Stalagmite lamina doublets: A 1000 year proxy record of severe winters in northwest Scotland?

Article *in* International Journal of Climatology · September 2002

Impact Factor: 3.16 · DOI: 10.1002/joc.800

INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **22**: 1339–1345 (2002)
DOI: 10.1002/joc.800

STALAGMITE LAMINA DOUBLETS: A 1000 YEAR PROXY RECORD OF SEVERE WINTERS IN NORTHWEST SCOTLAND?

ANDY BAKER,[a,]* CHRISTOPHER J. PROCTOR[a] and WILLIAM L. BARNES[b]
[a] *Department of Geography, University of Newcastle upon Tyne, Newcastle, NE1 7RU, UK*
[b] *School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, UK*

Received 19 September 2001
Revised 15 March 2002
Accepted 20 March 2002

ABSTRACT

Stalagmites can contain annual luminescence laminae, and some samples provide long continuous chronologies from which climatic information can be extracted. One such site is Uamh an Tartair in Assynt, northwest Scotland, where most stalagmites contain continuous laminae sets for the last two to three millennia. At this site, the normal mode of deposition is for one luminescent lamina to be deposited in autumn, derived from luminescent organic matter that is flushed onto the sample from the overlying peat. However, in the stalagmite investigated here, 43 lamina doublets occur, where two laminae appear to be preserved in a winter. We argue, both from the timing of these events within the 'Little Ice Age', as well as from analogous situations in alpine streams, that the doublets occur due to the presence of a second, spring melt flush of organic matter. The interpretation of stalagmite double laminae, therefore, has considerable potential as a palaeoclimate proxy, and at our study site, we suggest one of severe winters over the last millennium.

KEY WORDS: severe winters; stalagmites; palaeoclimate; annual laminae; northwest Scotland

1. INTRODUCTION

One area of research in speleothem palaeoclimatology is the investigation of speleothem laminae (Baker *et al*., 1993; Genty and Quinif, 1996; Genty *et al*., 1997; Ming *et al*., 1997, Qin *et al*., 1998; Brook *et al*., 1999; Polyak and Asmerom, 2001; Proctor *et al*., 2000, in press; Qian and Zhu, 2002). Laminae are often luminescent, derived from seasonal fluxes of organic acids that are trapped within the speleothem calcite and which derive from the overlying soil (Baker *et al*., 1993; Shopov *et al*., 1994). Annual luminescence laminae, which in temperate latitudes are deposited in autumn, can therefore provide an annual chronology. In addition, annual laminae can provide a high-resolution palaeoclimate or palaeoenvironmental record through the correlation of lamina width (annual growth rate) with climate parameters such as mean annual precipitation and monsoon strength (Ming *et al*., 1997; Proctor *et al*., 2000, in press; Qian and Zhu, 2002).

As well as using stalagmite lamina widths as a climate proxy, variations in lamina structure can also be utilized. The easiest to observe structure is that of a doublet, i.e. a structure with two luminescent peaks within 1 year of deposition. In a recent study, Baker *et al*. (1999) utilized duplicate records of variations in the structure of stalagmite annual luminescence laminae for the period AD 1910 to 1996 at Poole's Cavern, Buxton, central England. They determined that ten laminae (12% of total) over this period exhibited a double lamina structure. These were demonstrated to occur in years with high monthly or daily mean precipitation, with a high intensity (>60 mm/day) and a high quantity (>250 mm/month) of precipitation flushing luminescent organic material onto the stalagmites from either the soil or groundwater zones and generating a double

---

* Correspondence to: Andy Baker, Department of Geography, University of Newcastle upon Tyne, Newcastle, NE1 7RU, UK; e-mail: andy.baker@ncl.ac.uk

lamina. However, they noted that not all precipitation events generated double laminae; high-intensity events in summer were ineffective, due to either a soil moisture deficit and/or interception by the woodland canopy, and high rainfall months (>250 mm) failed to generate double laminae when preceded by two or more months of greater than 150 mm, suggesting that exhaustion of the organic acid supply can occur. The results from Poole's Cavern suggested that there is some potential in the analysis of stalagmite lamina structure as a climate proxy.

