Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone

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ABSTRACT

A severe drought in parts of low-latitude northeastern Africa and southwestern Asia ~4200 yr ago caused major disruption to ancient civilizations. Stable isotope, trace element, and organic fluorescence data from a calcite flowstone collected from the well-watered Alpi Apuane karst of central-western Italy indicate that the climatic event responsible for this drought was also recorded in mid-latitude Europe. Although the timing of this event coincides with an episode of increased ice-rafted debris to the subpolar North Atlantic, the regional ocean-atmosphere response seems atypical of similar Holocene ice-rafting events. Furthermore, comparison of the flowstone data with other regional proxies suggests that the most extreme part of the dry spell occurred toward the end of a longer-term climate anomaly.

Keywords: speleothems, Holocene, drought, geochemistry, Italy.

INTRODUCTION

The quasi-periodic nature of millennial-scale Holocene climate changes was first recognized in ice-rafted debris (IRD) in subpolar North Atlantic sediment cores (Bond et al., 1997). IRD event 3 (Bond et al., 2001), dated as ca. 4200 yr B.P. (4.2 ka), is of considerable interest because it coincides with a period of severe disruption to ancient civilizations in southwestern Asia and northeastern Africa (Hassan, 1997; Weiss et al., 1993; Possehl, 1997). Geological and archaeological evidence suggests that these societal upheavals were triggered by a multicentennial drought (Cullen et al., 2000).

The geographic impact of the ca. 4.2 ka event is poorly constrained. Lakes of monsoonal eastern Africa preserve evidence of a short-term and widespread drying phase (Gasse, 2000; Marchant and Hooghiemstra, 2004; Russell and Johnson, 2005), but similar evidence has yet to be recovered from lakes of western Africa (Cheddadi et al., 1998; Russell et al., 2003) and is virtually nonexistent in the middle latitudes of Eurasia (Jalut et al., 2000; Magny, 2004). Meanwhile, parts of South America experienced a wetter climate at that time, suggesting significant climatic antiphasing (Marchant and Hooghiemstra, 2004). Precisely dated records from climatically sensitive archives are essential to determine the extent and impact of these important events. This will improve our understanding of global trends in Earth's climate.

In this paper we present precisely dated multiproxy evidence from an Italian flowstone that shows the impact of the ca. 4.2 ka event on the western Mediterranean region. Flowstones are a type of speleothem deposited in caves by degassing vadose percolation waters. Climate-driven variations in feedwater geochemistry are embedded within the calcite as the flowstone accumulates. Precise radiometric dating by uranium-series methods ($^{230}Th/^{234}U$) allows these variations to be placed within an absolute time frame (Edwards et al., 1986).

MATERIALS AND METHODS

The flowstone sample for this study (RL4) was collected from Buca della Renella, a small (~250 m long, 300 m above sea level [a.s.l.]) multilevel cave in the Frigido River basin (Alpi Apuane karst), Italy (Fig. 1). The cave developed in an area of Triassic metadolomite, which receives a mean annual rainfall of 2000 mm and has a mean annual temperature of 12 °C. RL4 was sampled from a fanlike flowstone deposited at the margin of an epiphreatic passage. The sample is ~150 mm thick and was inactive at the time of collection (Data Repository Fig. DR1[1]). Flowstone $\delta^{18}O$ and $\delta^{13}C$ values were determined by gas-source mass spectrometry from powders drilled at 1.5 mm intervals. Subsamples were analyzed for Mg and Ca concentrations using standard inductively coupled plasma atomic emission spectroscopy. Measurements of organic fluorescence were made directly from RL4 using a fiber-optic probe coupled to a Varian Cary Eclipse spectrophotometer (McGarry and Baker, 2000). (For further details of analytical methods, see footnote 1.) $^{230}Th/^{234}U$ dating was performed on 13 20–30 mg samples using a Nu Instruments multicollector inductively coupled plasma–mass spectrometer (Hellstrom, 2003). Most samples yielded low $^{230}Th/^{232}Th$ ratios, indicative of significant quantities of nonauthigenic Th within the calcite (Table DR1; see footnote 1). A correction procedure (described in the data repository) was applied to the raw age data that incorporates the full range of $[^{230}Th/^{232}Th]_{initial}$ necessary to retain all age data points in correct stratigraphic order. An age model was constructed from the corrected data using a Bayesian–Monte Carlo technique (Drysdale et al., 2004; Fig. DR2). The corrected ages show that RL4 grew between ca. 1.27 ± 0.05 and 6.87 ± 0.43 ka (age errors are reported as 2σ uncertainties unless otherwise stated).

