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Applications of stalagmite laminae to paleoclimate reconstructions: Comparison with dendrochronology/climatology

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Abstract

Laminated stalagmites, observed in either ultra-violet or visible light or recognized via trace elements, are now widely recognized as a common deposition form. Annually laminated stalagmites should be expected in caves which have an overlying climate that has a strong seasonality, similar climate zones to where trees grow with distinct annual rings. Continuous laminated stalagmite chronologies (up to several thousand years) should be expected where some mixing of stored water occurs. Such stalagmites can be used to reconstruct climate, particularly through variations in lamina width. Such climate records would be relatively damped by mixing of 'event' water with 'stored' groundwater, constraining the amount of high-frequency climate signals contained in the stalagmite, but relatively long continuous lamina sequences permit the preservation of low frequency, centennial scale, climate signals. This contrasts with numerous tree ring climate records, which are frequently limited in preserving multi-centennial trends, due to the necessary removal of age related noise from relatively short tree segments. Laminated stalagmites and tree rings should therefore to some degree provide complementary climate information. Appropriate methods for compiling stalagmite layer chronologies and climatologies are presented.

1. Introduction

The rapidly expanding peer-reviewed published literature of paleoclimatic reconstructions derived from stalagmite growth layer thickness (e.g. Broecker et al., 1960; Genty, 1992, 1993; Baker et al., 1993; Shopov et al., 1994; Genty and Quinif, 1996; Genty et al., 1997a, 1997b; Brook et al., 1999; Proctor et al., 2000, 2002; Polyak and Asmeron, 2001; Baker et al., 2002; Burns et al., 2002; Tan et al., 2003; Frisia et al., 2003) have shown that a number of stalagmites certainly contain climate-respondent annual growth layers that then provide long continuous chronologies from which annual climatic information can be extracted. However, the work on stalagmite layers has not yet been widely utilized, and this may be partly due to uncertainty as to where to find long annually laminated records, or lack of established methodology. In 2002, Betancourt et al. statistically compared variations in layer thickness of a late Holocene stalagmite from Carlsbad Cavern, Southern New Mexico, USA (Polyak and Asmeron, 2001) with three independent tree-ring chronologies from the same region, and found no correspondence (Betancourt et al., 2002, see subsequent comments and replies by Baker and Genty, 2003; Asmerom and Polyak, 2004). Betancourt et al. (2002) suggested that laminated stalagmites should be held to the same rigorous standards in chronology building and climatic inference as annually resolved tree rings. This argument demands a serious consideration of the methodology used in high-resolution stalagmite/climate reconstruction work. Here we attempt to outline the methodology from which climatic reconstructions from stalagmite laminae have been or are being established in our research groups.

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2. Stalagmite lamina-chronology

The stalagmite growth layer, exhibited by luminescent or visible divisions produced by annual or seasonal meteorological cycles, provides a high-resolution time scale for paleoclimate research if it can be demonstrated to be annual. The methodology of building a chronology with stalagmite growth layers, a "stalagmite lamina-chronology", focuses on (1) the type of the lamina division, (2) when and why do various divisions form and (3) the methodology of establishing a lamina thickness chronology (LTC).

Three main kinds of stalagmite growth laminae from widespread global locations have been reported; these laminae types are not mutually exclusive and individual stalagmites can exhibit all three types of laminae within their growth, although this is uncommon. Firstly, luminescent laminae have been reported from NW Scotland (Baker et al., 1993; Proctor et al., 2000, 2002), England (Baker et al., 1999a), Belgium (Genty et al., 1997a), eastern Europe and N America (Shopov et al., 1994), Ireland (Ribes et al., 2000), N Norway (Linge et al., 2001), eastern China (Fig. 1a, Tan et al., 1999), and our unpublished data include the observation of luminescent laminae in stalagmites from Papua New Guinea. This luminescence, normally observed using conventional mercury light source UV reflected light microscopy (or exceptionally by transmitted laser excitation (Shopov et al., 2004) or confocal microscopy (Ribes et al., 2000)), is caused by the intrinsic fluorescence of natural organic matter, which causes the majority of UV excited fluorescence in cave calcites (Lauritzen et al., 1986; White and Brennan, 1989; Shopov, 1997). Luminescent laminae require regular fluxes of this luminescent material from the overlying soil onto the stalagmite. Secondly, laminae can be observed in calcite stalagmites using conventional transmission and reflection light microscopy (Fig. 1b), as reviewed by Genty (1993). Laminae observed under visible light have been reported from regions as diverse as New Mexico (Polyak and Asmeron, 2001), Brazil (Bertaux et al., 2002; Soubies et al., 2005), France (Genty, 1993, and references cited therein; Genty et al., 1997a, 1997b), Belgium (Genty and Quinif, 1996), Germany (Wurth et al., 2003), Italian Alps (Frisia et al., 2000), China (Tan et al., 1997), Oman (Burns et al., 2002), and our unpublished data include long visible lamina sequences from sites in Iran, Israel, Ethiopia, and

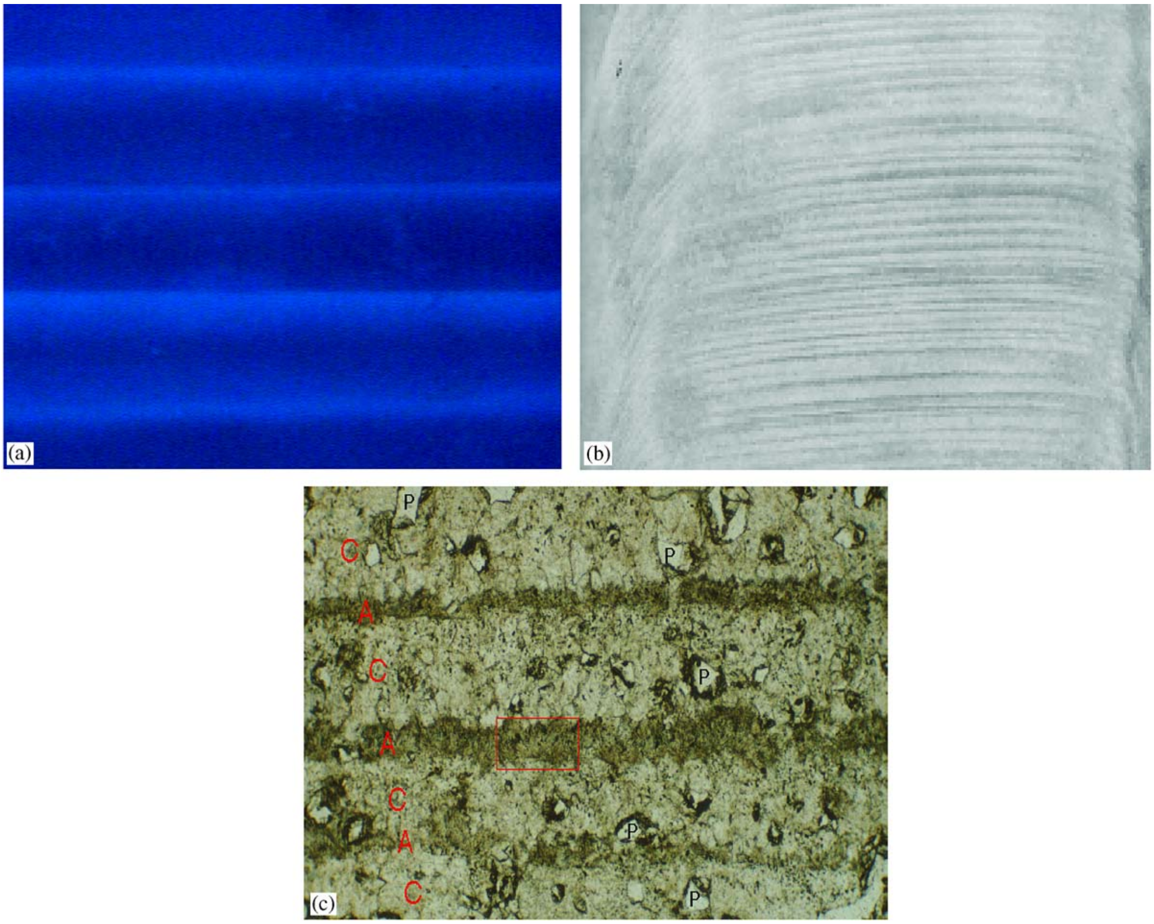

Fig. 1. Stalagmite growth layers. (a) China, luminescent excitation by UV light, (b) Belgium, with visible light, and (c) Botswana, alternating layers of calcite (C) and aragonite (A). Railsback et al. (1994) interpreted these to be annual couplets in which calcite represented the wet season and aragonite the dry season. 'P's indicate pore spaces. The area in the red rectangle is also shown a higher-magnification view in the website: http://www.gly.uga.edu/railsback/speleooatlas/Saimage0234.html.

