Paleoclimate reconstruction from the North Iberian Peninsula since last deglaciation: the El Pindal Cave speleothem record (Asturias, Spain)

Reconstrucción paleoclimática del Norte de la Península Ibérica desde la última deglaciación: el registro de la cueva de El Pindal (Asturias)

A. Moreno[1, 2], H. Stoll[3], I. Cacho[4], I. Vadillo[5], R.L. Edwards[2], E. Ito[2],
M. Jiménez-Sánchez[3] y B.L. Valero-Garcés[1]

1 Instituto Pirenaico de Ecología – CSIC, Apdo. 202, 50080 Zaragoza. amoreno@ipe.csic.es; blas@ipe.csic.es
2 Limnological Research Center, University of Minnesota, 310 Pillsbury Drive SE, Minneapolis, MN 55455 (EEUU) moren079@umn.edu; edwar001@umn.edu; eito@umn.edu
3 Departamento de Geologia, Universidad de Oviedo, C/ Arias de Velasco, s/n 33005 Oviedo. hstoll@geol.uniovi.es; mjimenez@geol.uniovi.es
4 GRC Geociències Marines, Universitat de Barcelona, C/Martí i Franqués, s/n 28080 Barcelona icacho@ub.es
5 Departamento de Geología, Facultad de Ciencias. 29071 Málaga. vadillo@uma.es

Abstract: The identification and description of abrupt climate changes since last deglaciation in the northern Iberian Peninsula and the understanding of the potential forcing mechanisms require the study of long, well-dated sequences that allow high-resolution reconstruction of past climate changes. Here we present stable isotope ($\delta^{18}O$ and $\delta^{13}C$) and elemental (Mg/Ca, Sr/Ca and Ba/Ca) records from two well-dated stalagmites from the northern coast of Spain, which span from 28,000 to 4800 years B.P., with average deposition rates of 20 and 50 mm/ka. We aim to (1) describe the sequence of climate changes that occurred since the LGM, (2) identify the timing and describe the structure of abrupt climate oscillations and (3) test hypotheses concerning the forcing mechanisms of hydrological variations for the last 30 ka.

Key workds: speleothems, abrupt climate change, last deglaciation, stable isotopes, U-Th dating.

Resumen: *La identificación y descripción de los cambios climáticos abruptos desde la última deglaciación en el norte de la Península Ibérica, así como la comprensión de los potenciales mecanismos que los causan requiere el estudio de secuencias largas y bien datadas que permitan la reconstrucción de los cambios climáticos del pasado con alta resolución. En este trabajo presentamos los registros de isótopos estables ($\delta^{18}O$ and $\delta^{13}C$) y de elementos traza (Mg/Ca, Sr/Ca and Ba/Ca) obtenidos a partir de dos estalagmitas de la costa norte española datadas mediante U-Th, que cubren el intervalo temporal entre 28,000 y 4,800 años, con tasas medias de depósito entre 20 y 50 mm cada 1000 años. Con este trabajo se pretende (1) describir la secuencia de cambios climáticos que ocurrieron desde el Último Máximo Glaciar, (2) identificar y describir la estructura de las oscilaciones climáticas de carácter rápido y, (3) evaluar hipótesis respecto a los mecanismos que causaron las variaciones hidrológicas de los últimos 30,000 años.*

Palabras clave: *espeleotemas, cambio climático abrupto, última deglaciación, isótopos estables, U-Th.*