In contrast to the study detailed above from a temperate maritime climate region, Linge *et al.* (2001) counted laminae in a stalagmite from Larshullet, a cave situated near the Arctic Circle in the Rana area of northern Norway. The area is characterized by a mean annual temperature of 3 to 4 °C and a mean annual precipitation of about 1500 mm. In these stalagmites, the number of laminae counted was in excess of the ages of the stalagmites as determined from radiometric (U–Th) dating. In this case, double laminae were common, and were explained as resulting from an annual spring snowmelt flush of organic carbon, as well as an autumn flushing of soil organic matter after dry and warm summers. Annual snowmelt flushes of organic carbon in spring are widely documented in mountain streams that experience significant snow cover and soil freezing (Hornberger *et al.*, 1994; Boyer *et al.*, 1997; Brooks *et al.*, 1999).

Here, we present the results of our investigation of double laminae within a stalagmite that has grown over the last ~1000 years in northwest Scotland. The presence of luminescent annual growth laminae in stalagmites from our research site, Uamh an Tartair cave in northwest Scotland, was first demonstrated by Baker *et al.* (1993). The Uamh an Tartair cave lies in the Traligill valley in northwest Scotland, at an altitude of 300 m; a fuller description is given in Proctor *et al.* (2000). A stalagmite from the cave was recently used to obtain a thousand year record of precipitation (Proctor *et al.*, 2000). SU-96-7 was a small (32 mm high) *in situ* stalagmite that was actively growing when collected in 1996. The drip rates onto the stalagmite recorded over the period 1996–2001 ranged from 1 min/drip to >1 h/drip. The stalagmite comprises clean calcite with no sign of any hiatuses, suggesting it grew continuously. Bomb carbon in the top 1 mm of the sample confirms it was actively growing when collected in 1996. Annual luminescent laminae are visible throughout the stalagmite, and a total of 1087 annual laminae are present; Proctor *et al.* (2000) assign a counting error of ±20 years based on possible miscounting due to poor lamina preservation or misclassification of double laminae that are found in the sample (see Section 2). Therefore, a thermal ionization mass spectrometry (TIMS) uranium series date on the basal 4 mm of the stalagmite was also obtained to provide a cross-check on the laminae count chronology. This yielded an age of the base of the stalagmite of 1262 years (error range of 1002 to 1349 years) before AD 2000. The error range reflects the uncertainty in the crustal value of ^{232}Th rather than in the analytical counting statistics (±33 years); see Proctor *et al.* (2000) for isotopic data. Given the additional time averaging effect due to the necessity to sample 4 mm of calcite, the errors of the TIMS U–Th analysis do not improve on those of the laminae count (±20 years), but does confirm the start of growth between about 1000 and 1350 years BP (Proctor *et al.*, 2000).

Annual growth lamina width in this stalagmite shows a high negative correlation with precipitation and a weaker positive correlation with temperature over the period of historical meteorological records (1879–1993). The stalagmite's high sensitivity to precipitation is due to the presence of a thin cover of peat overlying the cave. The peat becomes saturated in wet periods, leading to reduced soil respiration and low P_{CO_2} in the soil water, and in turn a reduced stalagmite growth rate in the cave below. This high sensitivity to precipitation, coupled with the fact that temperature has varied little over the last 1000 years, has allowed a long-term record of precipitation to be obtained from it. The precipitation record from the site is of particular significance, as northwest Scotland precipitation is tightly linked to the North Atlantic oscillation (NAO; Hurrell, 1995). Stalagmite SU-96-7 also contains a number of double laminae.

2. METHODOLOGY

Luminescent laminae were counted and their widths measured using techniques detailed in Proctor *et al.* (2000) to compile a record of annual growth rate for the stalagmite. Results of laminae counting for SU-96-7 are described by Proctor *et al.* (2000) and archived in the World Data Centre for Palaeoclimatology. At the same time as recording growth rates, double laminae were also recorded. Following Baker *et al.* (1999), double laminae are defined as the occurrence of two distinct maxima within the top 25% of any luminescence peak. One inherent source of error in recording double laminae is, of course, the possibility that a doublet is actually two years of deposition. As discussed above, this could lead to the false reporting of a double lamina, and this must be borne in mind when interpreting the results, with an increasing probability of the chronology being erroneous through time. As detailed earlier, given the errors associated with the TIMS U–Th analysis, no independent dating check is available to prevent this.