FLOWSTONE PROPERTIES

Each of the speleothem properties displays a number of oscillations, but a brief period of extreme values for each property is centered on ca. 4.1 ka (Fig. 2), which is within error of the ca. 4.2 ka IRD event 3 from the North Atlantic (Bond et al., 2001). The correspondence between the four independent flowstone properties provides a strong case for a single climate-forcing mechanism.

Speleothem $\delta^{18}O$ values are forced by changes in the $\delta^{18}O$ of the percolation waters (a proxy for local rainfall $\delta^{18}O$) and the temperature of water-calcite fractionation inside the cave (a proxy for outside air temperatures) (Hendy, 1971). The water-calcite fractionation

[1]GSA Data Repository item 2006024, additional description and age data, is available online at http://www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

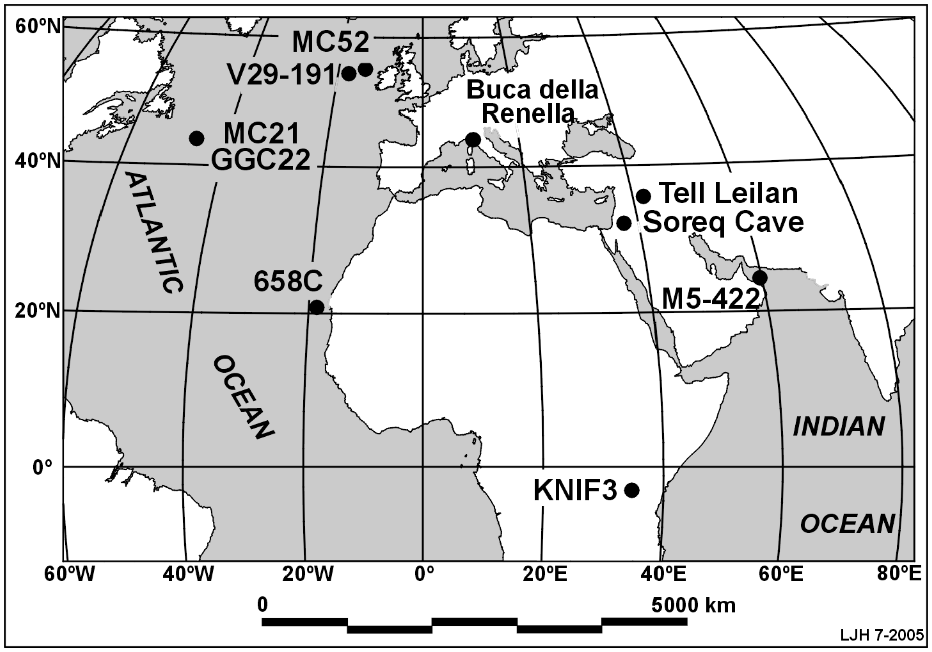

Figure 1. Location of Buca della Renella and other sites mentioned in text.

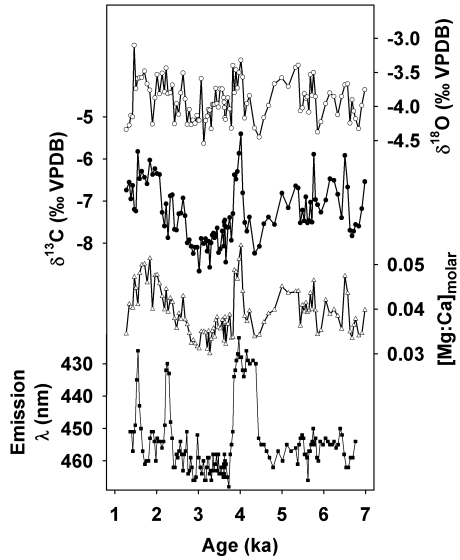

Figure 2. Time series of δ^{18}O, δ^{13}C, [Mg:Ca], and peak fluorescence emission wavelength for flowstone RL4. Note that y-axis for fluorescence emission has been inverted. VPDB—Vienna Peedee belemnite standard.