INTRODUCTION

The comprehension of recent past climate variations, mostly the ones related to abrupt climate changes, has been one of the main issues of paleoclimate research in the Iberian Peninsula during the past few years (eg. Moreno *et al.*, 2005). However, in spite of the great effort involved, many questions remain unsolved, particularly the response of terrestrial ecosystems to climate fluctuations during the last deglaciation and the Holocene, in terms of temperature and humidity changes. Although it is known from previous paleoceanographic studies that the Northern Iberian Peninsula responded to the North Atlantic rapid climatic changes during the last 25,000 years (Naughton *et al.*, 2007), the forcing mechanisms that transfer the signal, the timing of the ecosystem response and the synchrony between marine and terrestrial systems remain unknown. In addition, the timing of the last deglaciation in the mountains from the North Iberian Peninsula and the temporal relation with other European mountains are scientific questions still under discussion (Jiménez-Sánchez y Farias-Arquer, 2002). To address those questions, we present stable isotope ($\delta^{18}O$ and $\delta^{13}C$) and elemental (Mg/Ca, Sr/Ca and Ba/Ca) climate records from two well-dated stalagmites from El Pindal Cave in Asturias (northern coast of Spain, Fig. 1), which span from 28,000 to 4800 years B.P.

PRESENT DAY CLIMATIC SETTING

The study area is characterized today by Atlantic climate, i.e., high annual precipitation (about 1000 mm) due to the proximity to the ocean, occurring mainly in winter. Winters are mild and summers are cool with a very small annual temperature range (ca. 13°C).

Rainfall is mainly associated with mid-latitude storms from the Atlantic Ocean.

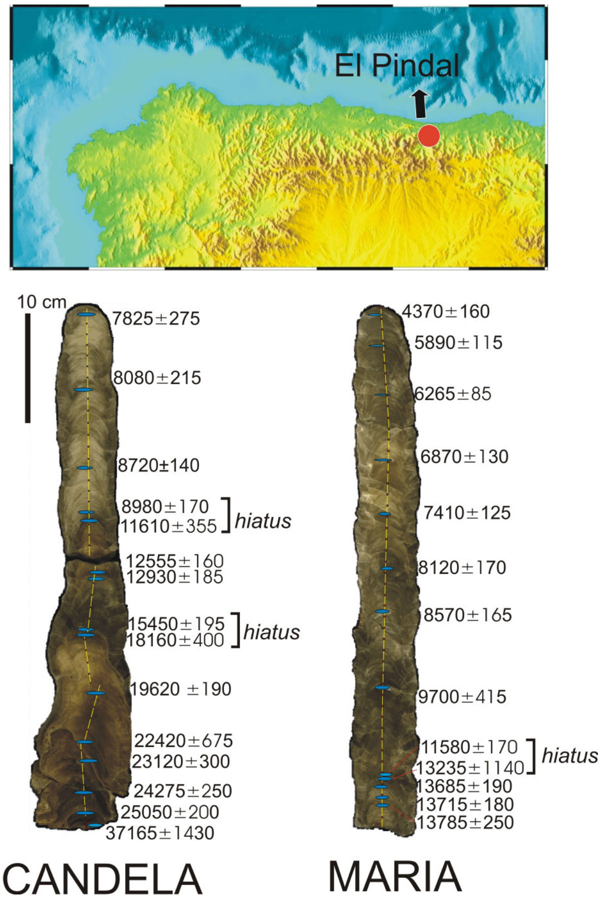

FIGURE 1. *(a) Location of El Pindal cave in Asturias (Spain). (b) Image of the analyzed speleothems from El Pindal cave: CANDELA and MARÍA. U-Th dates used to construct the age model are indicated (in years BP) and the position of detected hiati. See also Table I.*

Much of the present day climate variability in this region on a decadal timescale has been linked to a natural mode of atmospheric pressure variation, the North Atlantic Oscillation (NAO; Trigo *et al.*, 2004). NAO activity is indexed as the difference between normalized winter sea-level atmospheric pressure between the Azores high pressure and Icelandic low-pressure cells: a high NAO index is derived from a strong meridional pressure gradient that results in the North Atlantic depression tracks to follow a more northerly route. During low NAO index years, northwesterly winds are weaker and are guided to midlatitudes, thus bringing higher precipitation to the Mediterranean and large areas of North Africa. The measurement of chemical and isotopic composition of both dripwater and rainfall in the cave has allowed us to confirm the influence of the NAO in the precipitation. Thus, a high correlation (r^2=0.83) among positive NAO index and less negative oxygen isotopes of rainfall samples is evidenced. Correlation among NAO and amount of precipitation and temperature is much lower (0.3).

