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Deglaciation of the Vosges dated using ^{10}Be

JEAN-LUC MERCIER[1], DIDIER L. BOURLÈS [2], JAN KALVODA[3], RÉGIS BRAUCHER[2], ANETTE PASCHEN[1]

[1] Université Louis Pasteur, CEREG UMR 7007, Strasbourg
[2] CEREGE, Université Aix Marseille III
[3] Charles University, Faculty of Science, Prague

Abstract: A deglacial study shows the development of 6 push moraines at low altitude (~ 600 m a.s.l.) in the Vosgian area. Dated according to ^{10}Be at 11.5, 10.6, 9.7, 9.0, 8.3, and 7.9 ka, they indicate the occurrence, after the last glacial maximum (LGM) and well into the early Holocene, of frequent climatic oscillations on a millenial scale. Furthermore, a linear relation between ^{10}Be exposure ages and glacially eroded landscape elevation is evidenced. It allows the identification of 5 different paleotopographies implying rapid transitions from glacially eroded to fluvially eroded landscapes. Global climatic events such as LGM, Heinrich events H2, H3, Dansgaard-Oeschger interstadial IS2, IS4, IS5, IS6 are recognized as probable pacemakers in such landscape change.

Key words: geomorphology, ^{10}Be dating, Vosges

1. Introduction

The Quaternary geomorphological evolution of the mountain massifs in the Central Europe is bound to their specific geographical position. They were climatically affected by two local glacier systems, the one covering Scandinavia and the rest of northern Europe, the other the Alps. Both of them affected atmospheric circulation and shifted the hydrographic outflow. To simulate the geomorphological development of that zone, it is necessary to date the glacier landforms, to make correlations of the maximal extend of the glaciers in the Pleistocene, and to link the stratigraphy of valley glaciers to glacier moraines and to terraces of large rivers.

A confirmation of field observations by absolute dating would enable us to associate the Alps, the Vosges, the Giant Mountains, the Šumava Mountains, the Tatras, etc., to the stratigraphy of continental glaciation of northern Europe and to deepen our knowledge of palaeogeographical development of the Central European mountains. The lack of absolute chronology for the glacier events in the Central Europe has two negative consequences: the one is relative to the Quaternary stratigraphy and palaeo-environmental studies that are being carried on, the other to feeble correlations between the glacial stages of the North-European continental glacier and the Alpine glaciers.

The dating with the help of the ^{10}Be method is one of instruments enabling to study palaeogeographical processes and landforms changes in the Quaternary. However, it is necessary to choose appropriate sites to find on the continent traces of climatic oscillations visible both in Greenland ice and in sea sediments. Small valley glaciers at low altitudes that have a very short reaction and response time are more sensitive to climatic variations than the polar ones. Our attention has been aimed at the particular location of the deglaciated sector between the Scandinavian glacier and the Alps, that is between 48° to 53° n. l During warm spells, a retreat of the glacier is accompanied by a more or less intensive west circulation, which brings more humidity and by that more ice. An unwindy situation accompanied by an anomorphographical effect even more intensifies fluctuations of the climate. All this explains the choice of the Vosges, the Giant Mountains, and the Tatras in the line West-East inclusive other mountain areas in their neighbouring regions. In the same time the dating of terminal moraines in the Alps (Bodensee) and of the Scandinavian glacier allows to try the numerical modelling.

The continental glacial landforms (moraines, striated rocks, drumlins, etc.), used as indicators of the geographical extent of the major global glaciations triggered by astronomically driven climate changes, are also frequently used as time markers in Quaternary studies, geomorphology, and tectonics (Flint 1971, Hays et al., 1976, Washburn 1979, Ritz et al., 1995, Allen 1997, Siame et al. 1997, Bloom 1998). However, continental glacier production and dynamics in mountain areas not only depend on global climatic conditions but also are greatly influenced by the regional relief (Gillespie, Molnar 1995) which also has a major impact on the local climate. On this scale, particular orientation of the relief relative to the general climatic circulation, may induce climatic gradients that favour the formation and oscillations of glaciers (Geiger 1971, Yoshino 1975, Barry 1981, Oke 1995). A particular glacier application is in Kuhn (1981). Associated landforms thus appear to be ideal objects not only for identification but also for the dating of such climatic oscillations. Until recent progress in the Accelerator Mass Spectrometry (AMS) technique, the ages of glacial features could only be inferred from indirect measurements or from proxy histories of the global climate. The improved AMS technique now offers the opportunity to accurately date landforms through the measurements of their in-situ produced ^{10}Be concentrations accumulated during the exposure of rock surfaces to cosmic ray particle interactions. The theoretical principles were developed by Lal (1991) and Brown et al. (1991), and specifically applied to glacial geology by Nishiizumi et al. (1991, 1993), Brook, Kurz (1993) and Gosse et al. (1995). Synthetic information can be found in reviews by Lal (1988) and Cerling, Craig (1994). There are differences caused by secular changes in the production rate between the calendric time scale and the cosmonucleide time scale, throughout this paper "^{10}Be ka" refers to in situ-produced ^{10}Be exposure ages, and "kyr" refers to the ^{14}C time scale. Varves counting and ice core time scale are expressed in "ka" (1 ka = 1000 yrs).

Steep climatic gradients may have affected the Vosges massif in Eastern France (7°E) during the last glacial period because of: (i) a situation in the discontinuously glaciated corridor extending from 48° N to 53°N between the edges of the Scandinavian ice sheet to the north and the alpine ice sheet to the south; (ii) a topographic lee position with regard to the west-east general circulation, and (iii) its topography generating a significant precipitation gradient from west to east (200 mm/km). Hydrological and climatic synthesis in the area are in Atlas climatique du Fossé Rhénan Méridional (1995) and Ambroise (1995). All these characteristics make the Vosges mountains (Photo 1) a particularly well-suited region to study the climatic oscillations in continental Europe.