3. RESULTS

The double laminae recorded in stalagmite SU-96-7 are listed in Table I, and plotted in Figure 1 against the lamina width (annual growth rate) record. Lamina width has been demonstrated to correlate with mean annual temperature/mean annual rainfall ($r = 0.77$ with 95% confidence interval from 0.68 to 0.84 for decadal smoothed data; Proctor *et al.*, in press) and regional winter NAO strength ($r = -0.70$ with 95% confidence interval from -0.59 to -0.78 for decadal smoothed data; Proctor *et al.*, 2000). A total of 43 double laminae are observed over the last 1087 years (one every 25 years). Double laminae occur in years of growth rate no different (statistically similar using Student's t-test at the 95% confidence level) than single lamina years, suggesting no simple correlation with mean annual temperature or precipitation of the preceding or current year. No double laminae are observed over the instrumental period of temperature and precipitation returns, so interpretation will have to rely on earlier documentary and proxy evidence for the historical period.

4. INTERPRETATION

As discussed earlier, two possible causes of double lamina formation can be hypothesized. Firstly, a double lamina could be generated by seasonal imbalances in precipitation, such as observed at Poole's Cavern (Baker *et al.*, 1999). Secondly, double laminae might be generated by a second, snowmelt-generated flush of organic carbon, as observed in a stalagmite in northern Norway (Linge *et al.*, 2001) and commonly observed in alpine streams.

In the stalagmite, the first doublet occurs at AD 1837; none has occurred between 1838 and the present day. In contrast, periods of uneven rainfall distribution have often occurred in the last 160 years. For example, Figure 2 presents data for the period 1950 to 1970, and shows several years of two or more periods of water excess that might be expected to flush organic matter from the peat through to the underlying stalagmite. No laminae doublets were generated during this time. Several reasons for this are likely. Firstly, the continuous and very slow drip rate onto our stalagmite is indicative of a relatively large storage component of groundwater feeding the stalagmite. This will smooth the more rapid fluxes of peat-derived organic matter transported by the relatively minor contribution of a faster, fissure flow groundwater component. Secondly, the overlying peat will also smooth the rainfall signal by forming a continuously saturated layer above the cave for many months of the year; short periods of rainfall excess may have no effect on the underlying stalagmites if they occur when the peat is saturated. Figure 2 shows a five- and seven-point smoothing of the water excess time series, showing how a 7 month smoothing is enough to generate continuous and regular organic matter flushes as observed in the stalagmite for the last 160 years.

Lamina doublets are most common in our stalagmite between AD 1600 and 1850 in our stalagmite chronology. These years occur during a period of known cold (often unhelpfully called the 'Little Ice Age') and potential freezing of the peat or prolonged snow cover. The annual resolution chronology provided by the lamina record also allows us to compare the occurrence of doublets with historical records of individual cold winters, although difficulties have to be acknowledged when comparing our double lamina years that are based on annual band counting with a calendar chronology. Missing laminae or the mis-reporting of double laminae in our chronology can lead to offsets between the stalagmite and calendar years: Proctor *et al.* (2000) assigned a maximum error of ±20 years to the 1087 year lamina chronology for SU-96-7 for these reasons.

Table I. Double laminae preserved in SU-96-7, together with possible climate correlants[a]

Year based on stalagmite lamina count; ±20 year error by AD 900	Possible climate correlant (calendar age)	Historical or proxy evidence
1836	1837	Extreme winter in Scandinavia, ice from Denmark to Norway and along Norwegian coast, very cold in Scotland[b]
1835	1838	18th coldest year in CET
1691	1695	2nd coldest year in CET
1690	1694	5th coldest year in CET
1688	1692	5th coldest year in CET
		1690s are ‘1ll years of King William’ Scottish harvests (mostly oat) fail in 7 out of 8 years. Famine in Scotland[b]
1682	1684	Coldest winter in CET record, 27 inches of frozen ground at Manchester,[c] 5 months of snow cover in parts of Aberdeenshire[d]
1675	1675	8th coldest year in CET
1674	1674	19th coldest year in CET
1673	1673	29th coldest year in CET
1638		Severe sheep and cattle losses, harvests fail[b]
1615		
1611		
1558		
1556		
1502		
1475		
1460		
1450		
1417		
1412		
1399		
1397		
1395		
1393		
1372		
1370		
1356		
1355		
1312		
1254		
1253		
1233		
1126		
1124		
1080		
1075		
1074		
1047		
1005		
974		
924		
912		
911		

[a] CET: central England temperature series (Manley, 1974).

[b] Lamb (1995).

[c] Manley (1969).

[d] Manley (1974).

