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Late Holocene environmental changes recorded at Ghețarul de la Focul Viu, Bihor Mountains, Romania

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Abstract

This paper synthesizes the isotope and tree-ring data gathered at Focul Viu Ice Cave (Romania). The 850 ±50 year BP radiocarbon age (1160–1260 cal. AD) from 6.67 m depth of ice indicate, that the stable isotope data of the 7 m long ice core approximately represent the past 800–900 years. However, melting events introduce obvious hiatuses in the sequence. The response function analysis revealed that main growth influencing climate factors for *Abies alba* are June mean temperature and early summer water supply. The sufficiently represented part of the 420 year long tree-ring index curve suggests particular periods unfavourable for annual increment of firs: 2000–1980, 1940–1920, 1890–1870 and 1860–1820, while the favourable periods are 1980–1940, 1920–1890 and 1870–1860. The fit between the growth-favorable decades and the mud layer concentrations seems to be a promising dating method of ancient melting events and partially preserved remained ice bands. Previously negative intervals of Easton coefficient time-series were fitted to ice accumulating periods. These independent dating methods – Easton coefficient and fir index – show similarity back to 1730 for ice accumulation and melting periods.

Keywords: ice cave, oxygen isotopes, dendroclimatology, moist summers, Easton coefficient.

Changements environnementaux enregistrés à la fin de l'Holocène dans la grotte de Ghețarul de la Focul Viu, Monts de Bihor, Roumanie

Résumé

Le travail présente une synthèse des données isotopiques et dendrochronologiques relatives à la grotte glacière de Focul Viu (Roumanie). L'âge de 850 ± 50 ans déterminé par la méthode carbone 14 à une profondeur de 6,67 m dans la glace indique que les valeurs isotopiques d'une carotte de glace longue de 7 mètres couvrent à peu près les 800–900 dernières années. Néanmoins, des événements de dégels introduisent des lacunes chronologiques. L'analyse des réponses fonctionnelles a révélé que les facteurs climatiques influençant en premier lieu la croissance de Abies alba *sont la température moyenne du mois de juin et les précipitations tombées au début de l'été. La partie suffisamment représentée de la courbe d'indice des cernes (couvrant un intervalle de 420 ans) suggère des périodes particulières défavorables pour la croissance annuelle des sapins. Les périodes défavorables sont 2000–1980, 1940–1920, 1890–1870, 1860–1820, alors que les périodes favorables sont 1980–1940, 1920–1890, 1870–1860. La recherche d'une corespondance entre les périodes favorables et la fréquence des couches argileuses semble être une méthode prometteuse de datation des anciens dégels et des couches de glace. Les oscillations négatives des séries chronologiques du coefficient d'Easton ont été comparées aux périodes d'accumulation de glace. Ces méthodes indépendantes de datation — coefficient d'Easton et indice des cernes — montrent une concordance significative jusqu'en 1730 pour les périodes d'accumulation de glace et celles de dégel.*

***Mots-clés**: grottes glacières, isotopes de l'oxygène, dendroclimatologie, étés humides, coefficient d'Easton.*

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1. Introduction

Among the first pioneers Libby & Pandolfini (1977) compared the ^{14}C of bristlecone pine and δD, $\delta^{18}O$ ratios of tree–rings of Japanese cedar to isotope-trend of the Greenland icecap. Afterwards Baillie (1996) presented the linkages between acidity peaks of deep ice cores (Crête, Camp Century, Dye 3, GISP 2) and the narrowest rings of extra long tree-ring chronologies of Western Europe and North America. In addition Baillie (1996) wrote: "*The information in tree-ring and ice-core records is complementary, and it is important that they be compared.*"

A significant number of ice caves in temperate climatic region contain ice and wood remnants from same site and probably same time span. The first step towards the investigation of ancient environment from cave ice was achieved by Pop & Ciobanu (1949) based on the palynology of Gheţarul de la Scărişoara's ice strata. Later on numerous important observations were made concerning the connection between ice formation and external climate — cave climate in the case of Gheţarul de la Scărişoara (Şerban *et al.*, 1967; Racoviţă, 1972, Şerban & Racoviţa, 1987; Racoviţă *et al.*, 1987; Racoviţă & Şerban, 1990; Racoviţă & Onac 2000).

The first stable isotope analysis on cave ice from the Apuseni Mountains — and probably the first in the world — was prepared by Şerban *et al.* (1967). Şerban & Racoviţă (1987) suggested involving dendrochronology in cave ice research. The applicability of $\delta^{18}O$ data of cave ice in paleoclimatology was justified by Yonge & Macdonald (1999), and Schlatter *et al.* (2003) note the possibility to date the ice layers by using the rings of ice-bound logs.

We have found a correspondence between the impurity layers of the ice block, $\delta^{18}O$ data of a shallow ice core and the standardized ring width curve of a conifer species at Gheţarul de la Focul Viu.

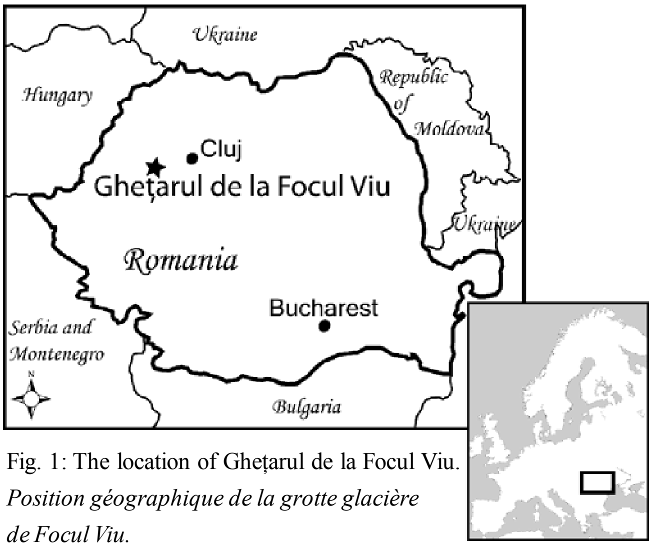

Fig. 1: The location of Gheţarul de la Focul Viu.
Position géographique de la grotte glacière de Focul Viu.

2. Site description

Gheţarul de la Focul Viu is located in the Bihor Mountains (46.27º N ; 22.68º E) approximately 50 kilometres far from Cluj (Fig. 1). The elevation is 1150 m above sea level. As the second largest ice cave in Romania it contains 25,000 m^3 (Orghidan *et al.*, 1984) of ice.

The ceiling of the Main Chamber is opened and the snow, rain and springtime meltwater enter the cave through the hole. Based upon morphological grounds the ice depth is assumed to be about 14 metres (Bleahu *et al.*, 1976). The Small Chamber is decorated by a huge ice column without floor ice.