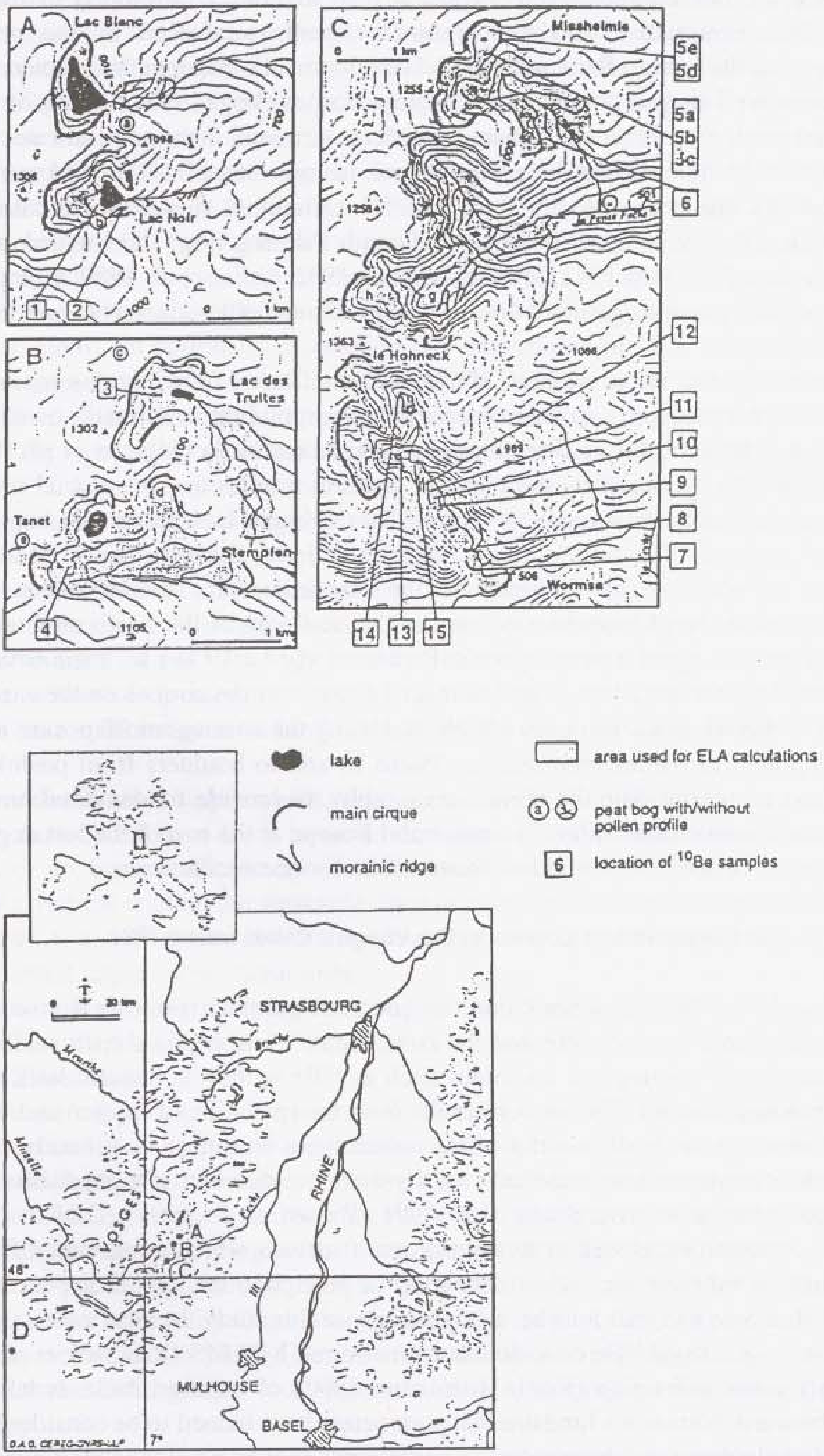

Fig. 1: Location of ^{10}Be dated samples and peat bogs in the Vosges

During the last climatic cycle, whilst a plateau glacier developed in the western Vosges, the precipitation and temperature gradients reinforced by the pronounced topography of the eastern flank induced the development of deep valley glaciers anchored in presently well shaped cirques in the eastern Vosges (Vogt 1992). Dating of peat bogs associated with the three well shaped western terminal moraines indicate that their emplacement likely occurred during the marine isotopic stage 3 (30 to 45 kyr). Although these datings are near the limit of the ^{14}C technique, they are validated by the palynological profile obtained from the La Grande Pile bog (Fig. 1D) situated on an older glacial deposit (Woillard 1978, Woillard, Mook 1982, Guiot et al. 1989, Guiot 1997). It is evidence of a previous greater advance of the central Vosges glaciers (Seret 1967, Seret et al. 1990).

By contrast, the upper valleys of the eastern flank of the Vosges massif exhibit numerous late recessional morainic deposits corresponding to climatic oscillations, as demonstrated by equilibrium line altitude (ELA) calculations (Mercier et al. 1996). The rain shadow effect induced by the climatic gradient implies that the glacial remnants in the bottom part of the main valleys of the eastern Vosges lack associated bogs and thus remained undated. Till and outwash sediments have therefore only been globally estimated as Wurmian by reference to the classical alpine classification. However, palynological study of bogs located on the cirque floors at the heads of some eastern valleys (Fig. 1) suggest a more specific Preboreal age (< 10 ka) for their development. The chronology for the advance and retreat of glaciers in the cirques on the eastern flank of this well-suited region has been established using the cosmogenic exposure age dating method applied to roches moutonnées (Photo 2) and to boulders from push moraines. This allows us to elucidate the chronostratigraphy, to provide fundamental new data on small scale climatic oscillations in continental Europe at the end of the last deglaciation, and to connect erosional glacial landforms with climatic oscillations.