RESULTS AND DISCUSSION

Geomorphology. El Pindal Cave (4°30'W, 43°23'N) is developed at 24 m above sea level, in a karstic massif reaching its highest surface in a marine terrace (rasa). Several phases of evolution were recognized into the cave, including block collapse of the roof, episodic flooding and detritic sedimentation and chemical precipitation of at least four speleothem generations over both alluvial and collapse deposits. The first generation yielded ages from 124.2 ± 1.5 ka BP to 73.1 ± 0.9 ka BP, giving a minimum age for the main detritic sediments in the cave (Jiménez-Sánchez *et al.*, 2006). The second one is represented in Fig. 1. The third generation gives an age of 3,71 ± 0,4 ka BP to the present, while for the fourth generation, with actively growing stalagmites in the cave, basal ages of 200 years BP are estimated by counting annual laminae.

Stable isotopes. The measurement of $\delta^{18}O$ and $\delta^{13}C$ isotopic composition of both speleothems (CANDELA and MARÍA) at the University of Barcelona and University of Minnesota shows significant variations along the records with these main results (Fig. 2):

- A high variability in the isotopic values is observed: 10‰ in $\delta^{13}C$; 3‰ in $\delta^{18}O$.
- Although still with different resolution and preliminary age models, both records present a good reproducibility of isotopic results (see Fig. 2), both values and main trends.
- $\delta^{18}O$ and $\delta^{13}C$ profiles are very similar, likely pointing to similar forcing mechanisms.

The high correlation observed among dripwater isotopic composition and NAO variability helps in the interpretation of $\delta^{18}O$ isotopes. Thus, more negative isotopic values would imply a more persistent NAO negative phase, likely leading to more precipitation in the Cantabrian range. At the long-term scale (eg. LGM vs Holocene), latitudinal migration of pressure cells affects the moisture source within the North Atlantic, the temperature gradients between origin and destination, and the distance from moisture source. These variations can be reflected in the isotopic composition in rainfall events with a depletion of $\delta^{18}O$ values when the system shifts to the north. On the other hand, the $\delta^{13}C$ record may be controlled by other mechanisms: (1) C3 *vs* C4 plants dominance (that would be related to the amount of rainfall; eg. less rainfall will force the presence of some C4 plants and then less negative $\delta^{13}C$ values will be observed) and/or (2) soil evaporative processes leading to isotopic enrichment in drier climates after vadose precipitation of calcite.

Correlation of less negative $\delta^{18}O$ and $\delta^{13}C$ values with cold periods in Greenland cores during the last deglaciation and Early Holocene suggests a rapid response in the isotopic composition of rainfall at the studied latitude (due to abrupt shifts to colder or drier climates, and/or, more persistent positive NAO phase).