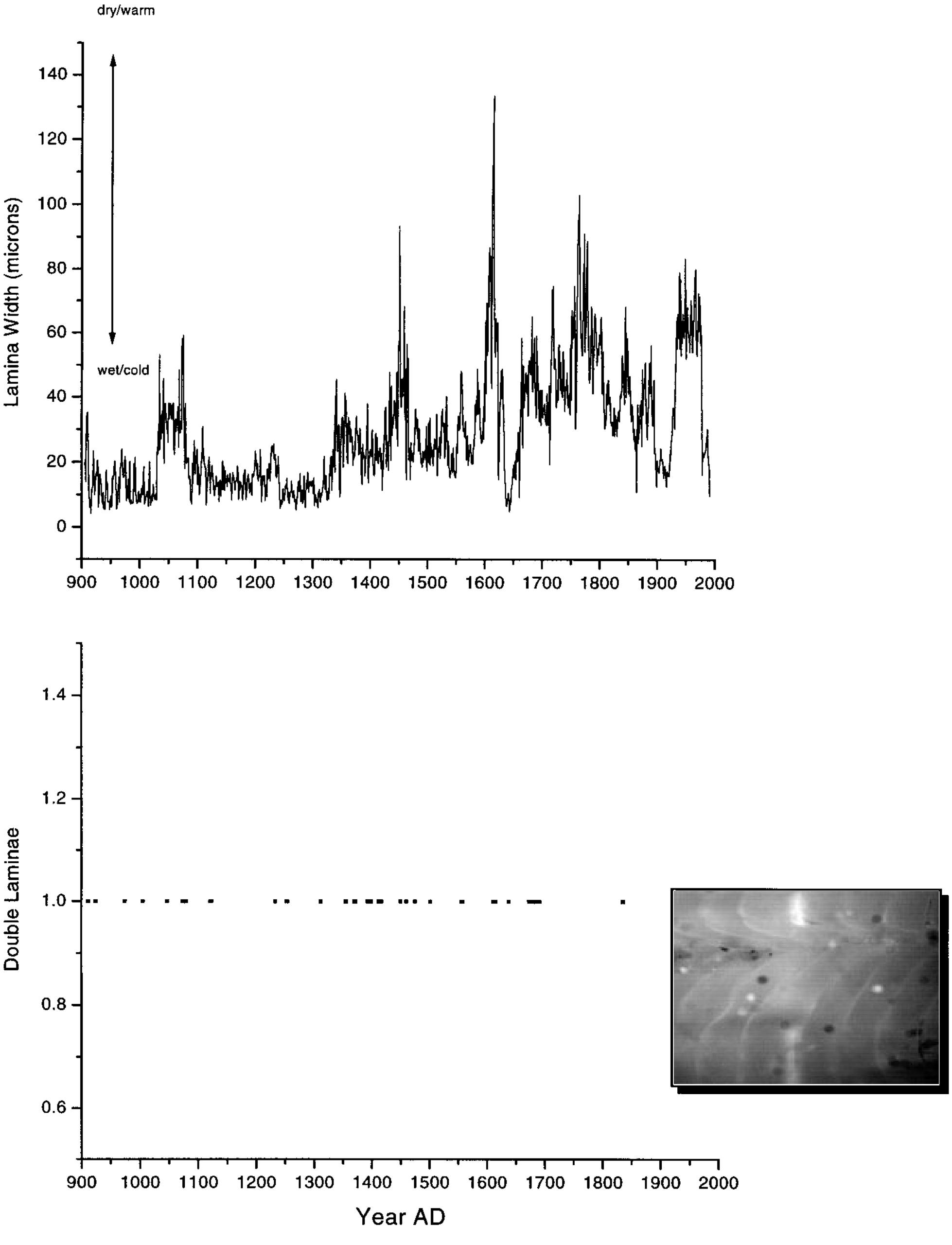

Figure 1. Stalagmite annual lamina width (top), adapted from Proctor *et al.* (2000), and timing of double laminae (bottom). An image of a typical double lamina (the very luminescent band in the centre of the image, number 310 from the top of the sample), probably AD 1684, the coldest year in the CET record

Records of snow cover suffer from reporting inconsistencies and their local nature (Manley, 1969), but other evidence, such as diary returns and the early part of the central England temperature (CET) series (Manley, 1974), can be informative. Table I shows, for example, that many of the coldest years in the CET record are those where we observe a double lamina. Not all of the coldest CET years are reflected in the record, though this is not surprising given: (1) the distance between the CET stations and our sample site (Assynt temperature and the CET series correlate at $r = 0.87$, Assynt temperature being 2.0 °C cooler); (2) the larger temperature errors associated with the early part of the CET record; and (3) the fact that mean annual temperatures may