2. Deglaciation events in the Vosges dated using ^{10}Be

Nuclear interactions between secondary energetic particles resulting from cosmic rays entering the Earth's atmosphere and the constituents of an exposed rock surface induce the production of cosmogenic nucleides such as ^{10}Be within its mineral lattice. The so-called "in-situ produced ^{10}Be" which results from the spallation of oxygen and, to a lesser extent, silicon, at the Earth's surface thus accumulates with time in minerals of surficial rocks until its concentration reaches a steady-state balance between production and loss by erosion and radioactive decay (Lal 1991, Brown et al. 1991). Due to its simple chemical composition as well as its tight crystal structure, which minimizes diffusion and contamination by meteoric ^{10}Be transported in precipitations, quartz appears to be the mineral of choice and will thus be used throughout this study. In most cases, calculation of exposure ages from ^{10}Be concentrations measured by AMS (Raisbeck et al. 1987) in the quartz mineral fraction (Kohl, Nishiizumi 1992) of exposed rocks is however not straightforward. Numerous fundamental parameters have indeed to be considered, i.e. the nucleide production rate; the removal of surface material by erosion; and, in mountainous environments, the geometric shielding of the cosmic rays by surrounding obstructions as well as the burial of the samples sites by seasonal snow cover.

As extensively discussed during the workshop on „Secular variations in production rates of cosmogenic nucleides on Earth“ (Masarik, Reedy 1995, Gosse et al. 1996), the present uncertainty in the spatial and temporal variability of the rate of production is the most significant source of error for exposure age estimates from cosmonucleide concentration measurements. It mainly results from poorly constrained temporal changes in the intensity of the Earth's dipole magnetic field strength and in the average geomagnetic latitude caused by secular variation of the dipole axis position. Taking into consideration the small geographical range of the studied samples (Fig. 1), and that the uncertainty linked to the scaling of the production rates using both the altitude and latitude polynomials of Lal (1991) is thought to be less than 10% (Masarik, Reedy 1995, Gosse et al. 1996), an optimistic production rate uncertainty of 10% was propagated to estimate an „absolute Tmin. error“ associated with the ^{10}Be exposure age calculations (Tab. 1). However, in the study of the relative sequences of the deglaciation patterns, the geographically tight locations of the studied samples (site latitudes ranging from 48°01' N to 48°06' N, Fig. 1) as well as the time span involved, leads us to consider only the analytical uncertainty while discussing the Vosgian ^{10}Be exposure ages ("relative Tmin. error", Tab. 1).

From north to south, the 5 studied valleys in the Vosges are (Fig. 1):

The **Lac Noir** cirque which contains a lake in its overdeepened part. Both cirque and lake are surrounded by a ~ 30 m high morainic lobe. (Ln1) was taken from the lower part of a roche moutonnée located between the lake and the upper cirque while (Ln2) was sampled from a ~ 28 m^3 granitic boulder lying on the inner part of the south side of the morainic lobe.

The **Lac des Truites** cirque which is the combination of: a) a central part comprising a peat bog surrounded by a 1 – 2 m morainic rampart, b) the lake itself behind a small dam, and c) an important outcrop of roche moutonnée, d) the „Altenwasen cirque“ limited by a vertical wall on the west side, by a moraine on the east and a nivation hollow on the south, e) and, to the north-east, a sub-cirque directly above the lake. (Lt3) comes from the central upper roche moutonnée.

The **Tanet** cirque which belongs to the upper part of the west-east Schildmatt valley. (Ta4) was taken from a boulder of a small recession morainic ridge limiting a peat bog within the Tanet cirque.

The Missheimle cirque which is one of the upper cirques of the **Altenbach** valley organized around four cirques. Five boulders (M5a-b-c-d-e) were sampled on the two moraines which have been emplaced on the lip of the Missheimle cirque, in front of a steep slope. M5b-e belonged to the inner moraine whilst M5a-c belonged to the outer. M5d is an angular boulder lying on the outer moraine near the cirque wall.

One 20 m^3 erratic boulder (A6) was sampled 2000 m beyond the Missheimle cirque. It is an element of a recessional moraine which is the only morainic deposit mapped as a „Riss“ moraine on the 1/50,000° Gérardmer French National Geological map. At the A6 sampling location, the glacier most likely became a hanging glacier above the Petite Fecht valley.

The **Wormsa** which is a textbook example of a U-shaped valley reaches 1363 m a.s.l. in its upper part. Four successive recession moraines lying 3000 m to 4500 m from the headwall of the main cirque are observed in its lower part. Their elevations range from

Table 1: Sample details and ^{10}Be results

Sample	Altitude (m)	Dip [1] (°)	Topographic shielding (%)	Mean snow cover duration[2] (week)	Mean snow thickness[2] (cm)	Corrected production rate (at./g/y.)	^{10}Be cocentration (10^5 at/g)	^{10}Be analytical error (10^5 at/g)	T_{min} (^{10}Beka)	Absolute T_{min} error (^{10}Be ka)	Relative T^{min} error (^{10}Be ka)
Ln 1*	971	21	5.01	12	42	13.2	0.68	0.16	5.1	1.5	1.2
Ln 2*	1.001	1	7.83	11	35	13.6	1.31	0.14	9.7	1.8	1.1
Lt 3*	1.110	19	6.31	14	71	14.5	1.37	0.14	9.5	1.7	1.0
Ta 4*	1.100	31	3.38	14	77	14.4	1.34	0.24	9.3	2.2	1.6
Ta 4bis*	1.100	31	3.88	14	77	14.4	1.40	0.15	9.8	1.8	1.0
M 5a*	1.102	28	4.46	16	108	14.0	1.60	0.13	11.5	2.0	0.9
M 5b*	1.102	15	4.46	16	108	14.0	1.49	0.14	10.6	1.9	1.0
M 5c*	1.102	30	4.46	16	108	14.0	1.60	0.15	11.5	2.0	1.0
M 5d*	1.102	0	6.53	16	112	14.0	0.75	0.15	5.4	1.4	1.1
M 5e*	1.102	16	9.04	16	112	14.0	1.48	0.15	10.6	1.9	1.1
A 6a*	850	0	9.58	13	52	11.9	1.71	0.14	14.4	2.5	1.2
A 6b*	850	43	9.58	13	52	11.6	1.77	0.18	15.3	2.8	1.5
W 7*	537	10	14.42	9	18	9.4	0.85	0.10	9.0	1.7	1.1
W 8*	572	8	14.09	9	20	9.7	0.81	0.10	8.3	1.6	1.1
W 9*	620	21	15.06	11	30	10.0	0.76	0.19	7.6	2.2	1.9
W 10*	628	16	17.12	11	32	10.1	1.01	0.13	10.1	2.0	1.3
W 11*	645	0	21.07	11	34	10.3	0.94	0.11	9.2	1.7	1.0
W 12*	699	38	25.47	11	37	10.2	0.64	0.08	6.3	1.2	0.8
W 13*	816	0	16.1	12	48	11.7	1.02	0.11	8.8	1.6	1.0
W 14*	951	8	21.85	13	61	12.9	1.16	0.12	9.0	1.7	1.0
W 15*	773	21	19.49	12	41	11.2	1.04	0.13	9.3	1.8	1.1