varies by −0.24‰/°C (Kim and O'Neil, 1997). This almost cancels the effects of air temperatures on the local rainfall δ^{18}O, which, based on the present-day temperature-altitude and rainfall δ^{18}O altitude gradients for the western side of the Alpi Apuane between 150 and 1300 m a.s.l. (Mussi et al., 1998), varies by 0.20‰/°C. Therefore, the cause of most of the ~1.4‰ amplitude in RL4 δ^{18}O must be other factors affecting rainfall δ^{18}O (e.g., changes in storm trajectories or rainfall amounts; Dansgaard, 1964). Modeling of rainfall isotope data in western Italy shows that the rainfall δ^{18}O is controlled in part by the amount of rainfall, which has been invoked as a major controller of speleothem δ^{18}O values in western Italy (Bard et al., 2002; Drysdale et al., 2004) and the eastern Mediterranean (Bar-Matthews et al., 1997). However, the importance of rainfall amount vis-à-vis shifts in storm tracks can only be resolved by considering other flowstone properties.

Variations in RL4 δ^{13}C values have several potential causes, the most likely being fluctuations in soil CO_2 input and water-flow rates (McDermott, 2004). Prehistoric human impacts (e.g., cultivation) are unlikely because of the inhospitably steep local terrain. Soil CO_2 production varies according to moisture availability and temperature. Moisture is directly related to rainfall amount and would influence flow-rate variations inside the cave. It is likely to be more important because of low Holocene temperature variability. Low-flow conditions enhance CO_2 loss because of longer travel times and preferentially remove ^{12}C from solution, causing carbon isotopic enrichment and higher calcite δ^{13}C (Dulinski and Rozanski, 1990; Hellstrom and McCulloch, 2000). A moderate but statistically significant positive covariation between δ^{18}O and δ^{13}C ($r = 0.55$, $n = 103$, $p < 0.01$) suggests some influence by variations in rainfall amount.

Partial control of δ^{18}O and δ^{13}C by rainfall amount is supported by [Mg:Ca]. During periods of negligible temperature variation, calcite [Mg:Ca] is dependent upon source water [Mg:Ca] (Fairchild et al., 2000). Reduced rainfall decreases flow rates in the cave, causing CO_2 degassing in the dewatered voids along the flow path. The longer travel times across the flowstone surface also enhance degassing. Prior calcite precipitation occurs upstream of a sampling site (Fairchild et al., 2000) and causes preferential loss of Ca^{2+}, enriching the [Mg:Ca] of the waters by the time they reach the sample. The [Mg:Ca] correlates well with both δ^{13}C ($r = 0.85$, $n = 103$, $p < 0.01$) and, to a lesser extent, δ^{18}O ($r = 0.70$, $n = 103$, $p < 0.01$) (Fig. 2), and the positive covariation is consistent with higher δ^{13}C and δ^{18}O being associated with lower flows.

Fluorescence changes in speleothems reflect variations in the degree of humification of organic matter in the overlying soil (McGarry and Baker, 2000). Compounds produced by humification are incorporated into the calcite via percolation waters. When rainfall is higher or temperature cooler, humification is inhibited because compounds are flushed rapidly from soils (Swift et al., 1979). Calcite forming in underlying caves at such times will incorporate organics that fluoresce at significantly longer peak emission wavelengths, while under drier or warmer conditions, humification is more advanced, with the calcite-bound compounds fluorescing at shorter emission wavelengths (McGarry and Baker, 2000). Variations in peak emission wavelength during times of relatively stable temperatures can act as a proxy for soil-flushing rates and, therefore, paleorecharge. The period of persistently low peak emission wavelengths envelops the episode of elevated stable isotope and [Mg:Ca] values centered on ca. 4.1 ka and is consistent with a drier climatic phase. The shift toward low emission values precedes the other three proxies by ~200 yr. However, this is largely due to the averaging effects of the relatively large (4.5 mm diameter) spot size of the fiber-optic probe used in the fluorescence measurements (Data Repository, see footnote 1).