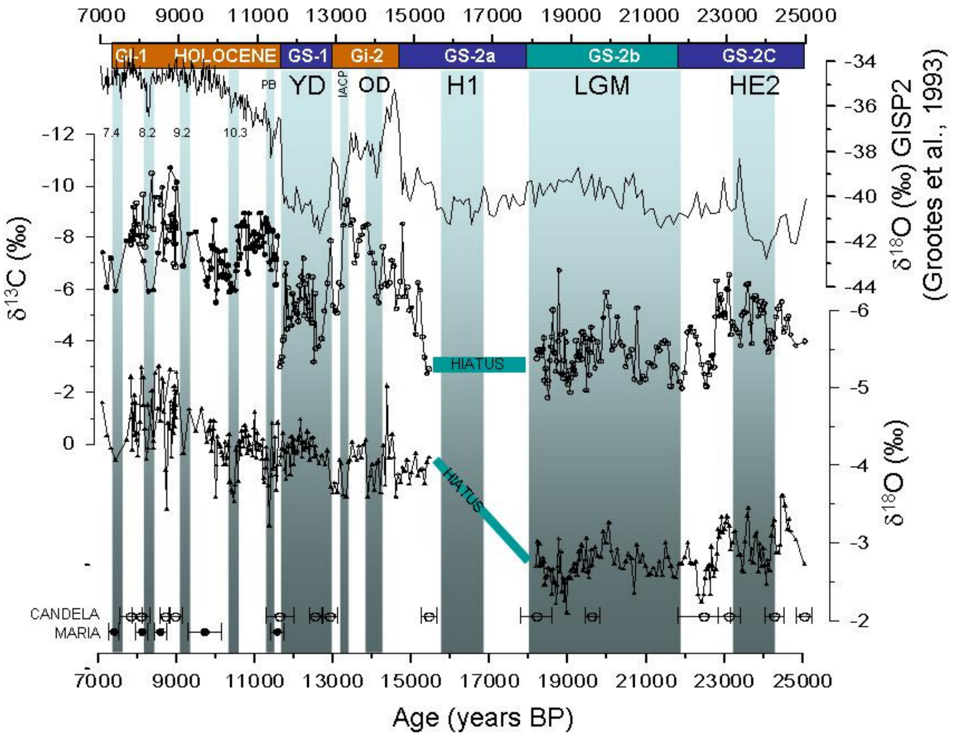

FIGURE 2. *Isotopic record ($\delta^{18}O$ and $\delta^{13}C$) for the whole record (showing CANDELA and MARIA samples) compared to GISP2 Greenland core. Shaded bands mark the cold periods: PB (Preboreal oscillation), YD (Younger Dryas), IACP (Intra Allerød Cold Period), OD (Older Dryas), H1 and H2 (Heinrich event 1 and 2) and LGM (Last Glacial Maximum).*

Trace elements. Trace elements analyses were performed on splits of the drilled isotope powders from both speleothems (CANDELA and MARÍA) from El Pindal cave using ICP-ES at the University of Oviedo (Spain). Measurement of Mg/Ca ratio at high resolution using LIBS (Laser-Induced Breakdown Spectroscopy) yielded excellent reproducibility with ICP data. Dripwater studies in the cave show that Prior Calcite Precipitation (PCP) is a significant control on trace metal ratios in dripwater which will in turn influence stalagmite element ratios. Slower drip rates during dry periods may allow more extensive CO_2 degassing and calcite precipitation on cave ceilings. Consequently, all divalent trace elements which possess partitioning coefficients in calcite <<1 (eg. Mg, Sr, Ba), are successively enriched in dripwaters during dry periods following a Rayleigh curve. Dripwater studies also reveal marine aerosols to be the dominant source of Mg in dripwaters, implicating potential changes in Mg supply to dripwaters during glacial sea level recessions. In the stalagmite record, stalagmite growth rate variations and long term processes like vegetation cover and soil response to climate may also influence trace metal ratios in the stalagmite records.

There is a clear increase of Mg/Ca at about 8 kyr BP (Fig. 3). Since El Pindal cave is right on the current coast and the mass balance for Pindal drips suggests currently about 80% of Mg could be from seasalt aerosols, then, the 2-3 fold increase in Mg content is thus potentially attributable to sea level rise. After this sea level rise, the amplitude of Mg/Ca variation is large, perhaps due to increased sensitivity of aerosol delivery to wind direction or speed. Sr/Ca and Ba/Ca ratios show maxima during Early Holocene optimum, 7.5 -5 ka, coinciding with the end of the most recent humid period in N. Africa. If these ratios are controlled principally by dripwater chemistry through PCP they suggest drier climates at this time. The steep drop of Sr/Ca and Ba/Ca around 5 ka coincides with a threefold reduction in growth rate and may reflect lower Sr and Ba incorporation in stalagmite at lower growth rates.