Notes

[1] Dip angles measured with reference to the horizon; * refers to roche moutonnée; # to boulder from moraines. and § to an erratic boulder. The production of ^{10}Be calculated from equations given by Lal (1991) is corrected to account for burial by seasonal snow cover and for topographic shielding. This last parameter is calculated by determining a production rate shielding factor, S, as the ratio of the remaining flux to the maximum flux:

$$S = 1 - \frac{}{} \sum \Delta\Phi_i \sin^{m+1} \Theta_{i},$$

where Θ is the dip angle, measured up from the horizontal, and Φ is the azimuthal angle, n is the number of obstructions and $m = 2.3$.

[2] Fifty-six years measurements from the Lac Noir weather station and 20 years measurements from 14 sites spread over 150 km^2 were used to modelize the snow thickness spatial variability and duration over the studied area. Errors were propagated using the analytical uncertainties given. An additional 10% uncertainty is assigned to the surface production rate while calculating the absolute $T_{min.}$ error. Beryllium blank ratios, uniformly less than 6.0×10^{-15}, were always at least ten times lower than the measured ratios.

506 to 600 m a.s.l. Because these push moraines are mainly composed of fine-grained material, only the second and third moraine contain candidate boulders for ^{10}Be dating (W7 – 8). Further up (upto 940 m a.s.l.) and across the valley, roches moutonnées were then sampled, from bottom to top: W9, 10, 11, 12, 15, 13 and 14.

Research of "La Grande Pile" pollen profile have been described by Woillard (1978), Woillard, Mook (1982), Guiot et al. (1989) and Guiot (1997). The other peat bogs studied in the publications are: a = Tockensee, b = Lac Noir, c = Gazon de Faing, d = Stillenbach, e = Tanet, f = Hirschensteinried, g = Rothried, h = Frankenthal. According to Crowley, North (1991), in this region the lowest part of the pollen profiles correspond to a Boreal age for sites a-h (8500 kyr ^{14}C) and to a Suboreal age for sites b-c-d-e-f and g (4600 – 5600 kyr ^{14}C).

The production rate was not only scaled to its latitude and altitude but was also corrected for shielding of the incoming cosmic rays by surrounding obstructions. This last parameter was carefully evaluated using image analysis of hemispherical photographs. The photographs looking upward being taken at each sample location such that the film plane is level, the topographic shielding relative to the case of free (2π) irradiation is calculated as equivalent to the percentage of the photograph that does not receive sunlight (Table 1). Since shielding by live biomass may reasonably be considered as minor (<3%) in a forested equatorial environment (Brown et al. 1995), it was neglected in the temperate oceanic environment of the Vosges where the biomass represents only 50% of that of the former (Cannell 1982).

The Vosgian environment also implies episodic winter burial of the studied samples by snow which affects the production rate. The data about snow cover were analysed and completed by J. Adjizian, R. Braun and A. Marchal (personal communication). For each sample, the reduction of production rate by the overburden of snow was calculated using: 1) a mean measured snow density of 0.281 g cm^{-3}; 2) a mean snow cover duration averaged over 56 years which ranges from 9 weeks for the samples collected at the lowest altitude up to 16 weeks for the samples collected at the highest altitude; 3) a mean snow thickness averaged over 20 years which ranges from 0.18 m for the sample collected at the lowest altitude up to 1.12 m for the sample collected at the highest altitude (Table 1).

Assumption of negligible losses as a result of rock weathering results in a calculated lower limit for the exposure age of a surface (Brown et al. 1991). It is possible, however, to estimate the losses induced by the abrasion of the boulders and bedrock surfaces (Photo 3), and hence to adjust the exposure ages obtained from the previously discussed corrected production rate. Previous regional estimates of erosion rates of the sampled rock type were lacking, but could be approximately estimated using the maximum differential height of ~ 4 mm between the granitic matrix and the more abrasion resistant quartz veins of roche moutonnée sample W9, along with the palynological ages of bogs located in the upper part of many upper eastern valley cirques (Fig. 1). This yields a low differential erosion rate of 0.4 mm ka^{-1}. This is most likely a maximum rate, the downslope, or distal location of the studied sample relative to the valley cirque, implying that the palynological age of bogs only gives a minimum duration of exposure for the boulder. Considering that the measured differential height is a lower limit, a maximum erosion rate of 1.6 mm ka^{-1} may thus be calculated by halving the exposure time and doubling the differential height. This still low post-glacial rock-erosion rate estimate is in agreement with the preservation of striations of the bedrock surface and induces compensation which would increase the calculated ^{10}Be ages by less than 1.5%.