DISCUSSION

Detailed examination of speleothem RL4 suggests that four diverse proxies attained extreme values ca. 4.1–3.8 ka, which corresponds to an interval of reduced moisture reaching the cave interior. The timing and multicentennial duration of this interval coincide with the collapse of Old World societies in southwestern Asia and northeastern Africa (Weiss et al., 1993; Hassan, 1997; Possehl, 1997). For example, in northern Syria (Mesopotamia), where the Akkadian civilization thrived in the fertile alluvial valleys and headwaters of the Tigris and Euphrates Rivers (Weiss et al., 1993), a 300 yr occupational hiatus commencing at 4.1 ± 0.2 ka (1σ) represents sudden abandonment of long-established settlements. This hiatus is capped by a thin tephra layer, overlain by as much as 1 m of

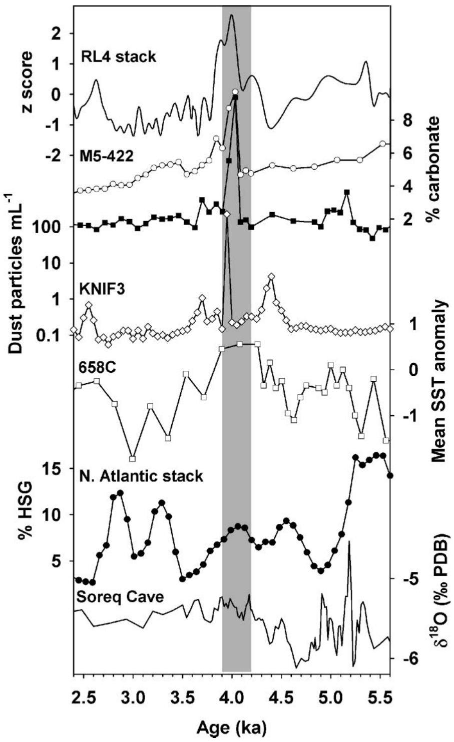

Figure 3. Comparison between RL4 and other proxy data for period 2.5–5.5 ka. RL4 stack was compiled by standardizing individual time series from Figure 2, resampling at 10 yr intervals, and taking mean of standard scores at each increment. Carbonate record (calcite: open circles; dolomite: solid squares) from marine core M5–422 (Gulf of Oman: 24°23.4′N, 52°2.5′E) is from Cullen et al. (2000). Dust record (open diamonds) is from ice core KNIF3 (Mount Kilimanjaro ice cap, 3°4.6′S, 37°21.2E) after Thompson et al. (2002). Mean sea-surface temperature (SST) anomaly record (open squares) is from marine core 658C (off West Africa, subtropical North Atlantic: 20°45′N, 18°35′W; deMenocal et al., 2000). Stacked hematite-stained grain (HSG) record (solid circles) is derived from three cores in subpolar North Atlantic (Bond et al., 2001). Soreq Cave (Israel) δ^{18}O data (32°N, 35°E) are from Bar-Matthews et al. (1997). Gray vertical band is 4.2–3.9 ka (ca. 2200–1900 B.C.) occupational hiatus from Habur Plains of former northern Mesopotamia (Weiss et al., 1993). PDB—Peedee belemnite standard.

eolian-rich sediments (Weiss et al., 1993), a succession mimicked in nearby marine sediments in the Gulf of Oman (Cullen et al., 2000; Fig. 3). Lakes in low-latitude eastern Africa also record a dry phase ca. 4 ka (Gasse, 2000), when a 30-mm-thick layer of dust accumulated on the Kilimanjaro ice cap (Fig. 3; Thompson et al., 2002). In the eastern Mediterranean, the shift to drier conditions, indicated by increasing δ^{18}O in Soreq Cave (Israel) speleothems (Fig. 3; Bar-Matthews et al., 1997), commenced several hundred years earlier (ca. 4.7 ka) but still culminated at the time of the Akkadian collapse. The timing of this shift at Soreq Cave is in good agreement with the sea-surface temperature record off the coast of western Africa (deMenocal et al., 2000; Fig. 3). It is also broadly consistent with the commencement of the multiproxy excursion in RL4, considering the large uncertainty associated with the 4.66 ka age in our flowstone (Table DR1 [see footnote 1]; Fig. 3).