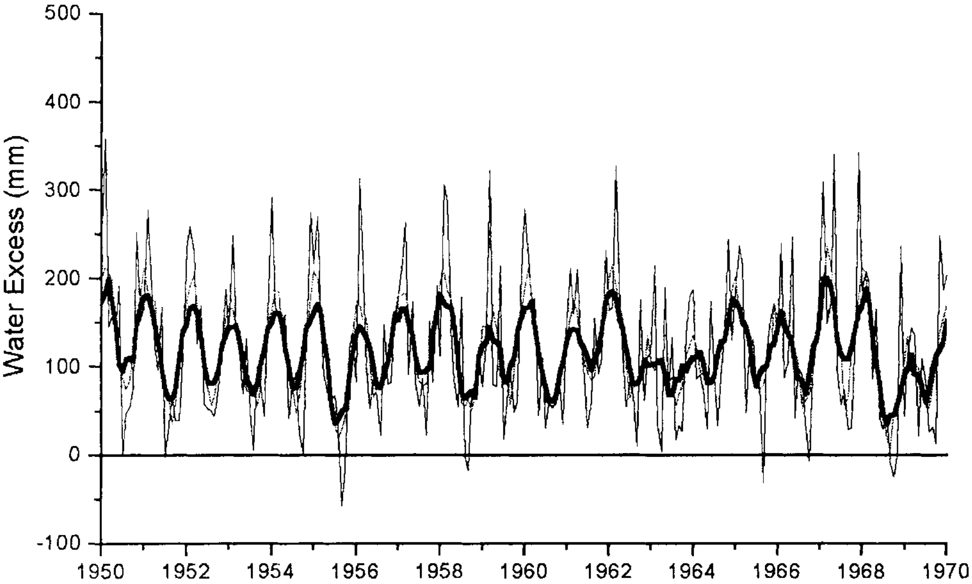

Figure 2. Water excess for the period AD 1950–70. Water excess is calculated following Thornthwaite (1955), using precipitation and temperature data from Stornoway and Glasgow respectively, which has been tuned to that of the nearby meteorological station of Knockanrock. Note that the 1960s have several years of imbalance in water excess, which are not recorded in the stalagmite, and which are not visible after five- (thin line) and seven-point (bold line) smoothing

not reflect the conditions required to generate a second stalagmite lamina. Other correlations between years of double lamina and CET parameters (monthly CET, winter CET) are worse, suggesting that lamina doublet deposition may depend on factors other than just temperature alone. Periods of double laminae do show an excellent correlation with periods of sea-ice cover in the Baltic (Koslowski and Glaser, 1999) in AD 1554–74, AD 1593–1630, AD 1655–1710, and AD 1763–1860. Baltic sea-ice cover has been correlated by the authors with prolonged blocking of the westerly circulation and negative NAO, a situation likely to produce unusually cold conditions in northwest Scotland.

The observed smoothing of subannual variations in precipitation by the existing peat cover implies that, in order to have a second flush of organic matter from the overlying peat, freezing must have changed the peat hydrology, maybe through the decoupling of the peat water and groundwater by freezing, thus allowing faster recharge from brief surface events such as a rapid thaw. In addition, a rapid thaw that provides a flush of organic matter from frozen peat into the groundwater would be likely to produce a lamina doublet, but would not be recorded in the low-resolution monthly temperature data.

5. CONCLUSIONS

Double laminae preserved within our stalagmite demonstrate a remarkable relationship with periods of cold climate, although our interpretation is hampered by the absence of either double laminae in the stalagmite or periods of cold climate over the period of historical meteorological records (1879 to the present). However, double laminae do occur during periods of known sea-ice cover in the Baltic Sea and cold years in the CET record. The former is ascribed to periods of enhanced atmospheric blocking, weak westerly flow and a negative winter NAO. Wanner *et al.* (1995) ascribe a similar blocking mode as dominant over the period 1678–96. Therefore, we suggest that, in SU-96-7, we have a record of cold winters that occur under periods of weakened westerly flow, and can be used to extend existing records back to *c.* AD 900. Further research using stalagmites from different climatic regions is encouraged to test further the utility of double laminae as a climate proxy.

ACKNOWLEDGEMENTS

This research was funded by the NERC (GR3/1A744). We thank Alex Scott (Scottish Natural Heritage) for sampling permissions, and Juerg Lutenbacher and an anonymous referee for their helpful comments.