Mixed deciduous/coniferous forest surrounds the cave. In the stand three species prevail: Norway spruce *(Picea abies),* European silver fir *(Abies alba)*, European beech *(Fagus sylvatica).* In addition the dead trees, which fall down by natural processes around the hole slump into the cave and the freezing microclimate conserves them from fungal decay (Fig. 2).

3. Methods

3.1. Environmental isotopes

(for detailed interpretation of isotope studies see Fórizs *et al.*, this issue)

A 772 cm long ice core was extracted in November 2001 from the ice floor of the Main Chamber. At the depth of 6.67 meters of the ice core a piece of wood appeared. In addition, a branch outcropping from the ice block at its sidewall at 11.1 meters depth was also sampled (Fig. 3). Both wood remnants underwent radiocarbon age determination. In February of 2002 we collected ice samples for tritium measurements.

3.1.1. Stable isotopes

Stable oxygen isotope measurements were carried out according to the idea of CO_2–H_2O equilibration described by Epstein & Mayeda (1953) and Roether (1970). The stable isotope measurements were made on Finnigan MAT delta S mass spectrometer.

Stable isotope compositions are expressed in the conventional delta notation:

$$\delta^{18}O = \frac{\left(^{18}O/^{16}O\right)_{sample} - \left(^{18}O/^{16}O\right)_{standard}}{\left(^{18}O/^{16}O\right)_{standard}} \times 1000$$

The Vienna Standard Mean Ocean Water (VSMOW) was used as a standard. The estimated analytical error is ±0.1‰. The oxygen isotope compositions were analysed at the Institute for Geochemical Research, Hungarian Academy of Sciences (Budapest). The data are shown in Figures 6 and 7.

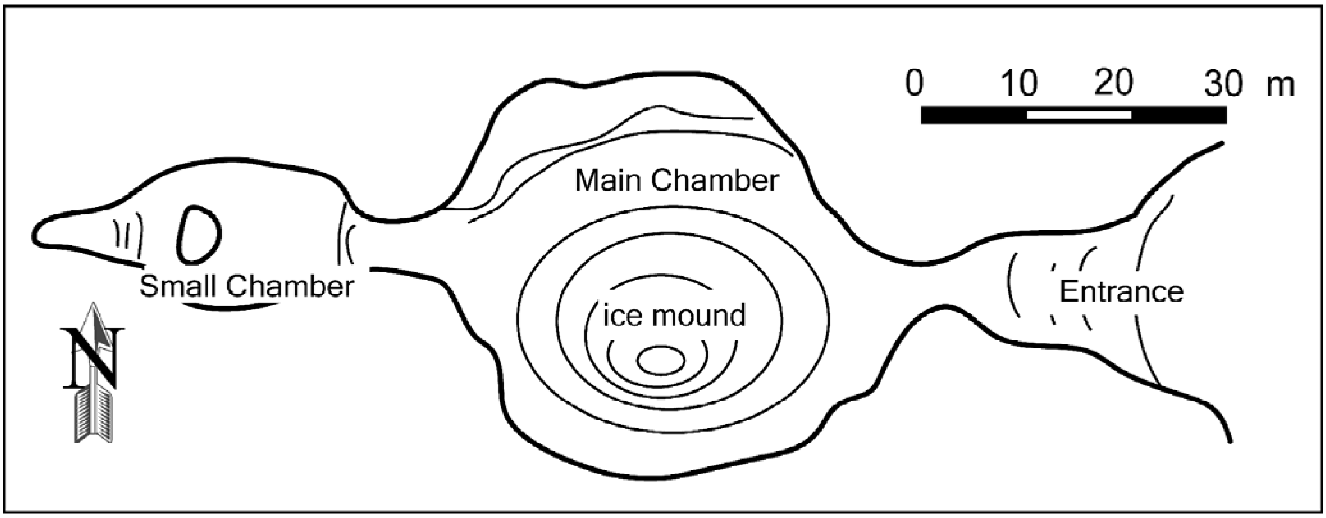

Fig. 2: The map of Ghețarul de la Focul Viu (surveyed by Viehmann & Şerban; after Bleahu *et al*., 1976).
Plan de Ghețarul de la Focul Viu (topographie par Viehmann & Şerban; d'aprés Bleahu et al., 1976).