Ireland. Visible laminae require a regular (often seasonal) alternation of the arrangement in space of crystals with a well-defined morphology (texture or fabric; Kendall and Broughton, 1978; Onac, 1997; Frisia et al., 2000). One description of laminae in hand specimen is an alternation from 'dark compact calcite (DCC)' to 'white porous calcite (WPC)' as defined by Genty (1992) and Genty and Quinif (1996) and can be formed by either regular alternations in dripwater chemistry or cave atmosphere. The precise controls on the formation of WPC and DCC are poorly understood, although there is a much better understanding of the crystal fabrics that form annually laminated stalagmites; an understanding of the formation mechanism of which can explain the conditions under which the crystallites in each laminae form (Frisia et al., 2000). Finally, alternations of aragonite and calcite growth layers have been reported, most notably from northwestern Botswana (Fig. 1c, ***Railsback et al., 1994). Again, the processes generating this lamina type are poorly understood: many factors have been implicated in the formation of aragonitic stalagmites (including temperature, drip rate and dissolved magnesium concentrations; see review in Frisia et al., 2002) and by inference calcite-aragonitic laminated stalagmites require such a threshold to be crossed with regular alternations. We have archived examples of these three types of stalagmite laminae from all over the world in our International Stalagmite Laminae Bank (http://www.gees.bham.ac.uk/collections/stalagmite-databank/search.asp).

The observation of regular laminae in stalagmites does not presume that they are annual in nature. Four methods of determining if the layers are annual have been reported.

(1) One method that has been widely reported is to compare the number of layer counts between well-dated layers. This might be by comparing radioisotope dates and the interval of time dated, through the difference between uranium–thorium age determinations (e.g. Baker et al., 1993), or radiocarbon age determinations (making the assumption of a constant 'dead' or geological carbon contribution, e.g. Broecker et al., 1960). The age error on uranium–thorium analyses determines the age range of stalagmites for which the annual nature of laminae can be confirmed: with a typical age error of around 1%, 500 laminae between 5000 ± 50 and 5500 ± 50 yrs BP can be demonstrated to be annual, but 500 laminae between $60{,}000\pm600$ and $60{,}500\pm600$ cannot. Similarly, the use of radiocarbon depends on a constant dead carbon proportion (which has shown to be typically 10–$15\pm5\%$ in Western Europe samples; Genty and Massault, 1997) and position on the radiocarbon calibration curve. An alternative radiometric methodology for use in modern samples is to compare the number of laminae with the ^{14}C bomb carbon signature which provides a useful marker of the early AD1960 s (Genty et al., 1998), or to use markers of a known event in the cave (such as building of tourist cave infrastructure, archaeological deposits of known age, or explosion like the one which occurred in the Postojna cave in 1943, Genty et al., 1998).

(2) The increasing number of observations of regular and rhythmic laminae in stalagmites in geographically widespread regions of the globe that have a strong surface climate seasonality suggests that annual laminae could be hypothesized to be the typical mode of deposition in such regions. In regions where there is a strong seasonal contrast of surface climate, either in rainfall amount (monsoon or low latitude climates affected by the ITCZ; laminated stalagmites include China, Oman, Ethiopia), a seasonal soil moisture excess (mid-latitude climates; laminated stalagmites including those from W Europe), or snowmelt (high latitudes; laminated examples include N Norway and alpine Italy), this climate signal may be transferred via either organic or inorganic natural tracers in the groundwater to the stalagmite. If stalagmites are sampled from relatively shallow (typically less than 30 m) depth, this would permit enough smoothing of this surface signal by mixing with stored groundwater to remove sub-annual 'event' signals, yet preserve the regular annual geochemical trace of surface climate in the cave drip water (for an understanding of karst dripwater hydrology, see Smart and Friederich, 1986; Vaute et al., 1997; Baker et al., 1997; Genty and Deflandre, 1998; Tooth and Fairchild, 2003; Baker and Brunsdon, 2003). Therefore, another test of the annual nature of laminae is the observation of drip waters in caves where laminated stalagmites are found, which cannot only determine if the layer is annual but also demonstrate how and when the layer forms. For example, the drip waters in Beijing Shihua Cave were analysed for dissolved organic carbon (DOC) concentration for a hydrological year, in an experiment designed to explain how and when the luminescent laminae shown in Fig. 1a form. The results show that there are seasonal variations in the DOC concentration in all drip waters. The DOC concentration peak from five sites all occur during the rain period in July (Fig. 2a, Ban et al., 2005) when there is hydrologically effective precipitation. A similar experiment measuring drip water luminescence of multiple drips over a hydrological year at the Brown's Folly Mine site in England (Baker et al., 1999b) also observed an increase in luminescent dissolved material during the period of hydrologically effective precipitation in autumn (Fig. 2b). These observations suggests that an annual flush of organic substances from the soil during periods of hydrologically effective precipitation form these laminae divisions, confirming that seasonal dry/wet shifts in climate zones as diverse as those in China and England can produce clear growth-layers and that the luminescent laminae are annual.

(3) A third test of the annual nature of laminae is to compare the observed lamina width with that theoretically predicted. Through the work of Dreybrodt (1980, 1981, 1988) and Baker et al. (1998) the factors that affect stalagmite growth rate are well understood; the significant determinants being, for a constant and close to atmospheric cave air pCO_2, the calcium ion concentration and

