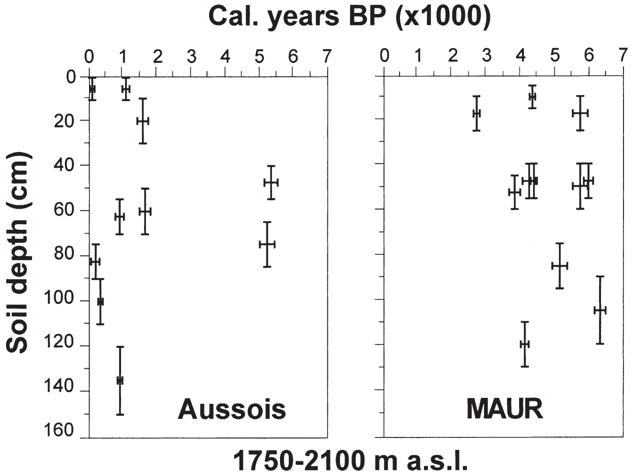

Figure 5 Distribution of AMS ^{14}C dates according to the soil depth between 1700 and 2100 m a.s.l. at Saint-Michel-de-Maurienne and Aussois (Vanoise massif, north French Alps). This altitudinal range is currently potentially forested and below the upper tree-line. The vertical bar indicates the thickness of the soil level containing the dated charcoal fragment, and the horizontal bar the range of the calibrated dates at 2σ.

the stratification assumption, except AUSSOIS 4 (Figure 3) and MAUR 7 (Figure 4). Moreover, some soil profiles showed an inverse stratification: AUSSOIS 1, 2 and 6 (Figure 3) and MAUR 4, 12 and 13 (Figure 4).

To obtain an overview of the soil-depth distribution of the charcoal dating, ^{14}C measurements were plotted per elevation class and per locality. Dating of profiles AUSSOIS 1–5 (1750–2100 m a.s.l.), which contain mainly late-Holocene measurements, are presented in Figure 5 together with data from Saint-Michel-de-Maurienne within the same elevation range. At Saint-Michel-de-Maurienne, no dates between 1700 and 2100 m a.s.l. are younger than 2700 cal. yr BP (Figure 5). No time-dependent burying pattern occurs. The distribution of charcoal fragments seems random. Figure 6 shows the same pattern obtained on soil from higher elevations (>2100 m a.s.l.). The random distribution noted in lower-altitude soils is also observed in higher elevations.

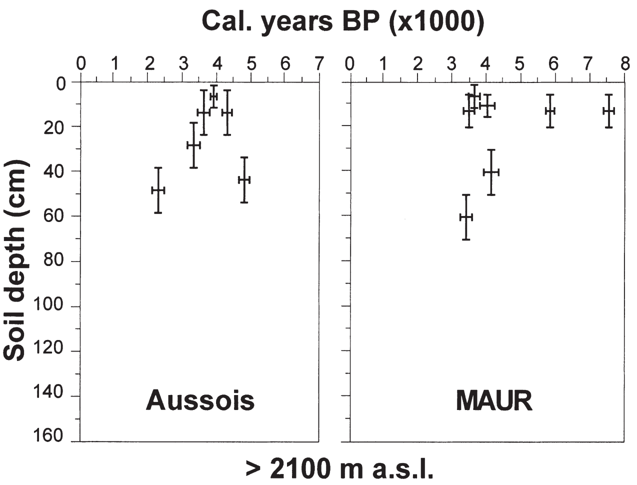

Figure 6 Distribution of AMS ^{14}C dates according to the soil depth above 2100 m a.s.l. at Saint-Michel-de-Maurienne and Aussois (north French Alps). Within the Vanoise massif, this altitudinal range is currently partially a park woodland up to the modern tree-line at 2300 m, and a grassland above 2400 m a.s.l. The vertical bar indicates the thickness of the soil level containing the dated charcoal fragment, and the horizontal bar the range of the calibrated dates at 2σ.

Charcoal concentration and depth, and stone lines

The vertical distribution of the charcoal concentration per level below 2000 m a.s.l. shows that when charcoal dates are recent (<1600 cal. yr BP; Figure 5 AUSSOIS) most charcoal particles are located in the upper levels, e.g., the top 30 cm in AUSSOIS 1–4 (Figure 3). On the other hand, when charcoal dates are older than 2400 cal. yr BP (Figure 5 MAUR), the charcoal concentration is located in the deepest levels or is more evenly distributed with depth (Figure 4b).

Profiles MAUR 4, 7 and 8 show deep lines of rounded stones (*c.* 10 cm in length) located at 55–60, 70–75 and 55–65 cm depth, respectively. Another stone line was observed in MAUR 3 localized at 2180 m a.s.l. (Carcaillet and Thinon, 1996) a few hundred metres from the first three profiles; however, no dating has been carried out on MAUR 3 charcoal due to the small mass extracted from this profile (Figures 1 and 2).