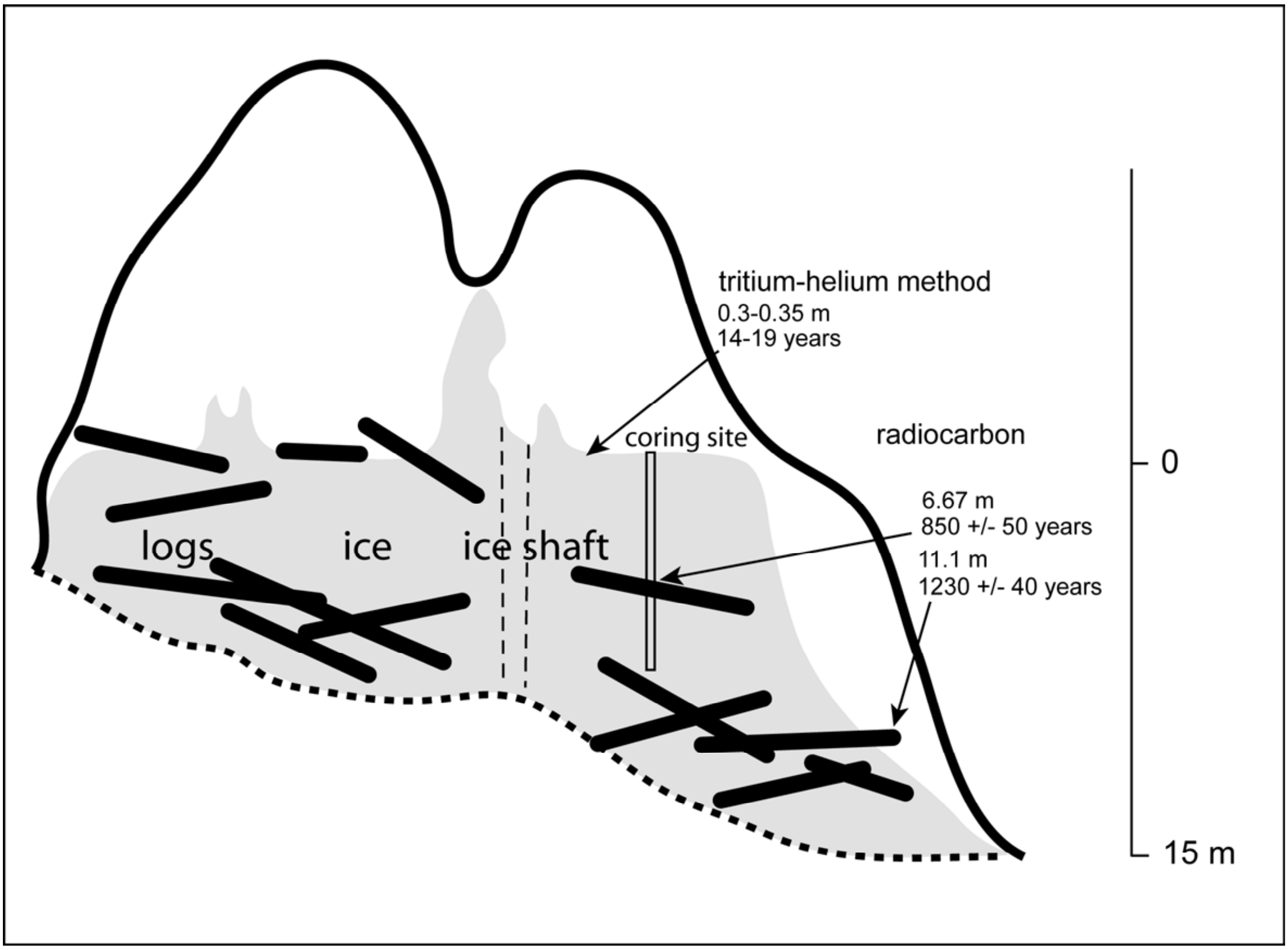

Fig. 3: Cross section sketch of Ghețarul de la Focul Viu showing the drilling site, the ice block and the ice-bound wood ages.
Coupe schématique de Ghețarul de la Focul Viu montrant le point de carottage, le bloc de glace et l'age des bois englobés dans la glace.

Table 1: The results of the ^{14}C datings. *Résultats des datations au ^{14}C.*

Lab. no.	Sample description	Depth from the surface of the ice block [m]	Radiocarbon age [years BP]	Calendar age* cal AD (1σ)
Deb-9392	*protruding branch from the ice wall*	11.10	1230 ± 40	720 – 730 750 – 870
Deb-9390	*wood in the ice core*	6.67	850 ± 50	1160 – 1260

*calibrated by the Radiocarbon Calibration Program Rev. 4.4.2. software (Stuiver & Reimer, 1993).

3.1.2. Radiometric datings

Radiocarbon datings of aforementioned wood samples were done at the Institute of Nuclear Research of the Hungarian Academy of Sciences, Debrecen, by gas proportional counting technique. Calibration of ^{14}C ages to calendar years was performed using the Calib 4.4.2 program used in conjunction with Calib. 4.0 (Stuiver & Reimer, 1993) (Table 1).

The Tritium content of the water samples were determined by T-^{3}He-ingrowth method at the Institute of Nuclear Research of the Hungarian Academy of Sciences, Debrecen. Tritium data are reported in tritium units (TU = one tritium atom out of 10^{18} hydrogen atoms) (Table 2). Figure 3 presents the obtained absolute ages.

Table 2: Obtained Tritium dates. *Résultats des datations au tritium.*

Depth of sample [m]	Tritium [TU]	Calculated calendar age, or false data**
0.30-0.35	8.40 ± 0.17	1984-1992 (most probable1984-1989)
2.95-3.05	4.40 ± 0.10	*contamination*
3.95-4.05	5.26 ± 0.11	*contamination*

**For calculation method and detailed explanations see: Kern *et al.*, 2003; Fórizs *et al.*, *this issue*.

3.2. Tree-rings

In the first step of tree-ring study we collected cores from living trees by increment corer. Two or three cores per tree were gathered from thirteen firs (*Abies alba*) eight spruces (*Picea abies*) and eight beeches (*Fagus sylvatica*). Afterwards the cores were mounted onto holders. Moreover thirty-seven disks were sawed from subfossil stems, lying on the ice surface or sticking out from the ice block. Following preparation (sanding, polishing) the width of each tree-ring was measured by Lintab measuring table and by TSAP-DOS software (Rinn, 1996) with an accuracy of 0.01 mm.

Amongst subfossil logs we identified fir and spruce specimens based on anatomical properties (Schweingruber, 1990). Unfortunately four of the conifer remnants were not measurable due to their bad condition. Finally thirteen firs, ten spruces and eight beeches were considered appropriate for further crossdating procedure.

In this study we concentrate on fir because this species seemed to give the longest tree-ring series. Hitherto seven subfossil fir samples were successfully conjoined to surface chronology, producing a 420 year–long series of tree-rings (Fig. 4).

3.3. Instrumental meteorological dataset

A reliable, contemporary meteorological dataset is essential for calibration of the proxy data. The longest instrumental meteorological time series in the region surrounding Ghețarul de la Focul Viu ice cave is available from Vlădeasa Peak (1838 m a.s.l., 46.77º N, 22.48º E). We have compiled monthly mean temperature data from 1961 to 1999 and monthly precipitation from 1974 to 2002. We would like to emphasize that these data are raw, measured values without any homogenisation.

4. Discussion

4.1. Strata of the ice block as climate archives

From a lateral view, numerous impurity layers are visible in the side of the ice block. In the shallow ice core we have also identified few significant muddy and calcareous layers but much less than expected from the lateral view. We have positioned them onto $\delta^{18}O$ curve of the ice core according to their measured depth (Fig. 6).

The impure layers have to be regarded as evidences of past melting events. There are three probable ways of origin of impure layers. On the one hand, the melting of upper boundary of ice block, driven by warm condition, when small amounts of airborne dust sediment from individual ice layers accumulate and form a bulk muddy stripe (Şerban *et al.*, 1967). On the other hand, periods with extreme precipitation, which leach soil particles into cave, accumulate thicker mud stratum on the surface of ice block (Şerban *et al.*, 1967). These effects can strengthen each other.