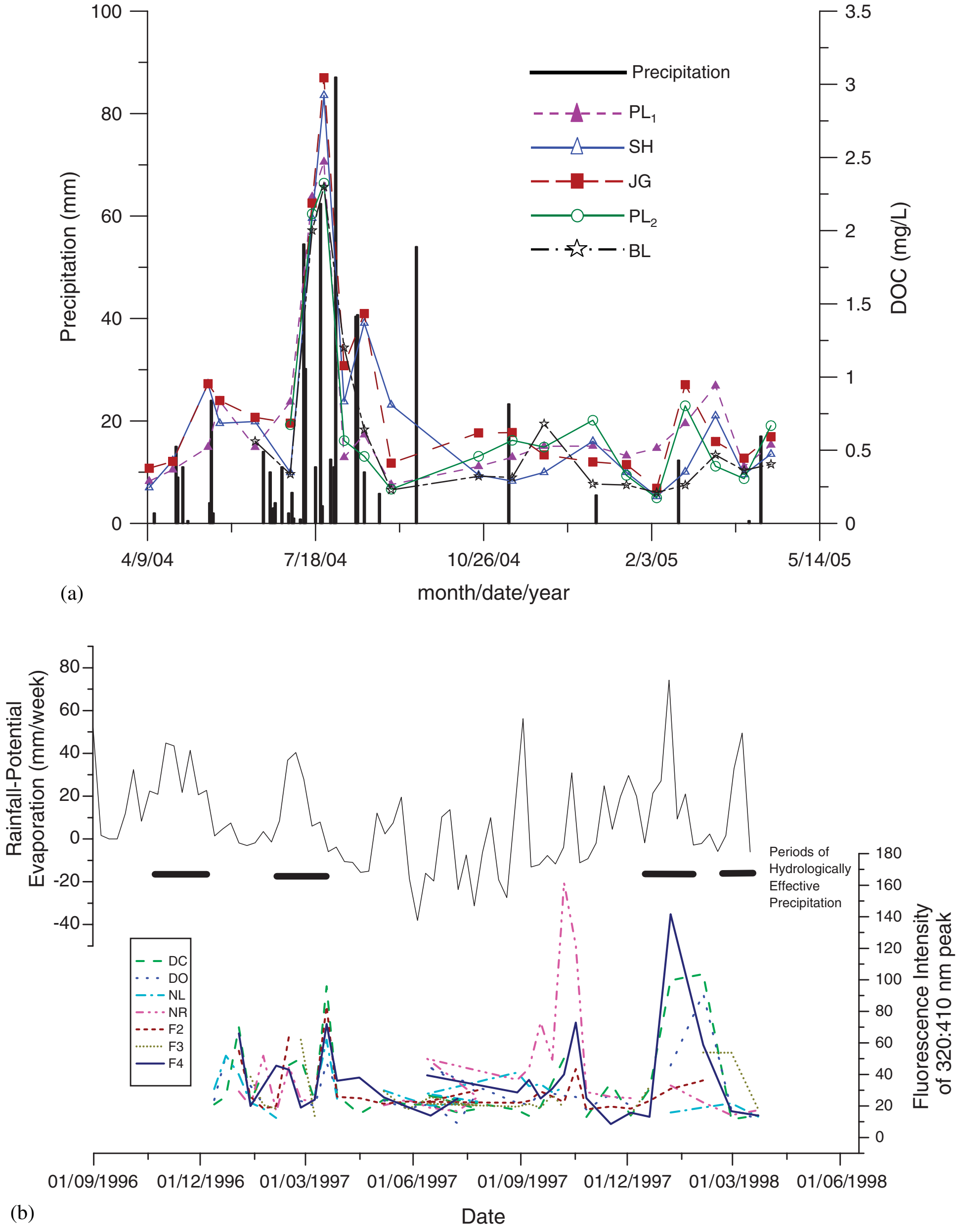

Fig. 2. The relationship between dissolved organic carbon and drip hydrology: (a) results of observing dissolved organic carbon (DOC) in drip waters at five points in Shihua Cave, Beijing, in 2004–2005. PL and PL2 are from the first level (closest to surface), JG at the second level, SH at the third level and BL at the fourth level; (b) dissolved organic matter luminescence of seven dripwaters in Brown's Folly Mine, Bathford, England in 1996–1998, compared to water excess and precipitation–evaporation (after Baker et al., 1999b). Subsequent calibration of luminescence intensity against DOC suggests a calibration of ~100 intensity units = 6 mg/l DOC.

the temperature of the drip water and the water supply rate (see Spötl et al., 2005) for a case where variable cave air pCO_2 is important. Baker et al. (1998) and Genty et al. (2001) demonstrate that there is a good correlation between observed, recent stalagmite growth rate and that theoretically predicted for six caves throughout Europe, with the principal determinant of growth rate being the calcium ion concentration. Therefore, assuming that the modern day drip waters can be related to those that are forming or have formed laminated stalagmites, measurements of calcium concentration of modern drip waters in caves where laminated stalagmites are present can also give an indication as to whether laminae are annual.

(4) A fourth test is to carry out in situ calcite growth experiments to recognize the annual formation of laminae observed in stalagmites. Fig. 3 shows the results of placing a tile up the surface of a sampled stalagmite in the Grotte de Villars, Dordogne: the tile was placed on the 22/8/1996 and removed on the 26/9/2000 and when sectioned demonstrates the presence of four annual visible laminae. Frisia et al. (2000) report similar experiments within the Grotta di Ernesto to confirm that laminae were annual.

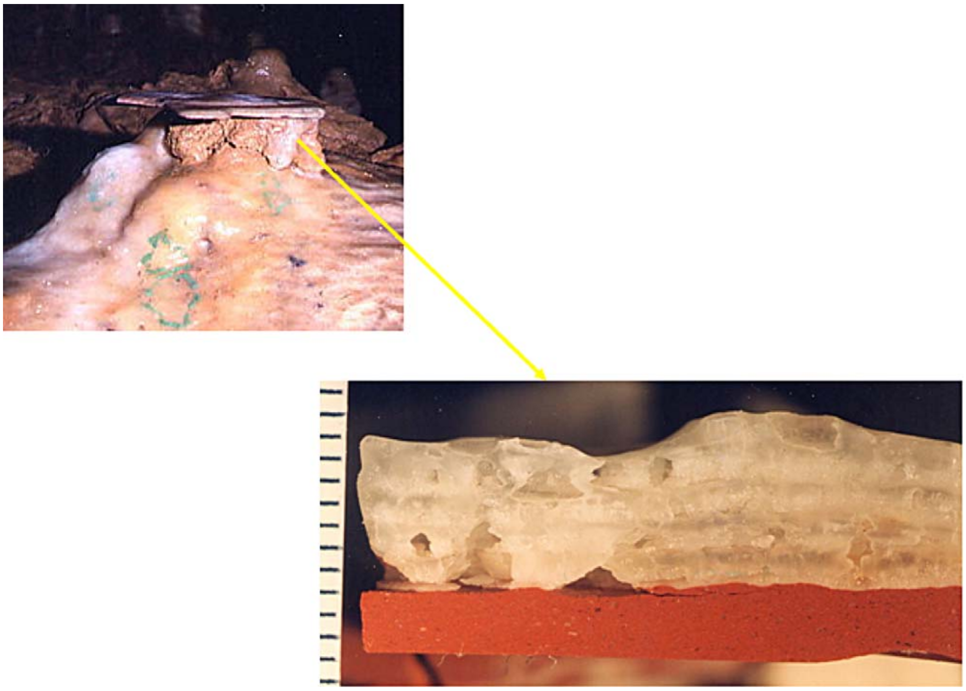

Fig. 3. Example of modern deposition experiment, Grotte de Villars, SW France, showing four visible laminae formed on a tile placed on a stalagmite for four years. Scale bar shows 1 mm intervals.

The development of a stalagmite lamina-chronology can only proceed if, in each case, the laminae can be confirmed to be annual. Additionally:

(1) The (annual) layer division has to be clearly visible (this is often achieved by adjusting image contrast and/or brightness using image analysis computer software). Although semi-automated and automated techniques to count laminae have frequently been discussed, these have at present achieved little success due to the low signal (lamina) to noise (inclusions, crystal boundaries, etc.) ratio in stalagmite images (certainly compared to tree ring methodologies). Our experience of manual lamina counting is that only several hundred laminae can be counted per day, which with replication and back-tracking along profiles has limited the number of published lamina records.

(2) Supra-annual or sub-annual layers (Fig. 4a and b) must be distinguished, if they exist, before establishing a chronology. The most direct way is to distinguish the nature (structure, shape, intensity) of the annual layers. For instance, we have found that the most notable characteristic of visible annual layers from northern China is their dark boundary (Fig. 5a) with a preceding very clear calcite layer; the dark boundary becomes bright (Fig. 5b) when moving the focus from the surface of the thin section into the sample because the dark boundary is not perpendicular to the focal plane, leading to increased reflected light, and determining the annual layer. In NW Scotland, although we observe thousands of years of regular luminescent laminae (Proctor et al., 2000, 2002), we also observed very occasional years with two laminae very close together, the first typically the most luminescent, and separated by a very thin horizon of amorphous dark material that could not be resolved at high magnification (Baker et al., 2002). At this site, the annual lamina is formed in autumn by the flushing of organic matter after the summer periods of soil moisture deficit, suggesting that the second less fluorescent lamina was formed in winter. By comparison with observational/station climate data, we could confirm that this second lamina was formed in years of severe cold, suggesting that it is a snowmelt or soil water thaw signal. Finally, in an Arctic stalagmite from N Norway, Linge et al. (2001) demonstrated from a TIMS uranium–thorium dated sample that statistically 1.4 laminae occurred each year. Here, the 'annual' lamina set was an intensely luminescent and regular lamina, hypothesized to be the regular spring snowmelt, which in some years this was followed by a weakly luminescent lamina formed in autumn in years where summer was warm enough to produce fresh organic matter and autumn mild enough for this to be transported to the groundwater system before the winter snowpack developed.