Expected accentuation by the local topography of the climatic perturbations is confirmed by the data which evidence the occurrence of 6 different Holocene push moraines at low altitude (Tab. 1 and Fig. 1). In addition, the results tied paleoclimatology and relief through a demonstrated structuration of glacial landscape by climatic pulses. The oldest analysed sample (A6: 15.3 ^{10}Be ka, Tab. 1) is an erratic boulder from the hanging Altenbach valley. All other 19 samples have ^{10}Be exposure ages corresponding to the Younger Dryas (YD) or earlier (Tab. 1). In the upper Altenbach cirque, 4 boulders (M5a-c-b-e) sampled from two distinct moraines allow us to distinguish between two YD phases. M5b and M5e from the innermost deposit yield similar ages at 10,620 yrs. The nearest outer accumulation samples, M5a and M5c are dated at 11,470 yrs.

The Missheimle sample exposure ages are in good agreement with the dates previously published for the YD Layer counting in ice cores yields a proposed date (10,720 ∍ 150) yrs for the end of YD in Dye 3 (Dansgaard et al. 1989), the proposed date (12,700 ∍ 100) yrs to (11,550 ∍ 70) yrs in GRIP (Johnsen et al. 1992) and to propose 12.9 ka and 11.7 ka in GISP 2 (Taylor et al. 1993). In the same core, Alley et al. (1993) propose (11,640 ∍ 250) yrs for the end of YD after a duration of (1,300 ∍ 70) yrs. Varve counting in Swiss lake sediment cores yields (Hajdas et al. 1993) proposed dates from 12,125 to 11,000 yrs. Whereas using moraines ^{10}Be exposure ages (Gosse et al. 1995), the proposed date is (11,000 ∍ 700) yrs. Recently, using morainic boulders ^{10}Be, ^{26}Al and ^{36}Cl exposure ages yields (Ivy-Ochs et al. 1996) the proposed dates from (11,800 ∍ 500) to (10,400 ∍ 400) yrs.

A nearby sample, Ln2, taken from a 28 m^3 granitic boulder (Photo 4) lying on the inner part of the south side of the Lac Noir morainic lobe testing indicated a younger positive event at 9.7 ka. In the Wormsa valley, all the studied glacial structures, 2 from 4 successive recessional moraines related to 4 positive glacial events and 7 dated roches moutonnées indicate emplacement or exposure ages prior to YD (Tab. 1 and Fig. 1C). In that valley a moraine W8 dated according to ^{10}Be at 8.3 ka could be synchronous with an abrupt cold event evidenced in the Greenland (GRIP Summit) ice-core at 8.2 ka and to a climatic change and a faunal shift at 8260 kyr BP in a North Atlantic core 28-03 (Klitgaard-Kristensen et al. 1998). Furthermore, a strong (r^2 = 0.998) negative linear correlation between the ^{10}Be exposure ages and the elevation was obtained for the samples W7 – 8 – 9 and 12. The observed decrease from the bottom to the top is in agreement with the erosional effect induced by a warm based glacier. Located in the upper part of the Wormsa valley, the roches moutonnées W13 – 15, which do not fit with this regression were most likely under the influence of a cold based glacier. According to the dynamics of such a glacier it is generally accepted that in most situations, dry-based glaciers are geomorphologically inactive (Gordon 1979, Paterson 1981), they thus probably belong to a preserved erosional surface (Fig. 1C). In the middle part of Wormsa, but upper on the slopes, the roches moutonnées RM W10 – 11 became exposed slightly earlier as the result of glacier surface downwards reduction (Tab. 1). Near the Missheimle cirque wall, an angular boulder (M5d) lying on the moraine and dated according to ^{10}Be at ~ 5.4 ka most likely indicates the last frost shattering in this area. Samples Ln1 and W12 yield the lowest calculated ages.

3. Discussion of 10Be dating results related to Late Glacial geomorphological processes

Previous geomorphological works in the Vosges have led certain authors (e. g. J. Tricart, M. Darmois-Theobald) to propose Late Glacial emplacement for low altitude valley glaciers and cirques moraines. Our data appear to quantitatively confirm the presence of permanent ice and glaciers at low altitude (i.e. 600 m) in Vosgian valleys at the beginning of the Holocene. In the Austrian and Swiss Alps, three to four moraines of YD ages (the so-called "Egesen" age, Koerschner 1978) are located at least 2,000 m above the similar accumulations in the Vosges. In the Alps, the paleoclimatological studies are done by ELA depression calculation using the Little Ice Age (LIA) moraine as a reference. Such a reference does not seem to exist in the Vosges, even if temporary glaciers were described (e. g. by M. Collomb in 1848 and B. Grad in 1871) in some Vosgian cirques at the end of LIA. One sentence in Mappi (1742) "Filix minor palustris. Nicht weit von dem Closter Peris vereiniget fich ein anderer Bach mit diesem und wird Weisbach genannt / weilen er gantz milchecht aussiebet / wegen des allgemach zerschmeltzenden Eises oder Gletschers aus der Weisen See" let us think that some firn could have exit near the "Lac Blanc" during LIA in eastern Vosges. Due to their latitudinal and continental location, the Alps were dryer and due to their size, alpine glaciers were less sensitive (in Gillespie, Molnar 1995) to rapid climatic changes than small valley glaciers. All these considerations may well explain the observed difference in moraine elevations during the YD and the beginning of the Holocene between Alps and Vosges. This may result from the combined interaction of regional and continental scales of atmospheric circulation: lee effect, snow drift, and more depressions. The position of the oceanic polar front fluctuated around 45°N during the Pleistocene (Duplessy et al. 1980, 1981) and the maximum precipitation moved southward during ice-sheet growth (Gasse, van Campo 1994). At the studied latitude, while the coldest phases were dryer, during the YD and the beginning of the Holocene the interaction between the polar front moving northward and warm Atlantic waters produced more depressions than nowadays (Sissons 1979, Crowley, North 1991).