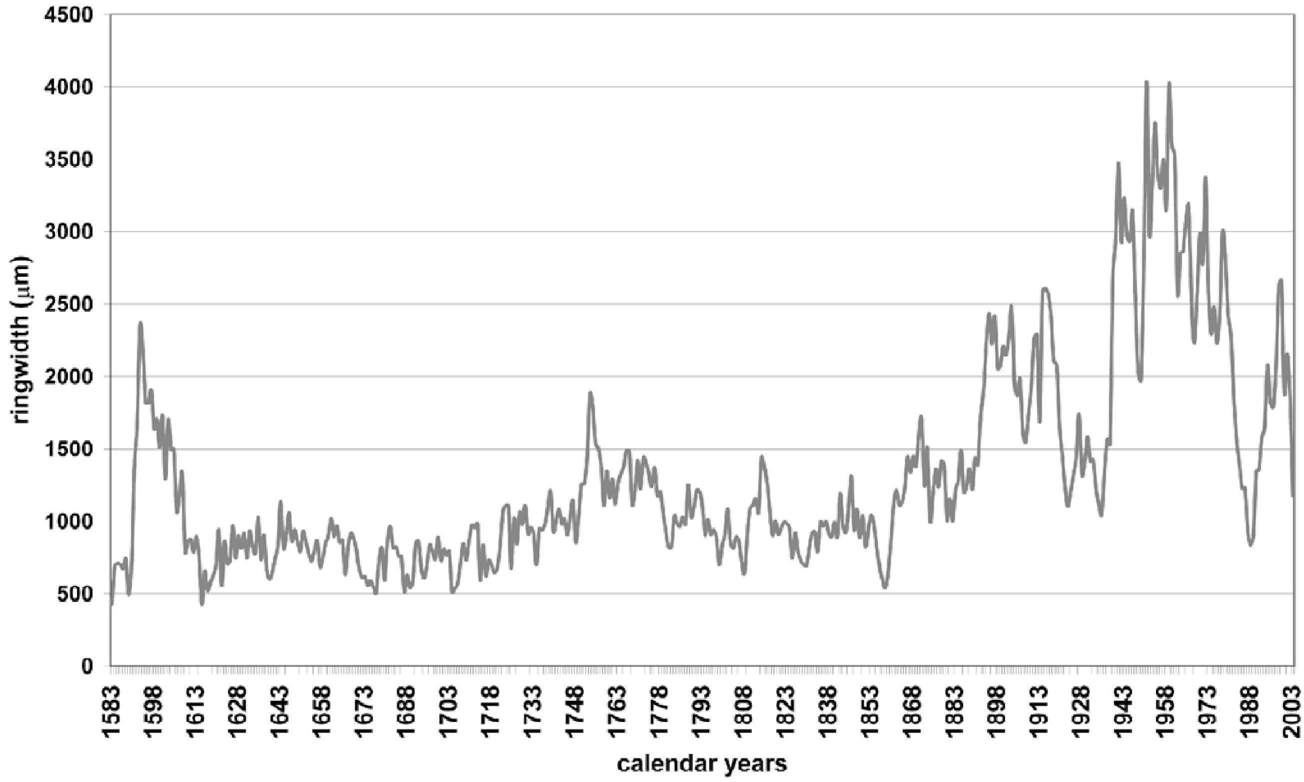

Fig. 4: The silver fir chronology (A.D. 1583–2003). *Chronologie du sapin (A.D.1583–2003).*

Finally, calcareous impurities can origin by two further processes. Current observations suggest that the material of calcareous layers originate mainly from host rock due to intensive frost driven rock disintegration, but carbonate precipitating from seepage water during freezing is also reported (Racoviță & Onac, 2000). The importance of precipitated carbonate in formation of calcareous layers is still in debate.

4.2. $\delta^{18}O$ ratios as climate archives

As stated above this cave ice is not a continuous record of past precipitation, because melting periods destroyed particular amount of the upper ice block and the mud layers indicate the discordances.

According to differences of short term and long term growth rates (Kern *et al.*, 2003) ice could be represented in the ice core only from the half of passed 800–900 years (Fórizs *et al.*, this issue). Additionally, undated fragments build the sequence and impossible to date the hiatuses by layer counting.

However, the origin of the ice is known. The field observations confirmed that the ice in the Ghețarul de la Focul Viu ice cave usually forms during the spring (Kern *et al.*, 2003), so the isotopic feature of ice characterizes the springtime water of the cave. The sources of water in the Ghețarul de la Focul Viu ice at spring are infiltrating melt water and spring precipitation, which directly gets into the cave.

In addition, researches on cave seepage water suggested that dripping water bears the average yearly isotopic composition of surface precipitation during whole year (e.g., Yonge *et al.*, 1985). In this case further observations are essential to determine the proportion of seepage water and inflow water in a given year ice formation in order to better understanding of the meaning of isotope signal.

4.3. Tree-rings as climate archives

The annual increment of tree is also sensible for fluctuation of ambient environment (Fritts, 1976). The basic concept is the more severe conditions prevail in the vegetation period, the narrower ring forms. But the climatic factors, which influence the annual growth, change site by site and species by species. Hence whenever tree-ring series are involved in climate study it is essential to reveal the main growth governing factors.

Raw ring-width values were standardized in order to eliminate the variations of stand dynamics and age-trend (Fritts, 1976; Cook & Kairiukstis, 1990). One-sided digital filter was used by 30 years long bandwidth to transform raw ringwidths to dimensionless indices because we aimed to decipher the decadal climate-driven variability from the ringwidth series. Afterwards arithmetic mean of indices was calculated to define the mean index series.

We investigated the connection between tree-ring index and climate parameters by the aid of DENDROCLIM2002 software