REFERENCES

Baker A, Smart PL, Edwards RL, Richards DA. 1993. Annual growth banding in a cave stalagmite. *Nature* **364**: 518–520.

Baker A, Proctor CJ, Barnes WL. 1999. Variations in stalagmite luminescence laminae structure at Poole's Cavern, England, AD 1910 to AD 1996: calibration of a palaeoprecipitation proxy. *The Holocene* **9**: 683–688.

Boyer EW, Hornberger GM, Bencala KE, McKnight DM. 1997. Response characteristics of DOC flushing in an alpine catchment. *Hydrological Processes* **11**: 1635–1647.

Brook GA, Rafter MA, Railsback LB, Sheen S-W, Lundberg J. 1999. A high-resolution proxy record of rainfall and ENSO since AD 1550 from layering in stalagmites from Anjoohibe Cave, Madagascar. *The Holocene* **9**: 695–706.

Brooks PD, McKnight DM, Bencala KE. 1999. The relationship between soil heterotropic activity, soil dissolved organic carbon (DOC) leachate, and catchment scale DOC export in headwater catchments. *Water Resources Research* **35**: 1895–1902.

Genty D, Quinif Y. 1996. Annually laminated sequences in the internal structure of some Belgian stalagmites — importance for paleoclimatology. *Journal of Sedimentary Research* **66**: 275–288.

Genty D, Baker A, Barnes WL. 1997. Comparaison entre les lamines luminescentes et les lamines visibles annuelles de stalagmites. *Comptes Rendus de l'Academic des Sciences, Serie II Fascicule A: de la Terre et des Planets Sciences* **325**: 193–200.

Hornberger GM, Bencala KE, McKnight DM. 1994. Hydrological controls on dissolved organic-carbon during snowmelt in the Snake River near Montezuma, Colorado. *Biogeochemistry* **25**: 147–165.

Hurrell JW. 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. *Science* **269**: 676–679.

Koslowski G, Glaser R. 1999. Variations in reconstructed sea-ice severity in the western Baltic from 1501 to 1995, and their implications for the North Atlantic oscillation. *Climatic Change* **41**: 175–191.

Lamb HH. 1995. *Climate History and the Modern World*. Routledge: London.

Linge H, Lauritzen SE, Baker A, Proctor CJ. 2001. Luminescent growth banding and stable isotope stratigraphy in a stalagmite from northern Norway: preliminary results for the period AD 1734 to 955 BC. In *Proceedings, 13th International Congress of Speleology*, Brazil.

Manley G. 1969. Snowfall in Britain over the past 300 years. *Weather* **24**: 428–437.

Manley G. 1974. Central England temperatures: monthly means 1659 to 1973. *Quarterly Journal of the Royal Meteorological Society* **100**: 389–405.

Ming T, Xiaoguang Q, Tungsheng L. 1997. Microbanding of stalagmite and its significance. *Journal of Chinese Geography* **7**: 16–25.

Polyak VJ, Asmerom Y. 2001. Late Holocene climate and cultural changes in the southwestern United States. *Science* **294**: 148–151.

Proctor CJ, Baker A, Barnes WL, Gilmour MA. 2000. A thousand year speleothem proxy record of North Atlantic climate from Scotland. *Climate Dynamics* **16**: 815–820.

Proctor CJ, Baker A, Barnes WL. In press. A three thousand year record of north Atlantic climate. *Climate Dynamics*.

Qian W, Zhu Y. 2002. Little Ice Age climate from Beijing, China, inferred from historical and stalagmite records. *Quaternary Research* **57**: 109–119.

Qin X, Liu D, Tan M, Li T, Lu J, Gu Z, Lu H, Ding Z, Guo Z, Liu J, Nie G. 1998. Grey characteristics of microbanding of stalagmite in Shihua Cave, Beijing and its climatic signification (I). *Science in China (Series D)* **41**: 151–157.

Shopov YY, Ford DC, Schwarcz HP. 1994. Luminescent microbanding in speleothems: high resolution chronology and palaeoclimate. *Geology* **22**: 407–410.

Thornthwaite CW. 1955. *The Water Balance*. Drexel Institute of Technology Laboratory of Climatology Publications in Climatology, vol. 8, number 1. Centerton: New Jersey.

Wanner H, Pfister C, Brazdil R, Frich P, Frydendahl K, Jonsson T, Kington J, Lamb HH, Rosenorn S, Wishman E. 1995. Wintertime European circulation patterns during the late Maunder minimum cooling period (1675–1704). *Theoretical and Applied Climatology* **51**: 167–175.