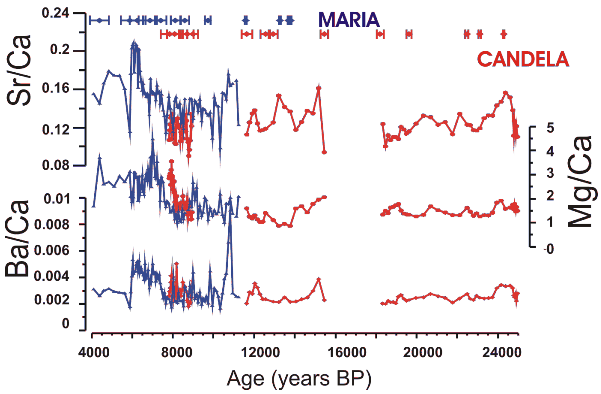

FIGURE 3. *Geochemical ratios obtained for both speleothems (CANDELA in red; MARIA in blue).*

CONCLUSIONS

This study represents a first attempt of reconstructing past climate variations in the north of Iberian Peninsula from speleothem records. Since a present-day high correlation between NAO index and isotopic composition of rainfall is observed, we interpret the $\delta^{18}O$ values from the studied speleothems as indicators of NAO activity. Thus, from 24.5 to 18 ka, the enriched $\delta^{18}O$ values point to dominant NAO positive index. On the contrary, during the deglaciation and Holocene, $\delta^{18}O$ values are more negative, likely reflecting an increase in moisture associated to a dominant negative NAO phase. This interpretation is coherent with the $\delta^{13}C$ record, pointing to C4 plants during the glacial and C3 plants since 14.5 ka BP. However, other factor to be taken into consideration when interpreting the long-term pattern is the change in moisture sources within the North Atlantic when there is a latitudinal migration of pressure cells (eg. from LGM to Holocene). The Mg/Ca indicates that the main increase in sea level occurred at 8 ka BP while Sr/Ca and Ba/Ca, associated to vegetation and driprate, point to warmer temperatures and possibly greater vegetation cover from 7.5 to 5 ka BP, synchronously with the most recent humid period in N. Africa.