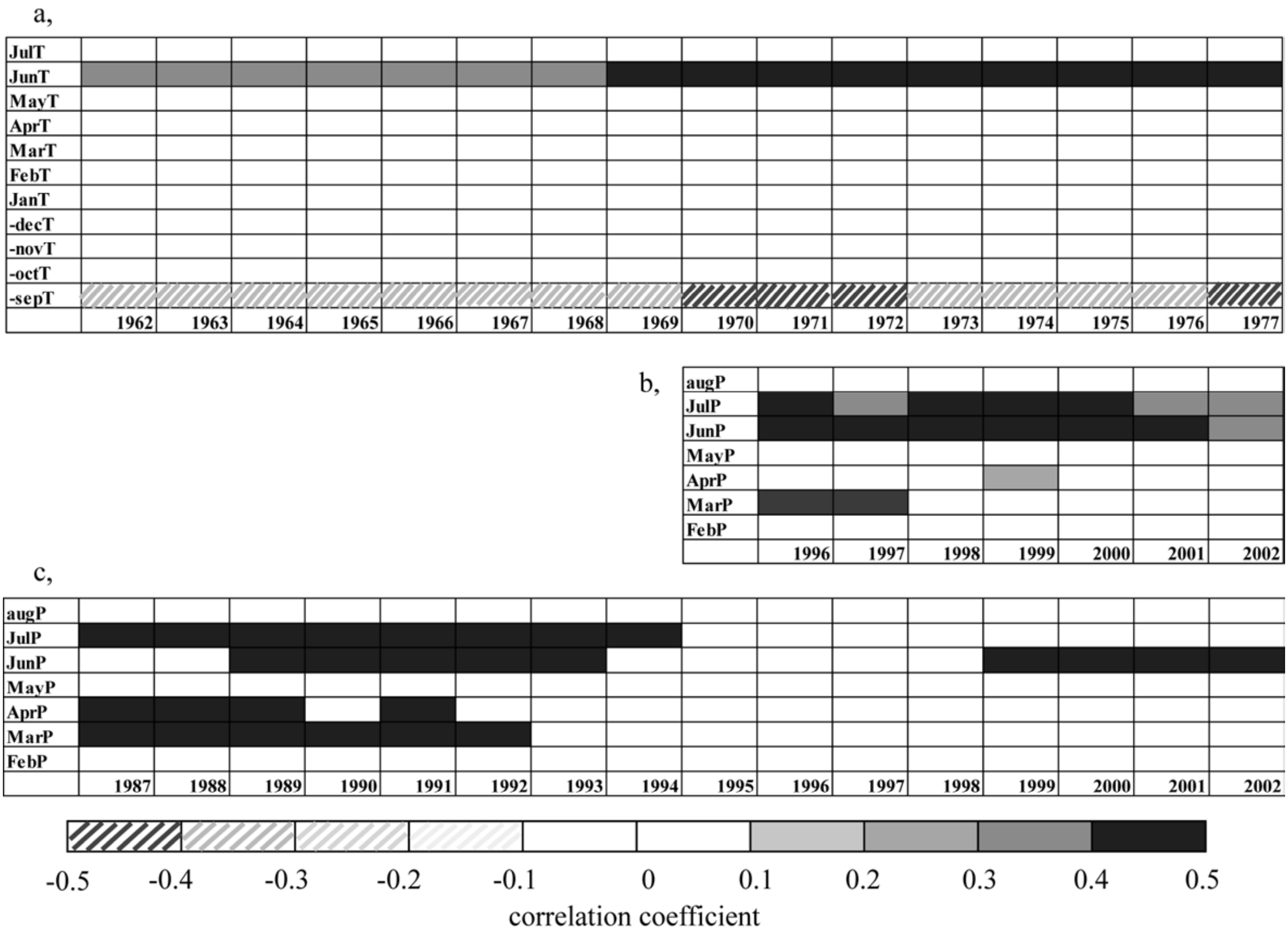

Fig. 5: Results of response function analysis. 95% significance level was checked by bootstrap method in all cases. The highly limited length of meteorological series force to analyse temperature–treering, precipitation–treering connection independently. **a**) Amongst the monthly average temperature data is the current year's June (JunT) and the previous September (-SepT) that show significant correlation. (23-year backward evolutionary interval analysis); **b**) 23-year running mean analysis suggests June and July precipitation(JunP, JulP) to be major consequently important factors. March and April (MarP, AprP) seldom have significant effect. But the graphical presentation of same number of year analysis shows results for just a few years. **c**) Decreasing the length of the moving interval more years appear in the graph, but the significant years partially become modified. The result of 14-year moving interval analysis implies that results of 'b' graph are quasi-constant because by shorter intervals the same months seem to be important. But particular year become insignificant due to decreased size of window of moving window statistic.

Résultats de l'analyse des fonctions de réponse. Un niveau de signification de 95% a été remarqué dans tous les cas par la méthode «bootstrap». Par suite du volume limité des données météorologiques, les relations entre la température et les cernes de croissance, d'une part, et entre les précipitations et les cernes, d'autre part, ont été analysées séparément. ***a)*** *Parmi les moyennes mensuelles de température, celles de juin (JunT) de l'année courante et de septembre de l'année précédente (-SepT) montrent une corrélation significative (avec une fenêtre de 23 ans et en progressant en sens inverse).* ***b)*** *L'analyse à l'aide des moyennes mobiles avec une fenêtre de 23 ans suggère que les précipitations de juin et juillet (JunP, JulP) ont l'influence la plus importante. Celles de mars et d'avril (MarP, AprP) n'ont que rarement un effet significatif. Néanmoins, la représentation graphique des analyses pour le même nombre d'années ne montre des corrélations significatives que pour quelques années.* ***c)*** *En diminuant la grandeur de la fenêtre, un nombre plus grand d'années apparaissent sur le graphique, mais les années significatives sont parfois différentes. Le résultat de l'analyse effectuée avec une fenêtre de 14 ans montre que les résultats figurés dans le diagramme "b" sont quasi constants, parce que les mois importants semblent être les mêmes. Mais certaines années deviennent insignifiantes à cause de la diminution de la fenêtre.*

(Biondi & Waikul, 2004) because the response function with moving and evolutionary intervals not only computes the correlations but also perceives the change of climate response (Biondi, 1997). DENDROCLIM2002 checks the statistical significance of correlations on 95% level by bootstrap method. After standardization significant autocorrelation remained in index series, which has to be considered in assessment of the response function result.

First graph in Figure 5 demonstrates that as far as temperature is concerned, the most important months are the growth's year June and previous year September that influence the annual increment of fir in a given year.

Correlation coefficients are positive between radial growth in a given year and same year June mean temperature. Meanwhile mean temperature of the September of the year before ring formation gives significant negative correlation. This ecological behaviour perfectly corresponds to the findings of Schichler *et al.* (1997), Desplanque *et al.* (1999) and Popa (2003). Thus the high value of previous September response can be partially attributed to high one-year-lag autocorrelation.