(3) Missing annual layers should not be commonplace. The most obvious sign of missing layers is the presence of a 'hiatus', which can be observed in polished or thin section though the identification of an erosion (dissolution) layer or through the deposition of detritus. Hiatuses can sometimes be determined and dated if the stalagmite is relatively young (~1000–10000 yrs BP, when age errors are less than the hiatus duration) and dating errors can be minimized (for example, in samples with high

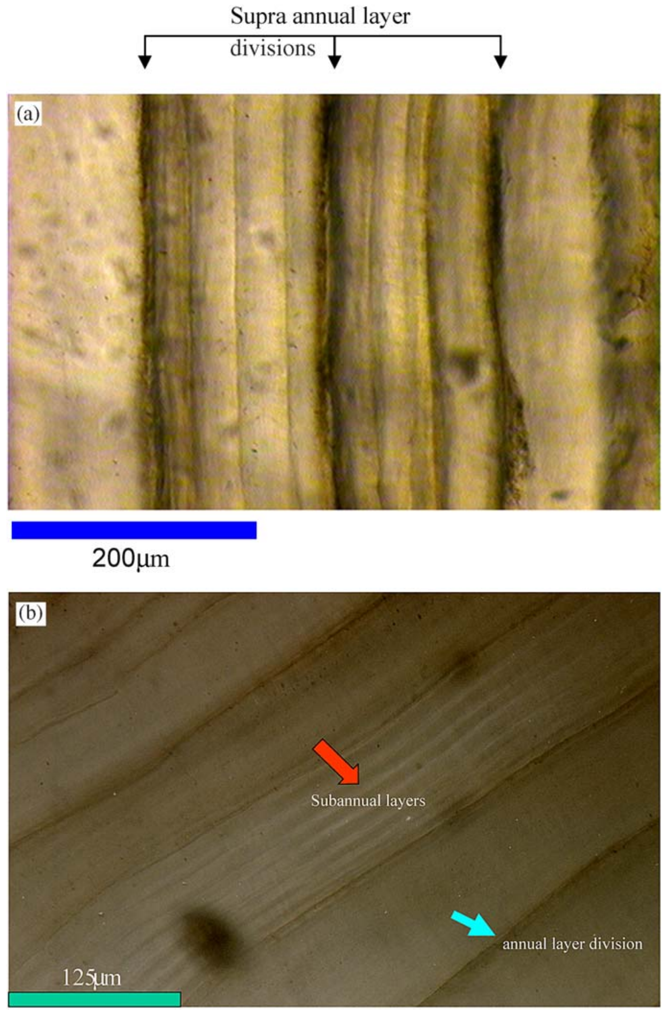

Fig. 4. (a) Three supra-annual laminae, easily observed with a low power objective lens under which the annual laminae cannot be observed, but which are much darker than the annual laminae (example from Water cave, Benxi, Liaoning Province, China). (b) Sub-annual laminae, which are common in stalagmites from northern China.

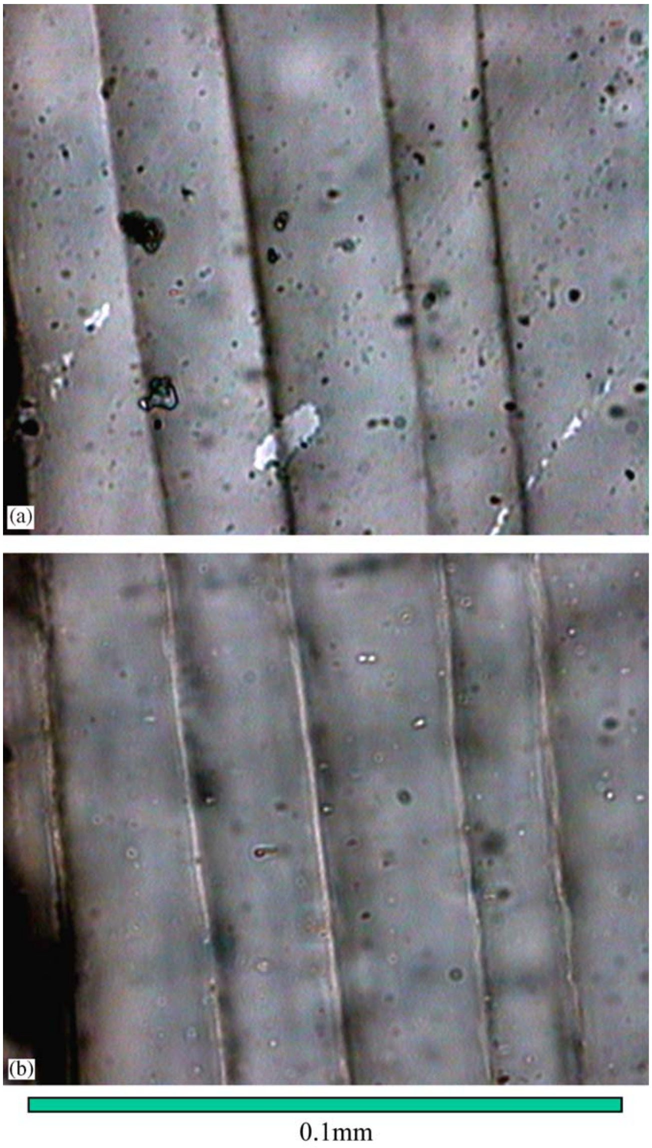

Fig. 5. Distinctive character of annual laminae in stalagmites from northern China (a). By shifting focus from the surface of the thin section into the sample (note the clear spots on the surface in *a* become indistinct in *b* after shifting focus deeper), the paired dark/light lamina becomes apparent (b).

concentration of uranium-238, and low concentration of thorium-232). Alternatively, with replicated lamina chronologies that would permit cross-correlation, wiggle-matching between stalagmites can be attempted. For instance, in annually layered stalagmites from Uamh an Tartair, NW Scotland, one stalagmite (SU-96-2) has hiatuses which were clearly visible with the presence of luminescent laminae (Fig. 6). Wiggle matching with other continuously laminated stalagmites in the cave allowed this hiatus to be identified to have lasted up to 95 years (in other words, 95 annual layers are missing, but some of which could have been deposited and then subsequently corroded by aggressive drip waters) at about 3300 yrs BP, but by needing to wiggle match and having to use uranium–thorium analyses to tie in this matching we have introduced several decades of age error in the layer count chronology. In contrast, some hiatus-like features in stalagmites might just be event surfaces with no gap in deposition. For example, in southern China where the rate of calcium carbonate precipitation in caves is usually high, we once dated two sides of the surface along which the stalagmite had cracked and which was possibly a hiatus. The ages were 471 ± 7 yrs and 474 ± 13 yrs (before 2000AD, see Table 1, WH9801-1, WH9801-2 and Fig. 7, stalagmite from Lipu, Guangxi, China); the two dates show possible continuous growth. Finally, a lamina might not form over the whole of a stalagmite surface if the water film does not cover all top surface of the stalagmite while calcite precipitates, this might be due to the formation of a splash cup, changes in the location of the drip sources (for example along the length of a drapery), changing mechanisms of transport of ions to growth sites, etc. Therefore it is important to count as close to the centre of the stalagmite as possible, to duplicate the count and to check all of the section for such features (see Fig. 8).

The issues of missing laminae and discontinuous deposition of stalagmites can produce significant error in constructing long and continuous lamina chronologies. Issues of chronology derived from the errors associated with uranium–thorium analyses on discontinuous lamina records are discussed in detail in Asmerom and Polyak (2004) and Betancourt et al. (2002). Similar limitations are reported from tree ring measurements, where missing or false (double) rings can occur in very cold and dry environments (Esper et al., 2002a, 2003b). In this case, any error in the estimation of the date of a tree ring can be resolved by cross-dating techniques (Douglass, 1929), something which is less easy to obtain in stalagmite records due to cave conservation issues. Successful cross dating, however, requires an underlying signal common to the trees within a site (e.g. temperature variations) and between sampling sites (e.g., Esper and Gärtner, 2001). Similar cross dating can be expected in stalagmite sequences by using stalagmites that have been sampled at a suitable depth such that mixing of event water with old storage water occurs (typically less than 30 m below the surface), buffering the stalagmite from short lived extreme surface climate events such as droughts or freezing, as shown by continuous lamina records of over 1000 yrs from Scotland (Proctor et al., 2000). However, if surface climate conditions become marginal for stalagmite deposition for longer time periods (such as too arid in the late Holocene in semi-arid New Mexico, USA, Polyak and Asmerom, 2001) or too cold in the 'Little Ice Age' in Artic Norway (Lauritzen and Lundberg, 1999)), unavoidable non-depositional hiatuses are likely to occur. Alternatively, changes in surface or cave climate or drip water chemistry could lead to an alternative threshold response, where a stalagmite regularly alternates between laminated to unlaminated growth phases, with samples having 'bundles' of decades or centuries of annual laminae as often observed in samples from SW France (Genty et al., 1995). Stalagmites that form in warm and wet temperate climates optimal for fast