Elsewhere, the existing evidence for a well-defined multicentennial drying event is less convincing. In low-latitude lakes of western Africa, the most consistent trend is for longer-term drying following the end of the African Humid Phase (Marchant and Hooghiemstra, 2004), although future well-dated, high-resolution records may reveal a multicentennial event ca. 4.2 ka. Pollen evidence for multicentennial drying from the western Mediterranean is also equivocal, but many of the numerous Holocene lake records between Portugal and Italy lack high-resolution data (Jalut et al., 2000).

The coincidence between a drying event at 4.1 ka in mid-latitude Italy and North Atlantic ice rafting at 4.2 ka suggests a direct link with North Atlantic circulation. Bond et al. (2001) argued that this and similar Holocene events were triggered by reductions in solar radiation, resulting in southward migration of ice-bearing polar waters into the stream of the North Atlantic Current, bringing cooler conditions to northwestern Europe. However, uncertainty prevails as to how the climatic response propagated to lower latitudes. Recent modeling of the Maunder Solar Minimum (Shindell et al., 2001) suggests a circulation pattern typical of a low-index state of the North Atlantic Oscillation (NAO), when the Azores High is weak. But this response is unlikely because it should bring more, not less, rainfall to the Mediterranean and the Middle East (Cullen and deMenocal, 2000); a simultaneous reduction in rainfall across the Mediterranean and the northern sector of the Middle East is actually consistent with a positive NAO phase (Cullen and deMenocal, 2000; Hurrell et al., 2003).

While drier conditions prevailed in western Italy, the eastern Mediterranean, southwestern Asia, and monsoonal eastern Africa, large areas of Southern Hemisphere South America experienced increased moisture, possibly due to the Intertropical Convergence Zone (ITCZ) being forced to a more southerly position (Marchant and Hooghiemstra, 2004). This cross-equatorial antiphasing is broadly consistent with climate responses to North Atlantic cooling during the last deglaciation (Bianchi and Gersonde, 2004) and the last glacial period (Wang et al., 2004), suggesting a consistent response under dramatically different climate modes. However, the stronger northeastern trade winds that usually accompany a southward shift in the ITCZ tend to increase cold-water upwelling off the coast of western Africa, producing cooler regional sea-surface temperatures (deMenocal et al., 2000). This is not the case for ca. 4.2 ka, for which time a warming trend is apparent (Fig. 3). This trend contradicts the sea-surface temperature response to other Holocene events at this site, which, together with evidence from the high latitudes (Hu et al., 2003), suggests a lack of consistency in the way different regions respond to particular IRD events. The IRD data of Bond et al. (2001) show variable intensity for each event, with the 4.2 ka event being of considerably lower amplitude than its neighbors. If a unique ocean-atmosphere circulation response typifies each event, this will confound attempts to find a universal explanation for propagation of these changes through the climate system.

The difference in the degree of abruptness of the proxy changes observed in the Oman, Kilimanjaro, Soreq, west African (658C), and RL4 records (Fig. 3) raises the important issue of how different paleoenvironmental archives respond to a given regional climatic event. For example, the dust events in the Oman and Kilimanjaro records are unquestionably abrupt, whereas longer-term drying can be inferred from the RL4 and Soreq Cave records. It is likely that the period of increased dust flux corresponds to maximal drying conditions, and therefore the Oman and Kilimanjaro sites only responded to the general drying when a more extreme climatic threshold had been breached. However, a strong peak in proxy response is less obvious at Soreq Cave and of longer duration in RL4. A review of the 8.2 ka event (Rohling and Pälike, 2005) argued that a brief and more extreme cooling event at 8.2 ka occurred over a longer-term cooling anomaly of 400–600 yr duration. There is a distinct possibility that a similar superimposition of episodes, this time involving moisture, occurred between 4.7 and 3.8 ka.

CONCLUSIONS

Multiproxy data from the RL4 flowstone provide the first unequivocal evidence that the effects of the 4.2 ka drought were felt in the middle latitudes of Europe. This in turn suggests a regional drying event extending across more than 40 degrees of latitude. Although its timing is statistically indistinguishable from IRD event 3 in the North Atlantic, the regional ocean-atmosphere response at this time was clearly complex. We suggest that further precisely dated multiproxy records using highly sensitive archives are needed before detailed regional paleocirculation patterns can be reconstructed for this and similar Holocene climatic events.

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