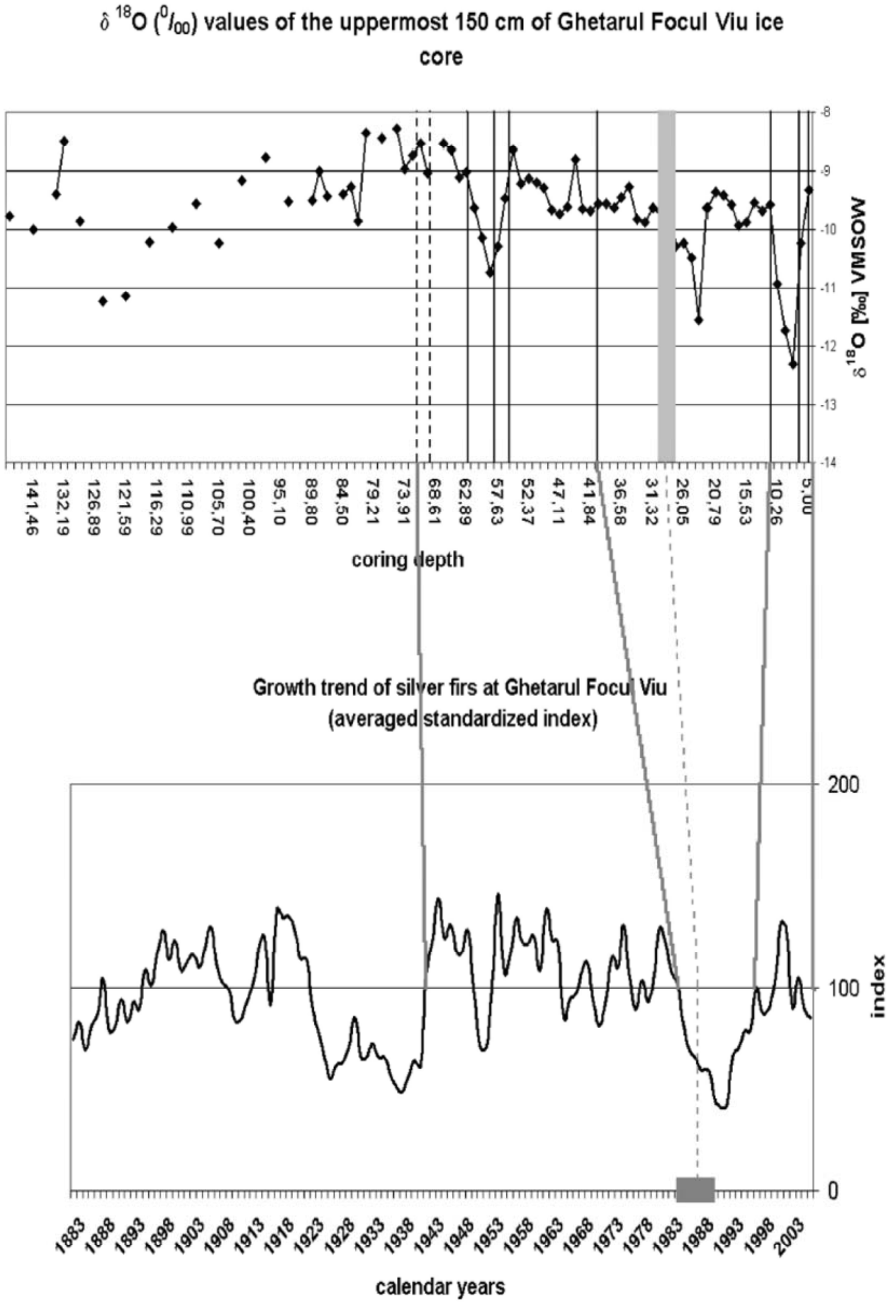

Fig. 6: The correlation between the ice layers and the tree-ring index of silver fir (*Abies alba* Mill.). Vertical lines indicate the position of muddy layers; dashed lines sign the calcareous layers. The wider grey stripe covers the 0.3–0.35 cm depth interval for which its tritium content indicated an infiltration date somewhere in the period of 1983-1989. The origin of wide rings and muddy layers assume similar environmental conditions (see details in the text). Hence we can match them to each other. The fact that longer wide ring periods connect to shorter ice intervals fairly harmonizes with the statement about melting effect. In addition the tritium age also perfectly corresponds to dendro age confirming the reliability of matching.

Corrélation entre les couches de glace et l'indice de croissance du sapin. Les lignes verticales montre les couches terreuses, les lignes pointillées, celles calcaires. La bande grise couvre l'intervalle de profondeur de 30–35 cm, dont le contenu en tritium indique une infiltration durant la période 1983–1989. La présence de cernes larges et de couches terreuses de même épaisses indique des conditions environnementales comparables (détails dans le texte), et c'est pour cela que ces éléments structuraux peuvent être mis en corrélation. Le fait que de longues périodes de temps avec des cernes larges peuvent être associées à des périodes avec des couches de glace minces est bien en accord avec l'effet de dégel. De plus, l'âge obtenu par datation au tritium correspond à l'âge des cernes, ce qui confirme une telle correspondance.

Comparison with the monthly precipitation yielded slightly more scattered results. Almost all months of the first half of the vegetation period positively correlate with the fir growth (Fig. 5). June and July seem to be more important consequently. Additionally, March and April also become determinant in particular years. Observations on the character of the fir growth also derived similar results (Popa, 2003; Wilson & Elling, 2004).

Thus wide ring forming periods refer to years with high precipitation growing season and warm June, while narrow rings indicate dry growing seasons and cool June.

5. Results

Applying the statements of the previous section we have matched the high index values to impurity layers and low index values to pure ice parts. The result of correspondence for the upper 150 centimetres of ice core is shown in Fig. 6.

The ice from the 0.3–0.35 m-depth interval is matched to index the period between 1980 and 2000, which fairly corresponds to the calculated tritium age. Assuming that this coupling is reliable, it offers opportunity to estimate the border date of hiatuses and of remained ice bands and the corresponding oxygen isotope composition of cave ice.

We have applied long term growth rate (0.84 cm/yr; Fórizs *et al.* this issue) to develop a simple linear age-depth model.

$$age_{calculated} = 2001 - h / 0.84$$

where 2001 is the date of ice coring and h the depth from the surface in centimetres. In Fig. 7 the upper x-axis presents calculated ages from long term ice accumulation rate, while the lower x-axis displays tree-ring count. The calculated and counted dates do not coincide so the simple age-depth model needs further refinement.

Figure 7 presents the total length of the tree-ring index curve. On the younger part of it narrow-ring and wide-ring years gather in quite clearly identifiable periods. At the older part of the curve this feature disappears owing to the lower representation of trees. The extreme high values at the end must be due to the juvenile rings of the oldest specimen.