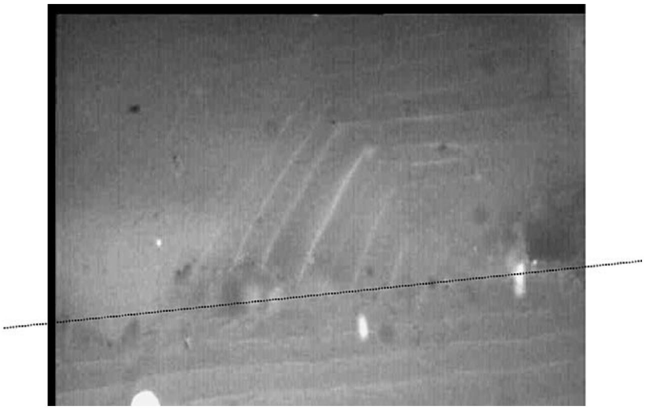

Fig. 6. Example of hiatus from stalagmite SU-96-2, Assynt, NE Scotland, observed under blue light excitation and × 20 magnification. Position of hiatus is labeled; note the annual luminescent laminae and the smaller crystals in the new growth phase. The length of the hiatus is estimated to be ~95 yrs at ~3300 yrs BP (Proctor et al., 2002).

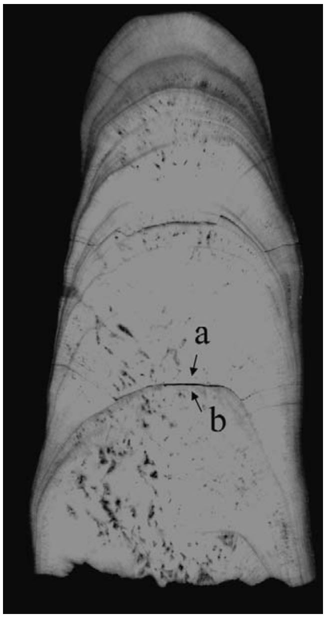

Fig. 7. Stalagmite section from Lipu, Guangxi, China, showing hiatus-like features. The two sides of the surface (*a* and *b* marked on the section), along which the stalagmite had cracked, are dated and shown to be of the same age.

Table 1
Results of uranium–thorium dating of some stalagmites from China

Sample no.	^{238}U (ppb)	^{232}Th (ppt)	$\delta\ ^{234}U^{a}$ (measured)	$^{230}Th/^{238}U$ (activity)	^{230}Th age (year) uncorrected	^{230}Th age (year) corrected	$^{234}U_{Initial}{}^{b}$
WH9801-1	3188 ± 3	564 ± 22	165.8 ± 0.7	0.00507 ± 0.00007	476 ± 6	471 ± 7	166.1 ± 0.7
WH9801-2	2479 ± 11	889 ± 15	160.7 ± 4.2	0.00512 ± 0.00013	483 ± 13	474 ± 13	160.9 ± 4.2
PH9901-1	105.2 ± 0.1	346.8 ± 6.8	161.3 ± 1.6	0.02613 ± 0.00268	$27670+325/-324$	$27588+327-326$	174.4 ± 1.7

$\lambda_{230} = 9.1577\times10^{-6}\,y^{-1}$, $\lambda_{234} = 2.8263\times10^{-6}\,y^{-1}$, $\lambda_{238} = 1.55125\times10^{-10}\,y^{-1}$.

[a] $\delta^{234}U = ([^{234}U/^{238}U]_{activity}-1)\times1000$.

[b] $\delta^{234}U_{initial}$ was calculated based on ^{230}Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured}\times e^{\lambda_{234}\times T}$. Corrected ^{230}Th ages assume the initial $^{230}Th/^{232}Th$ atomic ratio of $4.4\pm2.2\times10^{-6}$. Those are the values for a material at secular equilibrium, with the crustal $^{232}Th/^{238}U$ value of 3.8. The errors are arbitrarily assumed to be 50%.

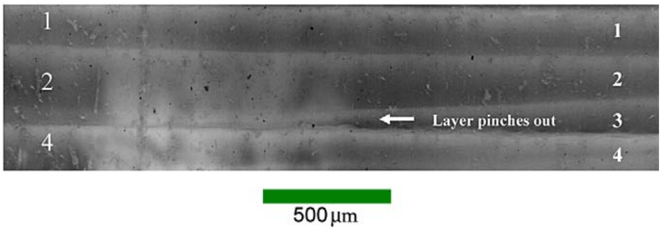

Fig. 8. A group of luminescent laminae show that one lamina (number 3 on the right) pinches out. The stalagmite is from Beijing Shihua Cave. The image has been converted from luminescent light to grey scale for more clarity.

stalagmite growth might be expected to lack such discontinuous lamina formation and longer duration hiatuses.

An accurate layer chronology is therefore more likely to be derived from stalagmites without any hiatuses, and therefore more likely to be from a suitable depth such that the stalagmite is buffered from short duration hydrological extremes, as well as from a climate zone warm and wet enough to sustain deposition. Ideally the stalagmite should be active when it is collected, as this will provide a precise start date as opposed to a floating chronology constrained by uranium–thorium analyses. The latter cannot be assumed by sampling a stalagmite where there is an observed active drip source; for example in Hulu Cave, Jiangsu Province, China, a small stalagmite fed by drip water and with no sign of dissolution on its top was sampled but found to have an age of 27,588 ± 327 yr (before AD1999, see Table 1, PH9901-1, TIMS-U-Th date). Placing a glass thin section on the stalagmite to be sampled for one month or more is the best way of determining whether the precipitating of calcite is occurring. Finally, the accuracy of any resultant lamina count must be reported. For example, Proctor et al. (2000) report the uncertainty introduced by the presence of occasional double bands as discussed earlier, quantified as a counting error of <20 years over 1000 yrs ($\sim$2%). Comparisons between duplicated lamina counts both within and between samples can also provide an estimate of counting error, as can comparison of counts between operators.

3. Stalagmite lamina climatology

If the change in the layer thickness can reflect surface climate variations, as discussed in Dreybrodt (1980, 1981, 1988), Baker et al. (1998), Genty and Quinif (1996), and Genty et al. (2001), then the methodology of quantitatively reconstructing climate from stalagmite growth layers can be defined as a "stalagmite lamina-climatology." Published examples where a quantified climate signal has been obtained from stalagmite lamina thickness include Brook et al. (1999), Proctor et al. (2000, 2002), Tan et al. (2003), Frisia et al. (2003) and Smith et al. (2006). Each record has a different sensitivity to surface climate due to the many factors that determine stalagmite growth rate, each of which have different sensitivity to surface climate forcing processes. Indeed the lamina thickness climatology (LTC) may be sensitive to seasonal or annual surface precipitation or temperature, similar to tree ring sensitivity, although the latter usually show only a spring or summer response maximum whereas stalagmites may respond to any season, depending on forcing mechanism. Individual stalagmites may have a different sensitivity to surface climate, depending on the relative amounts of storage and fissure flow components. It is important to recognize that although stalagmites within a cave may show similar LTCs (e.g. Proctor et al. (2002) demonstrate cross-correlations between two stalagmites SU-96-1 and SU-96-2 at $r = 0.32$ over a 1920 year period), a lack of correlation between stalagmites suggests different sensitivities to climate, due to different filtering of the climate signal by the karst system. Therefore, calibration of the LTC with instrumental or historical monthly observed data (rather than annually averaged data) is very useful to understand the precise climate sensitivity of any one stalagmite. Proctor et al. (2000) demonstrate through calibration against instrumental climate data that growth rate is strongly dependent on mean annual precipitation, and weakly dependent on temperature at their NW Scotland site, due to growth rate being primarily controlled factors that affect by CO_2 production in the overlying peat soil. Frisia et al. (2003) demonstrate that, in northern Italy, the lamina growth rate correlates best with instrumental winter temperature series, because in Apline settings the winter temperature controls the duration of soil microbial activity and period of water infiltration due to the winter freezing of the soil.