In addition to the two central Wormsa moraines (W7 – 8), and the roche moutonnée W9 dated according to ^{10}Be at ~ 7.6 ka, the occurrence of cooling events at the beginning of the Holocene is strongly supported by the ^{10}Be dating at ~ 9.7 ka and 9.6 ka of two moraines in different valleys, i.e. Ln2 in the "Lac Noir" valley and Ta4 in the "Tanet" cirque and at ~ 9.5 ka of roche moutonnées in the "Lac des Truites" valley (Fig. 1A, B). Furthermore, undated younger moraines have been described (Mercier et al. 1996) in the uppermost parts of these valleys. The evolution of the glacier of the Wormsa valley towards dead ice may be ^{10}Be dated at ~ 7.6 ka through the exposure age dating of the eroded roche moutonnée W9 which extends right across the valley. The last accumulation of semi permanent snow bank in the area can be dated through the exposure age dating of the roche moutonnée samples Ln1 and W12 located below easterly oriented nivation hollows, i.e. respectively, ~ 5.1 ka and ~ 6.3 ka (^{10}Be). The continuation of such early Holocene glacial events described above are in agreement not only with the sub-Boreal ages assigned by palynology (studies of J. P. Hatt, F. Firbas, J. Becker, C. Sittler, G.

Lemée and others) to bogs which developed on the cirque floors of some Vosgian valleys (Fig. 1D), but also with the results of Blanchon, Shaw (1995) in Atlantic Ocean region. We have to note that the catastrophic rising events described by Blanchon, Shaw (1995) in the Atlantic were not observed at Tahiti by Montaggioni et al. (1997) indicating an abrupt 6.5 m sea level rise at 7.6 kyr as well as with the contraction of the arctic glaciers between 8.0 kyr and 6.0 kyr recently evidenced by Koerner (1997) from an exhaustive study of their dynamics.

Landscape deglaciation demonstrated by elevation and ^{10}Be exposure ages in studied valleys of the eastern Vosges mountains is shown in Fig. 2. The full line slope is the regional vertical deglaciation velocity determined using the samples from the youngest glacial topography: W7 – 8 – 9 – 12. The E for "Ecurie" represents the interpolated age (7.9 ka) of the 4th inner Wormsa valley moraine. The dotted lines are translation of this line towards older Wormsa basal topography as well as other eastern Vosgian valleys. This negative linear correlation between the age and the lower elevation of a glacier tongue appears to be frequent. A verification made using data collected between 1850 and 1992 on 88 glaciers from the Austrian Alps (data gathered by G. K. Lieb from Graz University, Austria) yields a similar linear negative correlation with a determination coefficient (r^2) better than 0.97. Using thus the Wormsa calculated regression as a regional tool, we are able to estimate the ages of undated moraines (Fig. 2).

The almost perfect negative linear correlation between exposure ages and the elevation observed for the samples from the Wormsa valley (Fig. 2) offers the remarkable possibility of following the time transgressive switch from a glacial to a fluvial erosional

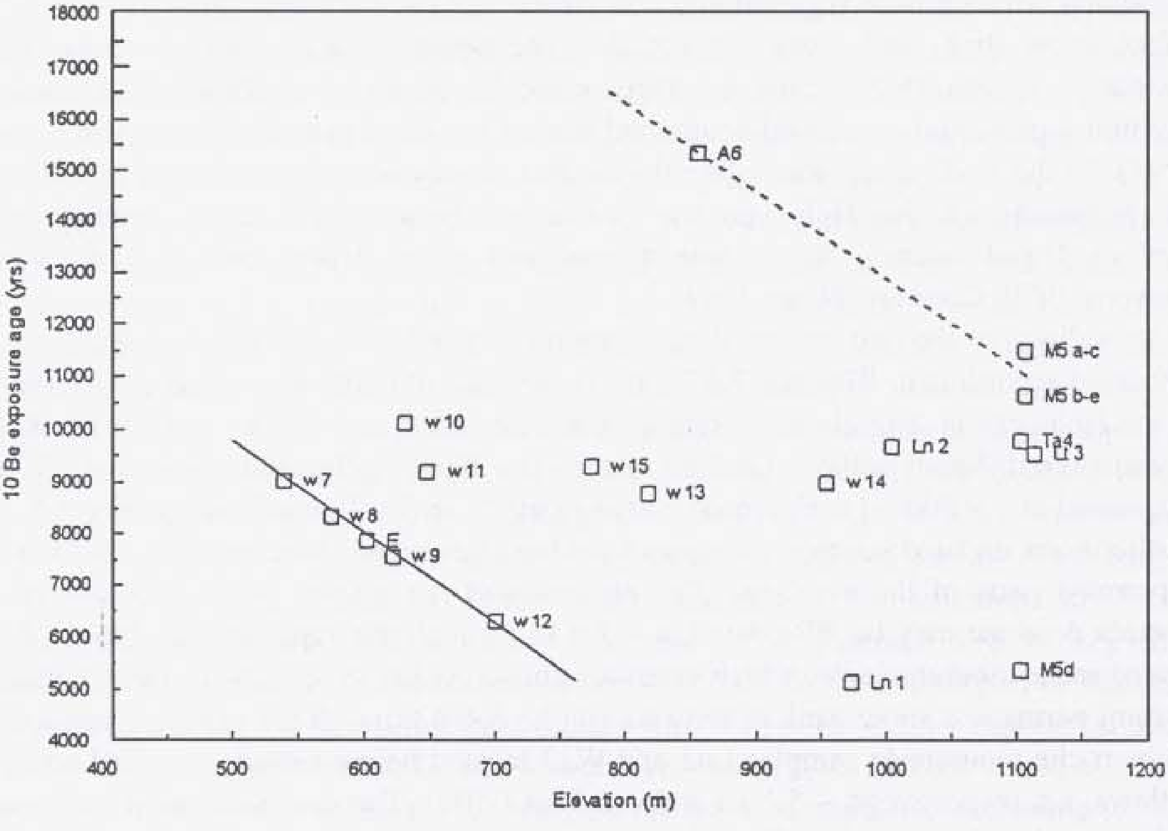

Fig. 2: Landscape deglaciation illustrated by elevation and ^{10}Be exposure ages in the eastern Vosges

system in an up-valley direction. The last glacial advance, associated with an abrasion phase, the basis for the cosmonucleide method, implies that the landscape sculpted below the glacier and the associated transported sediments all have the same cosmogenic zero age. A hypothetical instantaneous disappearence of the ice cover would then yield the same exposure age throughout the glaciated valley. By contrast, a realistic slow deglaciation provides: (1) a negative relation between elevation and exposure age along the glacier bed, (2) a positive one across the valley flanks.