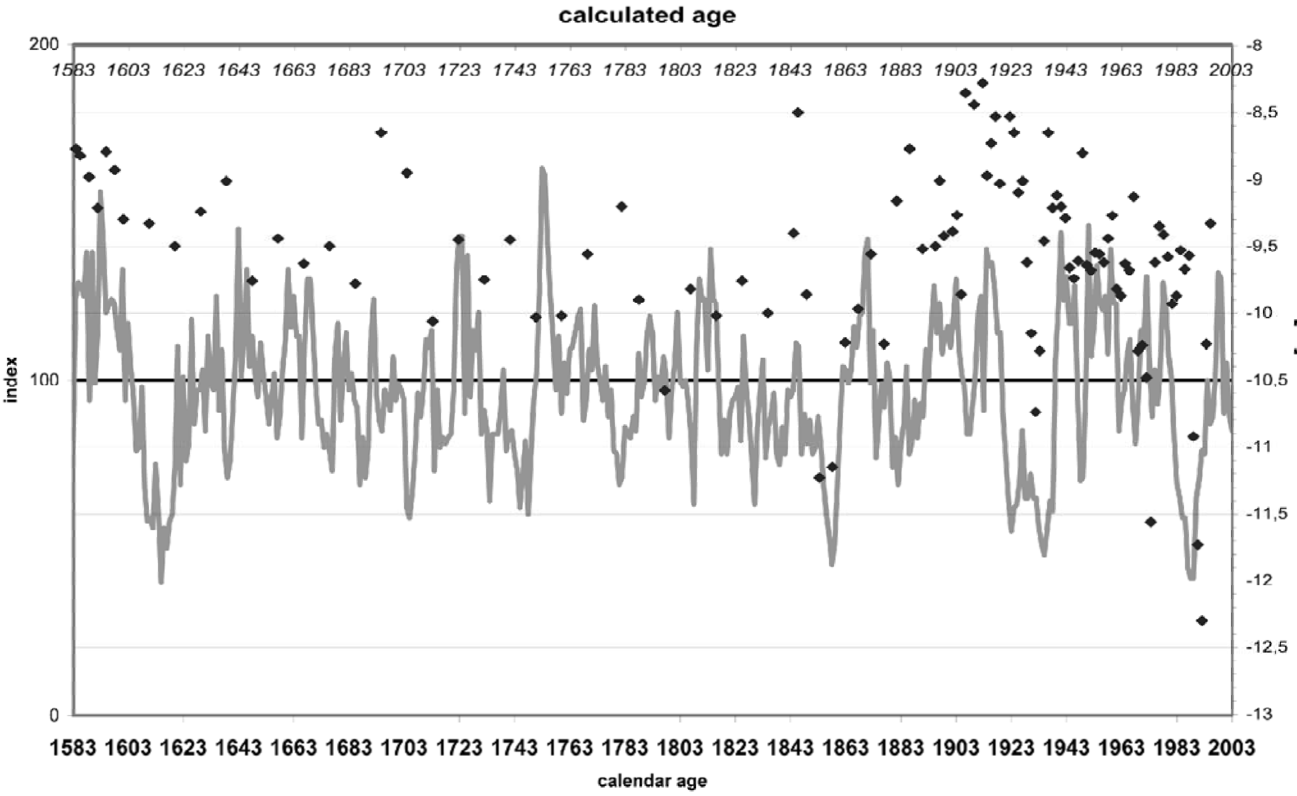

Fig. 7: . The $\delta^{18}O$ plot of ice core tuned to age scale using calculated long term growth rate. This figure presents the whole length of actually existing fir index. Wide ring and narrow ring periods can be differentiated till 1820's. The hectic running of the curve before can be due to the decreasing number of trees. The extreme maximum in the oldest years must be regarded as the effect of the age trend of the oldest specimen.

Valeurs du $\delta^{18}O$ dans un échantillon de glace, inscrites sur une échelle temporelle établie à l'aide du taux de croissance au long terme. Cette figure représente la totalité des valeurs de l'indice du sapin déterminées jusqu'à présent. Les périodes à cernes épaisses peuvent être séparées de celles à cernes minces jusqu'aux années 1820. Auparavant, l'aspect "en dents de scie" de la courbe est dû au nombre plus faible d'arbres. Le maximum qui apparaît à l'extrême gauche de la courbe doit être considéré comme une conséquence de l'âge de l'arbre le plus vieux.

In Figure 7 low index values are 2000–1980, 1940–1920, 1890–1870, 1860–1820. High index values are 1980–1940, 1920–1890, 1870–1860.

Racoviţă (1972) published the probable correspondence between Easton coefficient time series and ice layers of nearby Gheţarul de la Scărişoara. For reliable comparison we smoothed the fir index curve with 11-year moving window as Racoviţă (1972) did in the case of Easton coefficients, the graphical comparison being presented in Fig. 8. When we compare the Easton coefficient curve to the fir index curve, significant graphical similarity can be identified between the trends of the two curves from 1730 to 1970 (Fig. 8).

The Easton coefficients classify winter severity while the fir index characterizes years according to spring–summer humidity. The similarity diminishes before 1730. It is probably due to decreasing tree number in the averaged fir index series, and fewer specimens give an unreliable signal. However the similar undulation of the well-represented part of the index curve and the Easton coefficient curve suggests that conditions favorable for ice accumulation emerge contemporaneously in winters and spring–summertime as well as unfavourable conditions. It means the interference of winter and spring–summer climate is able to magnify the effect of each other from the viewpoint of ice deposition.

6. Conclusions

Response function analysis of the standardized fir (*Abies alba* Mill.) index series suggests that silver firs growth at Gheţarul de la Focul Viu is governed by June temperature and primary June and July — secondary March, April — water supply.

Parallel analysis of impurity layers in ice and tree rings seems to be a promising method to divide $\delta^{18}O$ series of Focul Viu ice core to dated sections. So, we can derive important information about the isotopic composition change of water in the cave, connected to the variation of surface water.

If climate-growth relationship is strong enough, then the sufficiently represented part of the index curve suggests that decades 2000–1980, 1940–1920, 1890–1870, 1860–1820 had cooler June and/or less humid June–July, while 1980–1940, 1920–1890, 1870–1860 had warmer June and/or more humid June–July than the average weather at the area of Focul Viu Ice Cave.

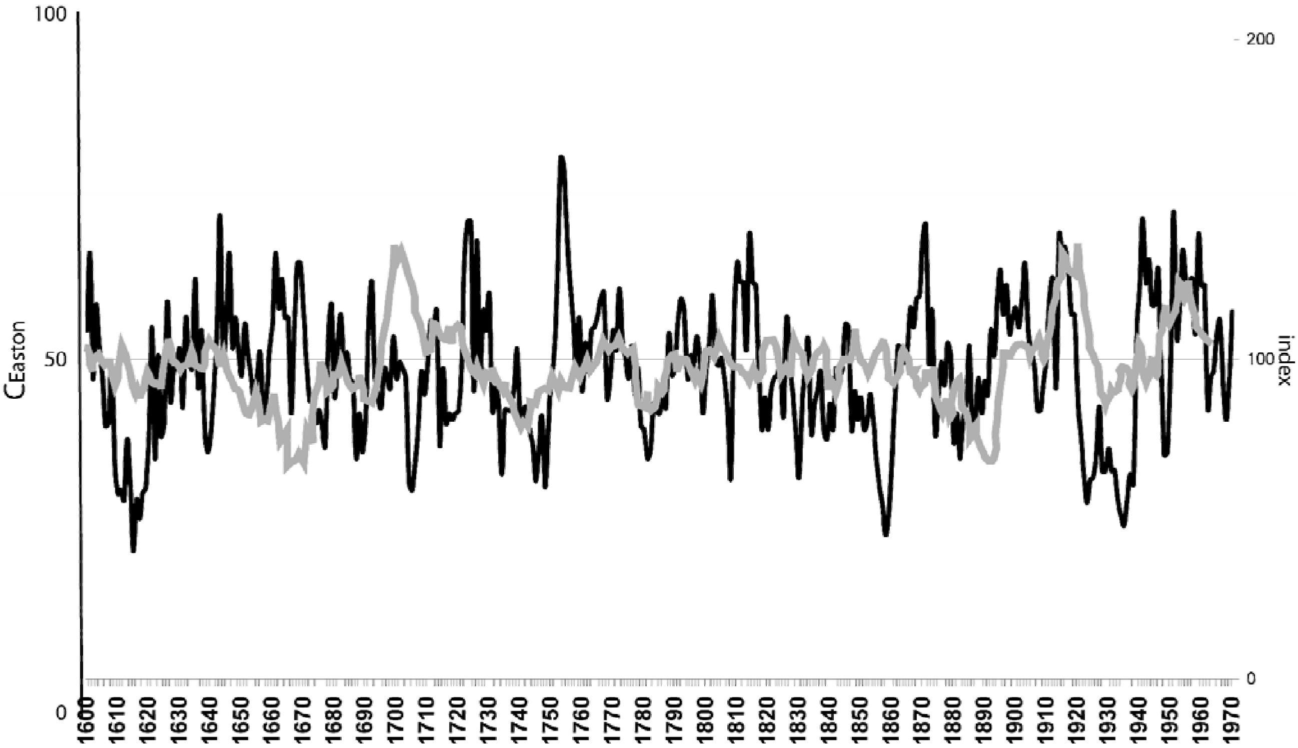

Fig. 8: The Easton coefficient time series smoothed by 11-year moving window (grey) and the same smoothed fir index (black) show similar fluctuation from 1970 to ~1730, despite the fact that Easton coefficient classify winter severity while fir index is sensible for environmental change of growing season.