The assumption that the annual layer thickness represents the amount of annual deposition for a stalagmite when using the layer thickness as a climatic proxy is best if the stalagmite has a typical 'candlestick' shape. We therefore suggest the use of columnar stalagmites for climate reconstruction as much as possible. Even with this ideal specimen shape, often the annual layer thickness at the early growth stage are a product of deposit geometry (for example, the angle of slope upon which the stalagmite is growing, or movement or slumping of the growing stalagmite into soft sediment), rather than drip water quantity or quality. Fig. 9 shows an example of growth trends early in stalagmite growth and the area for which lamina thickness chronologies can still be obtained. Due to the complexity of many basal growth stratigraphies, thickness climatologies should not be constructed except in some exceptional cases where the basal growth trend is predictable and can be removed by a fitting function (e.g. polynomial) so that the basal laminae can be used to reconstruct climate (Tan et al., 2002, 2003). Additionally, over the whole period of stalagmite growth, lamina thickness may demonstrate a long term trend of either increasing or decreasing growth rate. For example, for the last 1000 years a stalagmite in NW Scotland has a trend of increasing growth rate through time (Proctor et al., 2000), whereas that from Beijing over the same time period has a

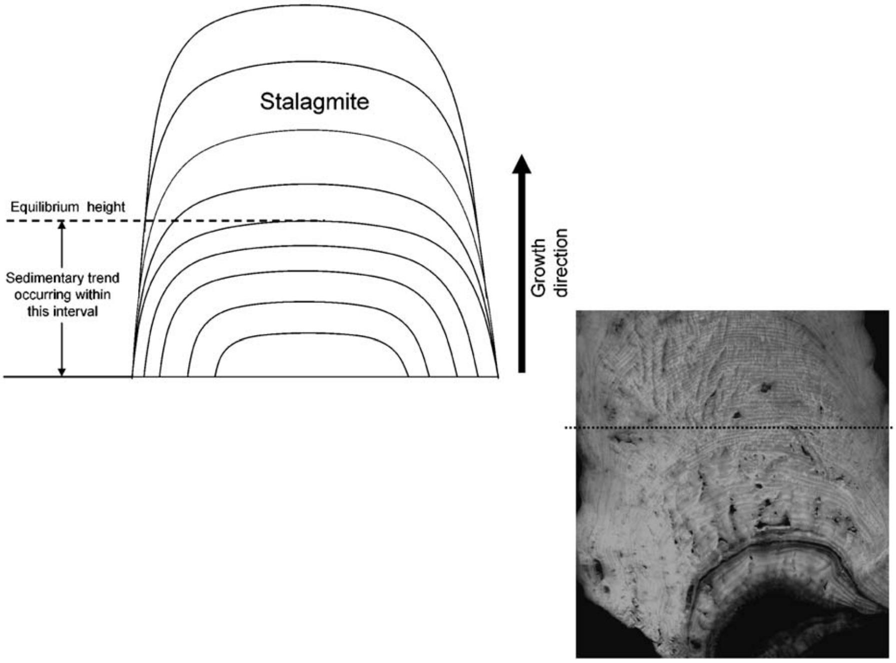

Fig. 9. Example of sedimentary trends formed at the early sedimentary stage in stalagmites and which relate to the growth surface. Horizontal dotted line indicates the equilibrium height: below it growth rate trends are not produced by climate and should be removed. Real sample from Xianren Cave, Puzhehei, Yunnan.

decreasing growth rate trend (Tan et al., 2003). Such trends might be due to local or regional surface climate trends, or related to long term changes in stored groundwater characteristics that can make up a significant proportion of the drip water. Care has to be taken to understand the process(es) generating these long term trends, before one can be confident in removing (or keeping) the low-frequency component within the dataset.

In more irregularly shaped samples, we frequently observe a within lamina variability of thickness that is greater than the between lamina variability. Although this is not a problem for determining a lamina chronology, it limits the use of these stalagmites in lamina-climatology. The data derived from any one measuring track may not represent the mean amount of annual deposition (Fig. 10) and measurement should proceed along several routes and their average can be used. Errors on the thickness measurement of each layer should also be supplied. The magnitude of measurement error depends on both lamina thickness and microscope resolution. Tan et al. (2003) for example claim absolute measurement errors of ±1.25 μm (using 20 × objective lens).

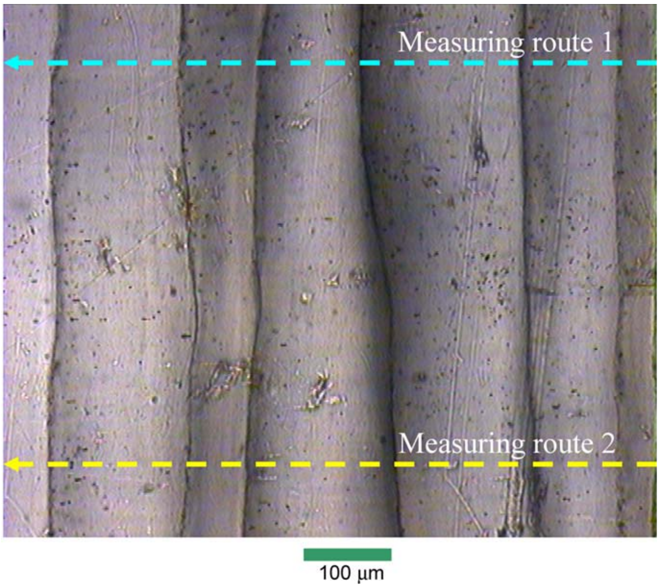

Fig. 10. Image of laminae that shows that any one lamina may not be constant in thickness within a measuring area; the result of measuring routes 1 and 2 are significantly different. Measuring laminae should be along several routes, and only the average data is correct. The stalagmite is from Beijing Shihua Cave, China.

The LTC need not have a linear correlation with surface climate. For example, in the data of Proctor et al. (2002) there are sustained periods of low growth rate that plateau at about 10 microns/yr and significantly greater inter-annual growth rate variability at high growth rates. Such a plateau at low growth rate might be expected if this reflects a non-linear response to surface climate; at this site soil CO_2 production is limited by peat water table depth, once fully saturated additional rainfall will not affect growth rate. In contrast, Frisia et al. (2003) has a LTC that appears to have a non-linear response to surface climate, oscillating between fast and slow growth rates. Fig. 11 shows that a non-normal stalagmite laminae width distribution is typical, with greater inter annual laminae width (and therefore climate sensitivity) at lower growth rates for most samples. If universally observed in stalagmite lamina width climatologies, then this suggests

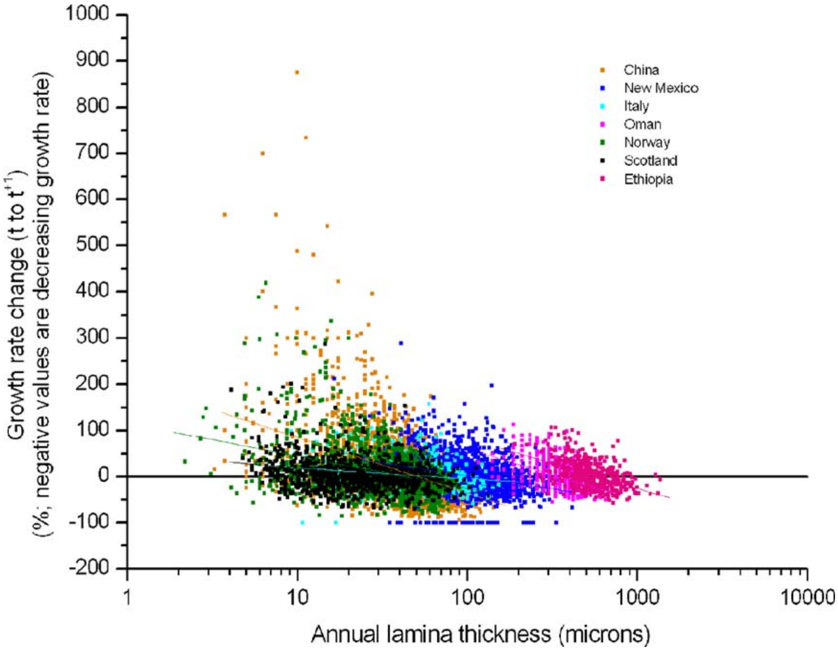

Fig. 11. Relationship between inter annual lamina width change (as a percentage of the previous years' lamina width) against lamina width for seven published or unpublished laminated stalagmite series (Scotland; Proctor et al., 2000; Norway; Linge et al., 2001; New Mexico; Polyak and Asmeron, 2001; Oman; Burns et al., 2002; China; Tan et al., 2003; Italy; Frisia et al., 2004; Ethiopia; Umer and Baker, unpublished data). Note that the continuously laminated records never decrease their lamina width from one year to the next by more than the previous years' growth rate, due to the buffering effects of stored water, but that at low lamina widths, rapid growth rate increases can occur, suggesting the gain of an event water component.

that data treatment should be considered only after careful exploration and understanding of the lamina width data.