The abandoned glacier bed plays the same role as a condensed interval in a chronostratigraphic sequence (Vail et al. 1977, Van Wagoner et al. 1988). Therefore, we propose a chronodynamic interpretation for this elevation vs. exposure-age relation. In this framework, cosmogenic exposure age is related to the time elapsed since the transition from a glacial erosional system to a fluvial one at the sampling site. By extension, the intercept of the negative relation corresponds to the initiation of the deglaciation process and therefore to the switching time between the two geomorphological processes. When applied to the Wormsa youngest glacier basal relict topography sampled through W7 – 8 – 9 and 12 (Fig. 2), this method yields an intercept of (17,965 ϶ 68) yrs which closely corresponds to the value generally attributed to the LGM. The associated slope of -16.7 yrs/m is mean a vertical deglaciation velocity^{-1}.

The homogeneous geomorphological characteristics of the studied area of the Vosges leads us to apply this calculated recession slope to samples from an older Wormsa basal topography as well as to samples from 3 other valleys. The thus implied intercept ages: 22.2, 26.3, 28.0, 29.5, 29.9 ka most likely correspond to the initiation of the recession of glacier tongues, downcutting by rivers. Geomorphological analysis of sampling localities allowed the identification in the valleys of the eastern Vosges of 5 different glacial paleolandscapes associated with 5 different time and space transitions from glacial to fluvial processes. The use of the cosmogenic dating method, and more specifically the relationships between ^{10}Be exposure ages and elevation, offers the possibility of providing a time scale for calibrating the necessary climatic changes from cold to warmer conditions. These changes in the glacial systems in the Vosges valleys, can possibly be related to 5 global climatic changes: three of them, LGM ~ 18 ka and Heinrich events H2 ~ 22 ka, H3 ~ 27 ka, classically Broecker (1994) identified as cold events in polar ice cores and in marine stratigraphy. These results strongly suggest that glacial erosional cycles were in progress prior to the periods of accelerated iceberg discharge to the North Atlantic, which coincided with phases of rapid valley glacier retreat and river incision. The latter events took place during the warmer conditions (Dansgaard et al. 1993) which can be related to the warming trend following LGM and the warm Dansgard-Oeschger interstadials IS2, IS4, IS5, and IS6.

4. Conclusions

The effects of glacier dynamics has been to construct both positive (push moraine) and negative (roche moutonnée) landforms in different Vosgian valleys, including the Wormsa valley, during the early Holocene climatic oscillations. The in-situ produced ^{10}Be exposure ages at 11.5; 10.6; 9.7; 9.0; 8.3 ka, and by numerical interpolation at 7.9 ka, obtained on push moraines, most likely indicate climatic events in continental Europe at the end of the last deglaciation. An important event at 7.55 ka (^{10}Be) was associated with the melting of the main Wormsa glacier. As suggested also by basal ^{14}C dates on pollen profiles, the permanent firn seems to have disappeared at around 5.1 ka dated using ^{10}Be.

It has also been demonstrated, using the cosmogenic method, that spatial transitions in the erosional regime along and across glaciated valleys can be time constrained. In the study area of the Vosges, such a switch in the geomorphological dynamics is triggered by changes from cold to warmer conditions which may be related to global climatic events (LGM = 18 ka, H2 = 22 ka, H3 = 27 ka, IS2 = 22 ka, IS4 = 27 ka, IS5 = 29 ka, IS6 = 30 ka). This method has also assisted in the solution of one of the main geomorphological questions on the balance between present day climate-driven processes and relict signatures of past climates. Cessation of periglacial processes on slopes, and of glacial erosion in the valleys of the Vosges probably occurred contemporaneously with the Heinrich iceberg discharge events, and renewed river incision which occurred during the Dansgaard-Oeschger interstadials.

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DATOVÁNÍ KONCE ZALEDNĚNÍ VE VOGÉZÁCH METODOU ^{10}BE

Résumé

Radiometrickým datováním metodou ^{10}Be a geomorfologickou analýzou glacigenních tvarů z období ústupu horského zalednění v několika údolích Vogéz bylo prokázáno nejméně pět klimatických oscilací v nejstarším holocénu. Náporové morény ve výškách pouze 600 m vznikaly před 11 500, 10 600, 9700, 9000, 8300 a 7900 lety, tání ledovce Wormsa proběhlo před 7700 lety a stálá firnová pole zanikala před cca 5100 lety (^{10}Be). Dále byla zjištěna lineární závislost mezi dobou obnažování skalního podloží a nadmořskou výškou reliktů činnosti ledovců, což umožnilo identifikovat pět období přechodu mezi glaciálně a fluviálně přetvářenou krajinou údolí ve Vogézách. Ledovcová eroze probíhala pravděpodobně v obdobích evropského maxima posledního glaciálu (před 18 000 lety) a jemu předcházejících period Heinrich 1, 2 a 3, zatímco říční činnost výrazně převládala během interstadiálů Dansgaard-Oeschger IS 2, IS 4, IS 5 a IS 6.