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Sample ID	**^{238}U ppb**	**$\delta^{234}U$**	**$[^{230}Th/^{238}U]$ activity**	**$[^{230}Th/^{232}Th]$ ppm**	**Age uncorrected**	**Age corrected**	**$\delta^{234}U_{initial}$ corrected**	**Depth mm**
CAN-C1	143 ± 0.3	173.1 ± 3	0.360 ± 0.0057	60.6 ± 1	39,581 ± 752	37,165 ± 1426	192.3 ± 3.2	2
CAN-C2	180 ± 0.3	164.9 ± 2	0.241 ± 0.0016	881.6 ± 7	25,161 ± 196	25,050 ± 203	177.0 ± 2.3	15
CAN-D1	497 ± 1.8	134.8 ± 3	0.228 ± 0.0020	1347.4 ± 13	24,348 ± 249	24,277 ± 251	144.4 ± 3.1	32
CAN-A2	149 ± 0.4	154.2 ± 4	0.222 ± 0.0024	863.0 ± 13	23,223 ± 293	23,117 ± 298	164.6 ± 4.5	60
CAN-A3	111 ± 0.2	164.2 ± 3	0.228 ± 0.0032	83.1 ± 1	23,604 ± 374	22,481 ± 675	175.0 ± 3.7	80
CAN-B1	188 ± 0.4	162.2 ± 2	0.193 ± 0.0016	1192.0 ± 13	19,685 ± 186	19,619 ± 189	171.5 ± 2.3	120
CAN-A4	120 ± 0.3	228.2 ± 4	0.191 ± 0.0038	775.4 ± 20	18,299 ± 399	18,204 ± 402	240.2 ± 4.5	175
CAN-B2	201 ± 0.5	165.7 ± 2	0.156 ± 0.0016	416.8 ± 5	15,603 ± 178	15,450 ± 194	173.1 ± 2.3	180
CAN-B3	161 ± 0.3	81.1 ± 2	0.121 ± 0.0016	2179.0 ± 58	12,957 ± 186	12,933 ± 186	84.1 ± 2.6	225
CAN-C3	165 ± 0.3	78.5 ± 2	0.118 ± 0.0014	4818.9 ± 315	12,567 ± 160	12,556 ± 160	81.3 ± 2.2	230
CAN-A7	91 ± 0.3	159.3 ± 6	0.118 ± 0.0034	1326.9 ± 83	11,677 ± 356	11,640 ± 356	164.6 ± 6.0	265
CAN-B4	112 ± 0.2	35.9 ± 3	0.082 ± 0.0015	1300.5 ± 37	9,008 ± 172	8,979 ± 173	36.8 ± 2.6	270
CAN-B5	150 ± 0.4	26.6 ± 3	0.079 ± 0.0012	3584.4 ± 217	8,730 ± 139	8,719 ± 139	27.3 ± 2.6	310
CAN-A9	140 ± 0.3	33.3 ± 3	0.074 ± 0.0019	1109.5 ± 55	8,130 ± 215	8,099 ± 215	34.0 ± 3.4	380
CAN-t	132 ± 0.3	33.9 ± 4	0.073 ± 0.0024	369.8 ± 15	7,933 ± 273	7,842 ± 277	34.7 ± 3.8	450
MAR-b	135 ± 0.3	241.8 ± 4	0.14981 ± 0.0024	444.6 ± 8	13,949 ± 241	13,820 ± 249	251.5 ± 3.9	20
MAR-D1	162 ± 0.5	249.8 ± 4	0.14852 ± 0.0018	3984.3 ± 146	13,727 ± 182	13,713 ± 182	259.7 ± 3.8	26
MAR-D2	157 ± 0.6	243.5 ± 4	0.14759 ± 0.0019	2424.8 ± 70	13,710 ± 191	13,687 ± 191	253.1 ± 4.6	36
MAR-A1	141 ± 0.5	219.4 ± 6	0.14415 ± 0.0112	144.6 ± 11	13,657 ± 1131	13,267 ± 1143	227.7 ± 6.7	44
MAR-C2	117 ± 0.3	228.2 ± 3	0.12455 ± 0.0017	1520.9 ± 43	11,612 ± 170	11,580 ± 171	235.8 ± 3.0	47
MAR-A3	139 ± 0.3	182.8 ± 4	0.10202 ± 0.0041	488.8 ± 21	9,805 ± 414	9,720 ± 416	187.9 ± 4.4	126
MAR-A4	213 ± 0.4	146.7 ± 3	0.08732 ± 0.0016	1493.9 ± 47	8,615 ± 165	8,591 ± 165	150.3 ± 3.2	195
MAR-C3	117 ± 0.3	143.9 ± 3	0.08279 ± 0.0016	626.8 ± 17	8,173 ± 167	8,118 ± 169	147.3 ± 3.2	233
MAR-B3	215 ± 0.5	124.9 ± 2	0.07408 ± 0.0012	11635.3 ± 1526	7,413 ± 126	7,411 ± 126	127.6 ± 2.1	282
MAR-A5	264 ± 0.8	128.4 ± 4	0.06935 ± 0.0012	995.8 ± 25	6,902 ± 130	6,873 ± 131	130.9 ± 4.5	332
MAR-B4	286 ± 0.8	120.5 ± 3	0.06272 ± 0.0008	5043.9 ± 277	6,269 ± 86	6,264 ± 86	122.6 ± 2.7	392
MAR-C4	171 ± 0.5	122.0 ± 3	0.05934 ± 0.0011	1039.8 ± 38	5,915 ± 113	5,891 ± 114	124.0 ± 3.0	435
MAR-t	171 ± 0.5	102.1 ± 4	0.04458 ± 0.0015	168.3 ± 6	4,496 ± 153	4,381 ± 163	103.4 ± 4.0	464

TABLE I. *The chronology of two stalagmites from El Pindal cave was obtained by U-Th following the procedures described in Edwards et al., (1986) using a Finnigan ELEMENT ICP-MS at the University of Minnesota.*

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