4. Comparison with dendrochronology/climatology

Stalagmite LTC may therefore contain a high-resolution climate signal that could be a function of annual and/or seasonal temperature and/or precipitation. Given the complex relationship between stalagmite growth rate and climate, each stalagmite and each cave must be monitored and calibrated to determine the precise climatic response. Since precipitation is relatively inhomogenous, should a relationship with precipitation be observed, then any climate reconstructions are likely to be local precipitation reconstructions (unless there is a strong correlation between local precipitation and a regional climate phenomena such as the North Atlantic Oscillation, Proctor et al., 2000). In contrast, surface temperature is more spatially homogenous and therefore it should be possible to compare the stalagmite LTC with regional temperature reconstructions

LTC should also be comparable with contemporaneous tree ring width (density) chronologies (RWC) from the same region if their growth is controlled by the same climate-related factors (Betancourt et al., 2002). The extensive coverage and precise dating offered by tree ring variables make them an invaluable source of high-resolution proxy data. There exists a wealth of literature concerned with the intricate relationship between tree rings and annual climate, across varying temporal, high frequency (Briffa, 2000; Frank et al., 2005) to low frequency (Briffa et al., 2001; Esper et al., 2003b) and spatial, localized (D'Arrigo and Jacoby, 1991; Büntgen et al., 2005) to hemispheric (Briffa, 2000; Esper et al., 2002b; Briffa et al., 2004; Cook et al., 2004b) scales. In addition, the number of samples which comprise a single chronology, and the vast network of tree ring chronologies, enable averaging of intra- or inter-site data, which minimizes the local effects and biases of individual trees, as opposed to speleothem proxies where generally climatic information is derived from a single sample. This suggests that it may be more appropriate to seek commonalities between reconstructions from tree rings and those from a suite of speleothem LTCs at a larger spatial scale (e.g. Northern Hemisphere).

It should be noted that there are important differences, as well as similarities, in the way in which stalagmites and trees preserve a surface climate signal; these have been summarized in Table 2. Most notable is the possibility of obtaining long (10^2–10^3 year) continuous stalagmite lamina records, that by the nature of the smoothing introduced during groundwater mixing, are capable of preserving low-frequency climate information at annual resolution, as opposed to tree ring records for which there are many more samples that are better at preserving high-frequency climate variability but which are limited in their ability to retain climate variations on a multi-centennial time scale (Esper et al., 2004). The biological age trend poses a major impediment to the progress of establishing low-frequency oscillations within dendroclimatological time series

Table 2
Comparison of the LTC and the RWC for their similarities and discrepancies

	Stalagmite lamina thickness climatology (LTC)	Tree ring width climatology (RWC)
Similarity between the LTC and the RWC	In addition to annual lamina, supra-annual layer and sub-annual laminae are possible.	In addition to annual rings, false and missing rings are possible.
	Sensitive to both rainfall and temperature, but not for the annual average in most cases.	Sensitive to both rainfall and temperature, but not for the annual average in most cases.
	Depending on hydrology, distinctive event horizons (detrital layers, etc.) can be used to tie records or to compare with other climate proxies.	Exceptionally narrow or wide rings ('pointer years') can be used to tie records or to compare with other climate proxies.
	Amplitude of any reconstruction is less than that of observed series.	Variance of mean chronologies is generally reduced in comparison to individual measurement series.
Discrepancy between the LTC and the RWC	A sedimentary growth rate trend is often present (either an increase or decrease), and might be removed.	A biological growth trend of decreasing ring widths (or densities) is generally present, and needs to be removed before chronology development.
	Depending on hydrology, likely to show non-linear relationship with surface climate, especially at periods of slow growth.	Samples from one site have similar correlation with a surface environmental factor, it is thus more suited to cross-dating.
	Samples from one cave may have different correlations with surface climate, it cannot be assumed that all samples can be cross-dated.	Mechanism of annual cycle correlates with the change in density of seasonal wood.
	Multiple processes cause an annual cycle i.e., annual layers can be formed by DOC flushing, by calcite/aragonite interlayers, etc.	
	Contains low-frequency signal, high-frequency signal smoothed by groundwater mixing.	Low-frequency signal is difficult to preserve, and frequently lost during the process of individual tree-ring standardization (applied to relatively short segments).
	Age of the topmost layer is uncertain unless actively fed by dripwater.	Age of any ring, from both recent and historic material, can be determined via cross-dating techniques.

(Briffa et al., 1996; Esper et al., 2003b). The removal of this non-climatic trend using traditional curve-fitting procedures, together with the inability to extract climate signals at periods exceeding the mean length of the sample series used to derive the chronology, the 'segment length curse' (Cook, 1985), incurs a loss of long term climatic information, and as such, the retention of low-frequency behaviour in RWCs has become a recent focus of dendroclimatological research (Briffa et al., 2001; Esper et al., 2002a, 2003a). The development of 'composite detrending methods', such as regional curve standardization (Briffa et al., 1996; Esper et al., 2003b) or age-band decomposition (Briffa et al., 2001), have been used successfully to produce low-frequency climate reconstructions. It is the various methods of processing tree ring data to retain low-frequency variability are suggested to be responsible for the differences in amplitude displayed in northern hemispheric temperature reconstructions (Cook et al., 2004a; Esper et al., 2004), in addition discrepancies between the procedural choices for the standardization and calibration of various large scale reconstruction data can have a significant effect upon the amplitude displayed by the temperature reconstruction (Esper et al., 2005). Comparisons between stalagmite reconstructions and tree ring reconstructions may reveal whether methods of retaining low-frequency behaviour in dendroclimatological series are successful, and may assist in the refinement of estimates of the temperature amplitude during pre-industrial times.

Differences between stalagmite and tree ring series are reflected in the statistical methods that can be used. Stalagmite time series show evidence that annual growth behaviour is strongly coupled to the deposition rate in the preceding years (Qin et al., 1999). This autocorrelation affects several statistical methods including the significance of regression techniques by violating assumptions on independency, and thereby reduces the degrees of freedom in such calculations. In dendroclimatology, this problem is addressed, for example, via the application of autoregressive models to remove biological persistence from the data. Resulting pre-whitened timeseries display equal variance across all frequencies, and are suitable for statistical climate signal detection (Cook, 1985). Application of such methodology and calibration, however, involves analyses of the autocorrelation structure of the target climatic data which itself might contain red noise variance (e.g. temperature), i.e. removal of persistence from the proxy records might limit the ability to meet the full spectrum of the target instrumental data. In contrast, the persistence displayed by speleothems could be an indicator of storage processes within the soil and epikarst zone, as suggested by the distinct lack of memory in climatic time series, and hence may contain information relating to climate in preceding months/years. Therefore an evaluation of the importance of this information is required to assess whether the removal of autocorrelation is appropriate.