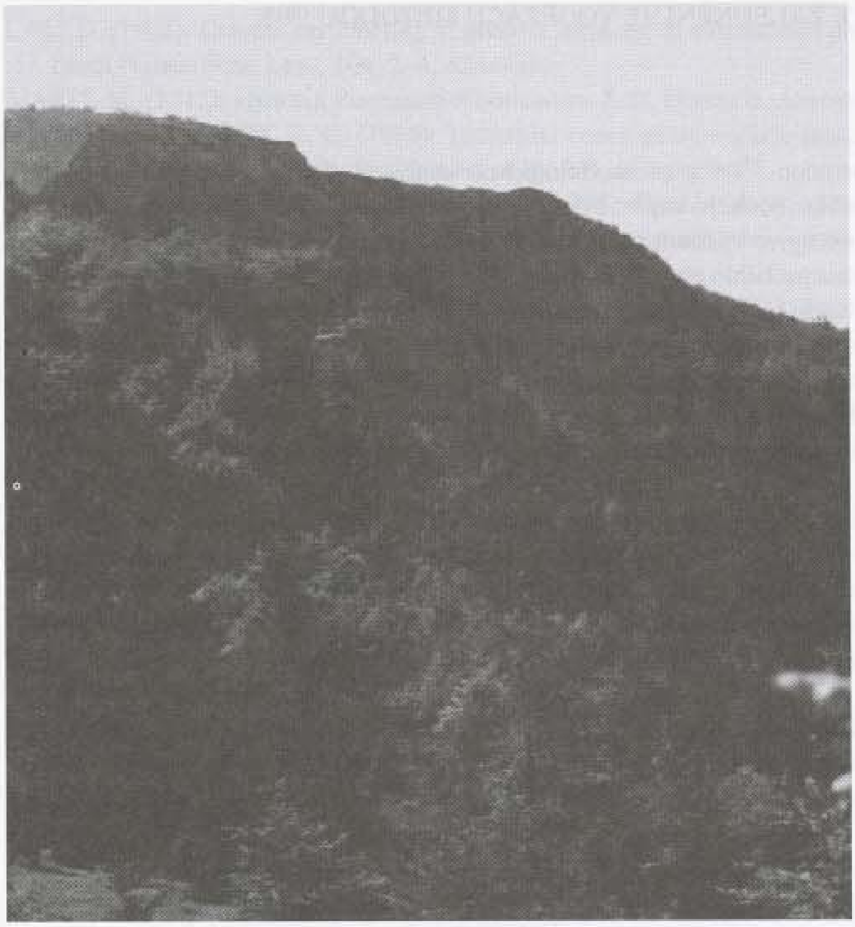

Photo 1: Rock slopes of a former glacial cirque with eastern exposition situated south of the Martinswand Rochers (1222 m) in the upper part of the Petite Fecht valley, the Vosges Mts., France

Photo Jan Kalvoda

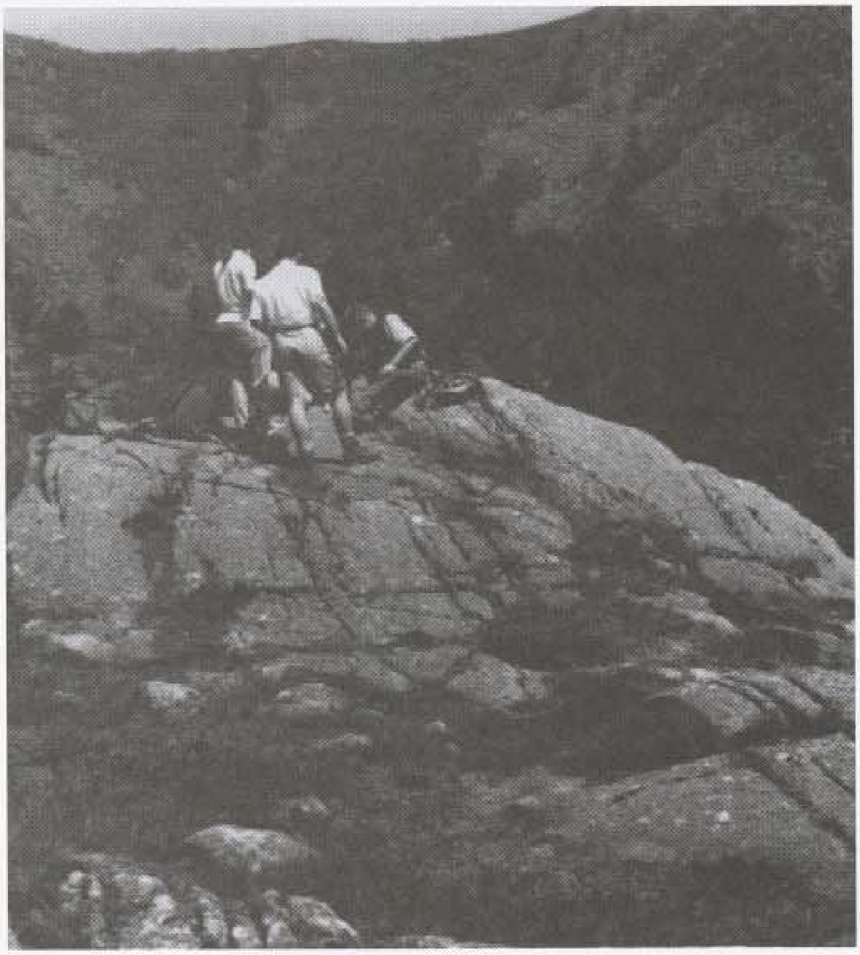

Photo 2: Roches moutonnées (granite sample Lt3) in the middle part (1100 m a.s.l.) of a glacial cirque in the Lac des Truites valley, the Vosges Mts

Photo Jan Kalvoda

Photo 3: Partly rounded microforms of glacier striaes on a roches moutonnée in the Wormsa valley (eastern Vosges) have been used for testing of rock weathering and erosion rates of granite surface since the last deglaciation period

Photo Jan Kalvoda

Photo 4: Granitic boulder (sample Ln2) on the inner part of the south side of the morainic lobe near the Lac Noir cirque in the Vosges Mts

Photo Jan Kalvoda