Série chronologique du coefficient d'Easton filtrée par une moyenne mobile de 11 ans (en gris) et l'index du sapin également filtré (en noir), montrant des variations similaires de 1970 à env. 1730, même si le coefficient d'Easton est significatif pour la rigueur des hivers, tandis que l'index du sapin est sensible aux changements environnementaux dans la saison de croissance.

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References

BAILLIE, M.G.L. (1996) Extreme environmental events and the linking of the tree-ring and ice core records. In: *Tree Rings, Environment and Humanity* (DEAN, J.S., MEKO, D.M., & SWETNAM, T.W. *Eds.*), *Radiocarbon*, pp.703–711.

BIONDI, F. (1997) Evolutionary and moving response functions in dendroclimatology *Dendrochronologia,* **15**, pp.139–150.

BIONDI, F. & WAIKUL, K. (2004) DENDROCLIM2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies. *Computers & Geosciences*, **30**, pp.303–311.

BLEAHU, M., DECU, V., NEAGREA, Ş., PLEŞA, C., POVARĂ, I., & VIEHMANN, I. (1976) *Peşteri din România*. Ed. Şt. Enciclopedică., Bucureşti, pp.127–128.

COOK, E. & KAIRIUKSTIS, L., *Eds*. (1990) *Methods of Dendrochronology: Applications in the Environmental Sciences.* Kluwer, 394 p.

DESPLANQUE, C., ROLLAND, C., & SCHWEINGRUBER, F.H. (1999) Influence of species and abiotic factors on extreme tree ring modulation: *Picea abies* and *Abies alba* in Tarentaise and Maurienne (French Alps). *Trees*, **13**, pp. 218–227.

EPSTEIN, S. & MAYEDA, T. (1953) Variation of the ^{18}O content of waters from natural sources. *Geochimica et Cosmochimica Acta*, **4**, pp. 213–224.

FRITTS, H.C. (1976) *Tree rings and climate*. Blackburn Press, 567 p.

KERN, Z., NAGY, B., FÓRIZS, I., KÁZMÉR, M., & SZÁNTÓ, Z. (2003) Investigation of age and evolution of cave ice formations based on isotopic analysis. *Karsztfejlõdés*, **VIII,** pp.321–332 (*in Hungarian*).

LIBBY, L.M. & PANDOLFI, L.J. (1977) Climate periods in tree, ice and tides. *Nature*, **266**, pp. 415–417.

ORGHIDAN, T.; NEGREA, Ş., RACOVIŢĂ, G., & LASCU, C. (1984) *Peşteri din Romania: ghid turistic*. Ed. Sport-Turism, Bucureşti, pp. 85–87.

POP, E. & CIOBANU, I. (1950) Analize de polen in Ghiaţa de la Scărişoara, *Analele Acad. Rom., Seria Geol., Geogr., Biol.*, **III,** *2*, pp. 23–52.

POPA, I. (2003) Analiza comparativă a răspunsului dendroclimatologic al molidului (*Picea abies* (L.) Karst.) şi bradului (*Abies alba* Mill.) din nordul Carpaţilor Orientali. *Bucovina Forestieră*, **XI,** *2*, pp.3–14.

RACOVI ŢĂ, G. (1972) Sur la corrélation entre l'évolution du climat et la dynamique des dépôts souterrains de glace de la Grotte de Scărişoara, *Trav. Inst. Spéol. „Emile Racovitza*", **XI**, pp. 373–392.

RACOVIŢĂ, G., ŞERBAN, M., & VIEHMANN, I. (1987) Tendances de long terme dans la dynamique des formations de glace de la Grotte de Scărişoara (Monts de Bihor). *Theor. Appl. Karstology*, **3**, pp.143–164.

RACOVIŢĂ, G. & ŞERBAN, M. (1990) Interprétation en vue d'une reconstruction paléoclimatique des particularités structurales et dynamiques du dépôt de glace pérenne de la Grotte de Scărişoara. *Studia Universitas Babes-Bolyai, Geologia*, **XXXV**, *2*, pp. 47–61.

RACOVIŢĂ, G. & ONAC, B.P. (2000) *Scărişoara Glacier Cave. Monographic Study.* Ed. Carpatica, Cluj-Napoca, 140 p.

ROETHER, W. (1970) Water-CO_2 Exchange Set-up for the Routine 18Oxygen Assay of Natural Water. *Intl. Journal of Applied Radiation and Isotopes*, **21**, pp. 379–387.

SCHICHLER, B., LEVANIČ, T., ČUFAR, K., & ECKSTEIN, D. (1997) Climate–growth relationship of fir in Dinaric Mountains in Slovenia using different standardizations and response function calculations. *Dendrochronologia,* **15**, pp. 207–214.

SCHLATTER, F., STOFFEL, M., MONBARON, M., & LUETSCHER, M. (2003) A new approach to dating firn accumulation in an ice cave in the Swiss Jura mountains., *8th Intl. Conf. on Permafrost*, extended abstracts (HAEBERLI & BRANDOVA *Eds*.) pp.143–144.

SCHWEINGRUBER, F.H. (1990) *Microscopic wood anatomy*., 3rd edition, 226 p.

ŞERBAN, M., BLAGA, L., BLAGA, L., CHIFU, A., & CIOBOTARU, T. (1967) Contribuţii la stratigrafia depozitelor de gheaţă din Gheţarul de la Scărişoara., *Lucr. Inst. Speol.* "*Emil Racovita*", **VI**, pp.107–140.

ŞERBAN, M. & RACOVIŢĂ, G. (1987) Sur l'information paléoclimatique comprise dans le dépôt souterrains de glace de la Grotte de Scărişoara (Monts de Bihor) et sa valorisation pour une prognose de long terme., *Theor. Appl. Karstology*, **3**, pp.133–143.

STUIVER, M.& REIMER, P.J. (1993) Extended C-14 data-base and revised CALIB 3.0 C-14 age calibration program. *Radiocarbon*, **35**, *1*, pp. 215–230.

RINN, F. (1996) *TSAP Reference Manual (version 3.0).*, Heidelberg, Germany, 263 p.

YONGE, C.J., & MACDONALD, W.D. (1999) The potential of perennial cave ice in isotope paleoclimatology. *Boreas*, **28**, pp. 357–362.

YONGE, C.J., FORD, D.C., GRAY, J., & SCHWARCZ, H.P. (1985) Stable isotope studies of cave seepage water. *Chemical Geology (Isotope Geoscience Section)*, **58**, pp. 97–105.

WILSON, R. & ELLING, W. (2004) Temporal instability in tree-growth/climate response in the Lower Bavarian Forest region: implications for dendroclimatic reconstruction. *Trees*, **18**, pp.19–28.

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