Long water residence times within the soil and epikarst zones may have the additional effect of damping high-frequency variability; implying that low-frequency behaviour may be more easily extracted from the stalagmite time series. This could prove invaluable due to the heightened interest in long term variability and the problems associated with extracting this information from tree rings. Indeed, spectral analyses of a temperature reconstruction from a Chinese stalagmite revealed centennial scale temperature fluctuations (Tan et al., 2003). Tan et al. (2003) compare the relationship between the climate of Beijing and of the Northern Hemisphere (NH). So although there is no temperature-dependent tree ring based RWC in Beijing, we can use the NH tree-ring/summer-temperature series (Briffa, 2000) to test the Beijing stalagmite LTC. Cross wavelet analysis was used to examine the covariation of the two time series at varying time scales (Fig. 12). This clearly demonstrates that the coherent structure of the two series is dominated by the low-frequency domain, with very limited covariation displayed at periods less than 100 years compared with the significant band of stationary power at periods greater than this. This comparison indicates that the low-frequency temperature signal is contained by the long Beijing LTC, which agrees with the recent work of Moberg et al. (2005), who reported a multiple high- and low-resolution climate reconstruction over the past 2000 years for the NH which included both speleothem lamina and tree ring proxies (including the Beijing stalagmite record which contributes 5.2% of the low-frequency component of the reconstruction), although Moberg et al. (2005) used only the lower-frequency component in the final chronology. This result thus suggests that stalagmite laminae have a great potential to become a link between high-resolution records that vary in their preservation of high and low-frequency climate signals. The presence of undesirable statistical characteristics within LTC time series need to be tackled before this link can be made.

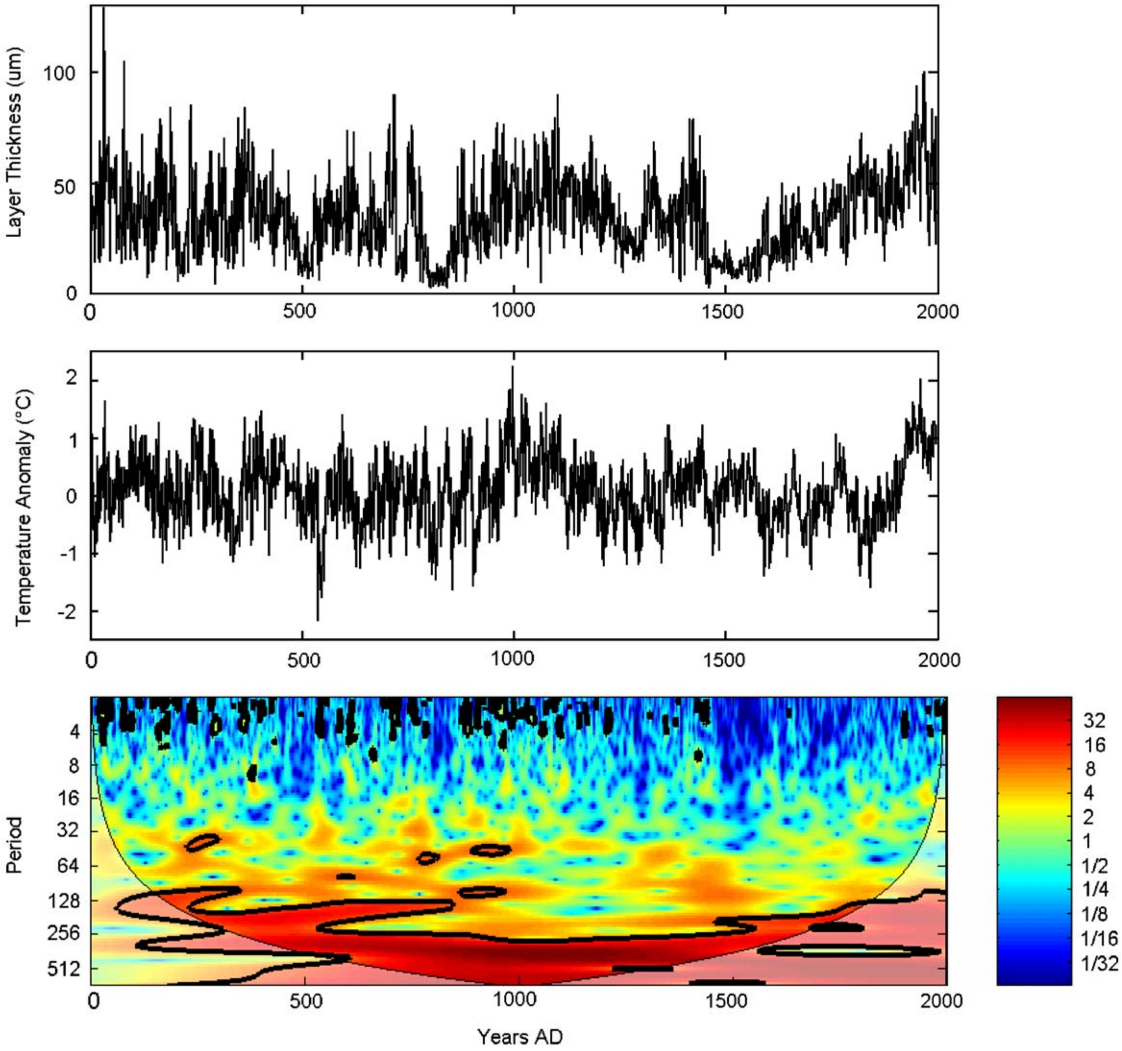

Fig. 12. Testing Tan et al. (2003) LTC (red) with Briffa's NH summer temperature (blue) reconstructed by tree rings (last 2000 years). The growth trend has been removed from the LTC. Data from: www1.ncdc.noaa.gov/pub/data/paleo/speleothem/china/shihua_tan2003.txt and http://www.cru.uea.ac.uk/cru/people/briffa/qsr1999/. Cross wavelet and wavelet coherency Matlab software courtesy of A Grinsted, available from: http://www.pol.ac.uk/home/research/waveletcoherence/download.html.

5. Conclusion

Stalagmite laminae must be used more frequently and effectively in paleoclimate reconstruction, both as a chronology for other proxies or as a directly useable ring lamina width climate proxy. A basic issue for stalagmite lamina-climatology now is to precisely understand the relationship between growth rate and surface climate and environmental conditions, so that further laminated sequences can be discovered and so that we can develop further climate-respondent LTCs. Process based (modern cave monitoring) and multi parameter (both different proxies within stalagmites as well as between different climate proxies) studies are essential in this regard and are being successfully applied to other climate proxies (Baumgartner et al., 1989; Lough, 2004). A second issue is the need to develop 'rules' or reporting conventions for future papers using annual speleothem lamina for climate reconstructions. For example, these should include: (a) reporting the number of transects counted for each given time period and the standard deviation of those measurements, (b) reporting the reproducibility of the replicated annual layer identification and measurement between different researchers, (c) report calibration statistics with local climate parameters, (d) fully reporting U/Th statistics used for verifying hypothesized annual laminations, (e) providing a full description of cave and subsurface hydrology, (f) reporting and interpreting the processes explaining any correlation (or lack of it) between lamina widths of overlapping speleothems, (g) fully describing and providing the rational for any normalization/detrending procedures. Similar reporting rules in dendrochronology serves that community well, allows the quality of any chronology to be evaluated by others, and would provide the same opportunity for stalagmite palaeoclimatology.

Laminated stalagmites appear to be common in caves where there is strong seasonality in the overlying climate, with modern laminated samples correlating with cold or temperate climates with seasonality in temperature and/or rainfall (correlating with Köppen climate zones Bs, Bw, Cs and Cf). With additional samples, it should be possible to develop cross-dating methods if it is possible to demonstrate that the thickness of the growth layers of different stalagmites from the same cave, or from stalagmites from different caves, show the same growth rate trends. Given that different stalagmites within one cave can show a different climate response due to differences in their hydrological connection to the surface, a beneficial concept is to consider 'species' of stalagmite that potentially have similar hydrological connections (e.g. soda-straw fed candlestick stalagmites may be more likely to have more storage (low frequency) signal than curtain fed, broader stalagmites). Smith et al. (2006) demonstrate that low-frequency trends in growth rate between caves can correlate with large scale (northern hemisphere temperature) climate, demonstrating the potential for lamina width based climate reconstructions. The differing nature of speleothem time series compared to those of dendrochronology make cross comparison desirable, particularly since both laminated stalagmites and trees with rings appear likely to occur in the same climate zones. Although one elegant solution to the comparison of high-frequency climate variability found in tree rings compared to low-frequency stalagmite laminae can be found in Moberg et al. (2005), useful low-frequency variations in RCS detrended tree-ring chronologies should not be excluded from larger scale averages. The derivation of a dimensionless stalagmite LTC series, similar to those used in dendroclimatology, may offer a potential solution that can assist in the minimization of the effects of autocorrelation, non-stationarity and non-linearity within the time series.

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