Discussion

Single charcoal fragments are not stratified although charcoal contentrations seem age/depth distributed

If we consider charcoal fragments without taking into account their mass distribution, the present data evidence that between 1700 and 2600 m a.s.l. the burial depth of charcoal fragments in soils does not follow their age. These results suggest that charcoal particles are not stratified in the soil profiles. Because some soil pits were dug at sites where colluvial processes are not possible due to their position on the top of moraines (AUSSOIS 2–4) or the top of a ridge or a slope (AUSSOIS 6–8, MAUR 9–12), it can be inferred that biological or geomorphic mechanisms are the main causes of the non-stratification of charcoal fragments and other particles at least up to 400 μm in diameter.

The apparent but coarse relationship between the mass concentration of charcoal per level and the age of the burned vegetation at intermediate-elevation sites seems inconsistent with the results exhibiting the non-stratification of ^{14}C-dated particles above 400 μm in diameter. My dating strategy only considers a single charcoal fragment buried at a given depth, whereas the charcoal concentration takes into account all charcoal above 400 μm. The single fragment gives an age that could be not representative from the whole assemblage if it has been submitted to reworking. The dating of a pool of charcoal would thus conduct to give a mean age of charcoal assemblages. The two strategies considering a single fragment and a pool of charcoal have been separately applied and provide two different conclusion on soil stratification. Indeed, it is amazing to notice that the pool method has been applied to support the assumption of soil charcoal stratification (Thinon, 1978; 1992; Berli *et al.*, 1994; Vernet *et al.*, 1994) and to provide a relationship between charcoal age and the burying depth to estimate the organic-matter accumulation rate (Boulet *et al.*, 1995). To confirm the hypothesis of coarse age/depth distribution of charcoal masses, several charcoal fragments proportional to the charcoal concentration per level should be pooled for dating and compared to a series of dates obtained from single fragment.

Charcoal layers and stone lines: a combined tool to estimate the time-frame of bioturbation

The stone lines occurring in MAUR 4, 7 and 8 have been preliminarily interpreted as the result of slope erosion following a fire dated by the charcoal fragments in the same profiles (Talon *et al.*, 1998), assuming that charcoal fragments are stratified in soils. Although this study demonstrates that charcoal particles above 400 μm and generally around 1 mm are not stratified, the six charcoal dates of these three profiles indicate fire deforestation of plants between 5900 and 2600 cal. yr BP (Table 5; Figure 4). These stone lines occur just below the maximum of charcoal concentration. The burying of charcoal fragments would be slowed down in comparison with the burying of stones a few centimetres in length under the soil bioturbation. Indeed charcoal fragments can be trapped by plant-root layers during their downward burial and upward reworking by the soil fauna, while stones are too large to be reworked by most soil invertebrates. It is thus not inconsistent that stone lines are buried deeper and faster than charcoal mass layers, which were produced only a few years before the slope erosion.

A stone line is 'a residual but dynamic polygenetic layer that is often of mixed lithology' (Johnson, 1993). The stone lines and the charcoal accumulation between 55 and 80 cm indicate the maximum depth of burying particles by the soil fauna. Because at this elevation (1960 m a.s.l.) dung beetles are limited to a depth of 20–25 cm, these stones lines are probably the results of anecic earthworms, whose presence is confirmed by cocoons or by individuals (Table 3). Johnson (1990; 1993) described the burial process of stone lines and has proposed a hypothetical time of 50 000–200 000 years for this process even if it is 'probably too great by several orders of magnitude' (Johnson, 1993). My data from middle-elevation soils in Saint-Michel-de-Maurienne (upper mountain and lower subalpine belts) show that the time is definitely shorter, maximum 4000 years (Figure 5). At a similar elevation in Aussois, using both the charcoal concentration per profile in AUSSOIS 2, 3 and 4 and their dates (Figure 5), I estimate that most small particles above 400 μm need less than 2000 years to move downward by 25–30 cm. This rate applies to the majority of particles produced by a fire period occurring since 1600 cal. yr BP, even though isolated fragments can move to the bottom of a 1 m profile in less than 500 years (AUSSOIS 1 and 4, Figure 5).

At higher elevation, especially up to 2300 m a.s.l., charcoal fragments never abound in soils (Figures 3 and 4). However, they mainly occur in the upper horizons. All dates are mid-Holocene, between 7600 and 3400 cal. yr BP. I have not found evidence for earthworms at these high-elevation soils. I consequently hypothesize that reworking processes are less intense at high elevations. The hypothetical limit of abrupt decrease of bioturbation would correspond to the modern upper forest limit. If reworking mechanisms occur, they possibly result from the activity of dung beetles and ants (*Myrmica*) and of freeze-thaw processes. However, some small land-snail shells known to have a short residence time in soils were observed between 45 and 60 cm in an alpine calcic soil at 2850 m a.s.l. (Talon, 1997). This author suggested that soil reworking within the alpine belt should be fast in spite of the elevation of the sample profile.

The strategy based on the ^{14}C dating of charcoal fragments and the quantification of charcoal concentration per soil level provides a time-frame for reworking of soil particles.

Palaeoecological implications

Because wood charcoal buried in soils is becoming a much-used tool for reconstruction of plant assemblages and fire history during the Holocene, it is crucial to improve knowledge on the migration of fragments in natural soils. This taphonomical study shows that charcoal fragments can be localized at any soil depth after a few centuries depending from elevation, while the depth of a charcoal mass resulting from a fire episode seems roughly distributed according to time. According to the present study, it appears that the soil-charcoal study cannot yield a precise chronology of the vegetation change based on the stratification of charcoal assemblages. Indeed, the main feature of the charcoal assemblages is that they are not continuously recorded, because the interval between two fire events might attain a few centuries in subalpine and alpine belts (Carcaillet, 1998).

Because charcoal occurrence is a common feature in such mountain environments (Tessier *et al*., 1993; Berli *et al*., 1994; Tinner *et al*., 1996; Talon, 1997), and because soil is a ubiquitous palaeo-environmental deposit at low and middle elevations, the main contribution of soil-charcoal studies is to yield spatially precise insights on plant-population distribution and fire occurrence during the Holocene (Payette and Gagnon, 1985; Filion *et al*., 1991; Carcaillet, 1998). Therefore, study of the upper tree-line change is probably one of the best applications of pedoanthracology based on taxonomic identification of charcoal (Carcaillet *et al*., 1998; Talon *et al*., 1998). In addition, at high elevations, especially in the dry inner valleys, peat, ponds and lakes are rare, woody vegetation is sparsely distributed, and pollen production is irregular at the tree-line. These facts limit the use of conventional analysis as pollen, stomata or macro-remains, and places higher value on soil-charcoal study.

Conclusion

I documented the mixing of charcoal in soil profiles from middle and high elevations in the Alps. Soil fauna in soil mixing is probably important, especially in view of previous studies which have commonly underestimated this factor. The minimum time for a charcoal particle to migrate down in the soil profile to a depth of 100 cm is less than 500 years at 2000 m a.s.l., but most of the charcoal production of the two last millennia remains in the upper 30 cm. After 2500–6000 years, the major part of the charcoal mass was buried at a depth of 40–70 cm for elevations below 2000 m. The concentration and the depth of a charcoal layer and stone lines probably result from surface erosion following fire deforestation events and can be used to estimate the maximum depth of migration of soil fauna. Soil materials are not really stratified at the middle and high elevations. This has implications on the use of soil as a classical palaeoecological sediment based on stratigraphy. First, it is not necessary to sample soil material at different horizons as indicated before for high elevations (Carcaillet and Thinon, 1996; Talon *et al*., 1998). The exception is buried soils displaying a clear stratigraphy in Subarctic environments, where further the soil fauna is generally limited to the litter layer (Payette and Filion, 1993). Second, soil can definitely be used to reconstruct with high spatial precision, past burned plant population supported by high number of ^{14}C dates yielding a Holocene chronology. However, this conclusion for high-elevation soils from the Alps based on 34 AMS ^{14}C dating cannot yet be generalized to soils in other climatic regions. This needs new studies based on a large number of radiocarbon measurements. The ^{14}C dating of charcoal fragments buried in soil provides a new method to investigate soil-bioturbation processes throughout the Holocene.

Acknowledgements

Financial support was provided by the French Environment Office (Ministère de l'Environnement) through the programs DRAEI 92184 (to J.-J. Brun), DRAEI 93019 (to L. Tessier), and DGAD 95227 (to C. Carcaillet), and by a grants to the author from the French Education Office (Ministère de l'Éducation Nationale, de l'Enseignement Supérieur et de la Recherche). I gratefully thank F. Courchesne, K.J. Edwards, J.T. Gray, F. Guibal, S.T. Jackson, F. Magnin, T. Nakagawa, P. Germann, R.J. Schaetzl, B. Talon, H.E. Wright and anonymous reviewers for comments. I acknowledge M. Barbero and J.-L. de Beaulieu. for the laboratory facilities. I thank H.N. Barakat, J.-J. Brun, L. and M. Didier, A. Nicault, B. Talon and M. Thinon for the field assistance. I also thank S. Payette, P. Trehen and B. Van Vliet-Lanoë for their enlightening discussions during my PhD defence.

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