Speleothem evidence from Oman for continental pluvial events during interglacial periods

Stephen J. Burns
Dominik Fleitmann
Albert Matter
Institute of Geology, University of Bern, CH-3012 Bern, Switzerland
Ulrich Neff
Augusto Mangini
Heidelberg Academy of Sciences, D-69120 Heidelberg, Germany

ABSTRACT

Growth periods and stable isotope analyses of speleothems from Hoti Cave in northern Oman provide a record of continental pluvial periods extending back over the past four of Earth's glacial-interglacial cycles. Rapid speleothem growth occurred during the early to middle Holocene (6–10.5 ka B.P.), 78–82 ka B.P., 120–135 ka B.P., 180–200 ka B.P., and 300–325 ka B.P. The speleothem calcite deposited during each of these episodes is highly depleted in ^{18}O compared to modern speleothems. The $\delta^{18}O$ values for calcite deposited within pluvial periods generally fall in the range of −4‰ to −8‰ relative to the Vienna Peedee belemnite standard, whereas modern speleothems range from −1‰ to −3‰. The growth and isotopic records indicate that during peak interglacial periods, the limit of the monsoon rainfall was shifted far north of its present location and each pluvial period was coincident with an interglacial stage of the marine oxygen isotope record. The association of continental pluvial periods with peak interglacial conditions suggests that glacial boundary conditions, and not changes in solar radiation, are the primary control on continental wetness on glacial-interglacial time scales.

Keywords: speleothems, stable isotopes, Oman, monsoon, uranium-series method.

INTRODUCTION

How climate in Earth's tropical regions varied over the course of Earth's glacial-interglacial cycles of the past several hundred thousand years remains largely unknown. Even more acute is the lack of knowledge of continental, as opposed to marine, climate variation. The most commonly used archive of continental climate change, lakes, are generally not long-lived enough to provide information on glacial-interglacial time scales, nor are lacustrine sediments easily dated beyond the range of the radiocarbon method. Speleothems, calcium carbonate deposits in caves, offer the potential for considerably longer, interpretable records of continental climate variation (e.g., Dorale et al., 1992) including reconstruction of paleorainfall intensity (Bar-Matthews et al., 2000). Here, we attempt to develop a record of continental climate variation for southern Arabia, a region affected by one of the most important components of tropical climate, the Indian Ocean monsoon. The record covers the past four glacial-interglacial cycles, and is based on observed periods of rapid growth and stable isotope data in speleothems from Hoti Cave in Oman.

The Indian Ocean monsoon is one of the major weather systems on Earth, and both marine and continental records show that its intensity has varied considerably in the recent past. For example, an early Holocene intensification of the southwest summer monsoon, followed by its dramatic reduction in the middle to late Holocene is recorded by changes in upwelling indicators in marine sediments (Clemens et al., 1991; Sirocko et al., 1993; Overpeck et al., 1996), by variations in lake levels across the Sahel region of Africa (Gasse and Street, 1978; Ritchie et al., 1985), in Arabia (McClure, 1976), and in India (Bryson and Swain, 1981), and by speleothem growth in northern Oman (Burns et al., 1998). On longer time scales, knowledge of monsoon variation comes almost entirely from marine sediments (Anderson and Prell, 1993; Rosteck et al., 1997). Yet, these records primarily register changes of wind intensity and may or may not reflect changes in available moisture on the continents. As a result, they leave unanswered some fundamental questions concerning climate variations in continental regions affected by the monsoon. In particular, does continental pluviality vary in concert with marine upwelling and/or wind strength, and are periods of increased continental wetness in the region primarily controlled by changes in solar insolation or by glacial boundary conditions such as the extent of glaciation on the Himalayan plateau or sea-surface temperatures?

GEOLOGIC SETTING AND METHODS

Hoti Cave is a through cave in northern Oman, in the foothills along the southern margin of the Oman Mountains (Fig. 1). This 4.5-km-long cave is hosted by the Natih Forma-

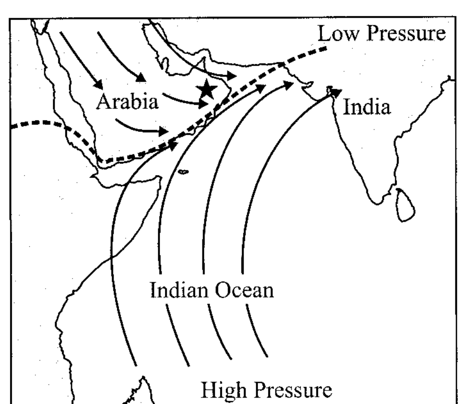

Figure 1. Map showing location of Hoti Cave (star) and generalized modern, summer, surface wind pattern. Dashed line is approximate location of intertropical convergence zone, the present northern limit of monsoon rainfall.

tion, a Cretaceous limestone. The present climate is arid to semiarid; average rainfall is ~200–250 mm/yr (Food and Agriculture Organization, 1987). Groundwaters in the region are recharged primarily by cyclonic low-pressure systems moving from the Mediterranean Sea southeast across the Arabian Peninsula during the winter months (Weyhenmeyer et al., 2000). The northern limit of the summer monsoon, the intertropical convergence zone, is located generally south of the Arabian landmass (Hastenrath, 1985). Oxygen isotopic values of rainfall in the vicinity of Hoti Cave range from ~0 to −2‰ (Macumber et al., 1997; Weyhenmeyer, 2000).

We collected whole or sampled by drilling seven large fossil stalagmites and one large flowstone from the cave. These inactive stalagmites ranged from ~30 cm to 3 m in height; the flowstone is 2.7 m thick. In addition, we collected drip waters from several locations in the cave together with small active stalagmites beneath the drips. Only one active stalagmite taller than 30 cm was found. More typically, active stalagmites are ~10 cm in height. Temperature and humidity measurements were taken at numerous locations in the cave.

The ages of deposition of the samples were determined by measuring their U/Th ratios by thermal ionization mass spectrometry; we made a total of 51 measurements for all samples (Table 1[1]). Analytical procedures for the separation and purification of thorium and uranium were as described by Ivanovich and Harmon (1993). U/Th measurements were performed on a multicollector mass spectrometer (Finnigan MAT 262 RPQ) with a double filament technique. Uranium and thorium were measured in semi-peak-jump mode and peak-jump mode, respectively. Calibration of Faraday cup to ICM efficiency was made adopting the natural $^{238}U/^{235}U$ of 137.88. To determine the uranium and thorium concentrations, defined quantities of a $^{233}U/^{236}U$ double spike and a ^{229}Th spike were added. Th/U ages were corrected for detritus following Ivanovich and Harmon (1993), assuming a $^{232}Th/^{238}U$ isotope ratio of 3.8. The reproducibility of the isotope ratio of $^{234}U/^{238}U$ and the concentration of ^{232}Th of standard materials is 0.3% and 0.8% (2 σ), respectively. For details about measurements of standard material see Frank et al. (2000).

More than 500 oxygen isotope analyses were done on the speleothems. For each, ~5 mg of powder was drilled from the sample and analyzed with an on-line, automated, carbonate preparation system linked to a VG Prism ratio mass spectrometer. Results are shown as the per mil difference between the sample and the Vienna Peedee belemnite (VPDB) standard in delta notation. Reproducibility of standard materials is 0.08‰. Drip water $\delta^{18}O$ values were measured using an on-line, automated equilibration system. The values are reported against the Vienna standard mean ocean water (VSMOW) standard, and have a reproducibility of 0.08‰.

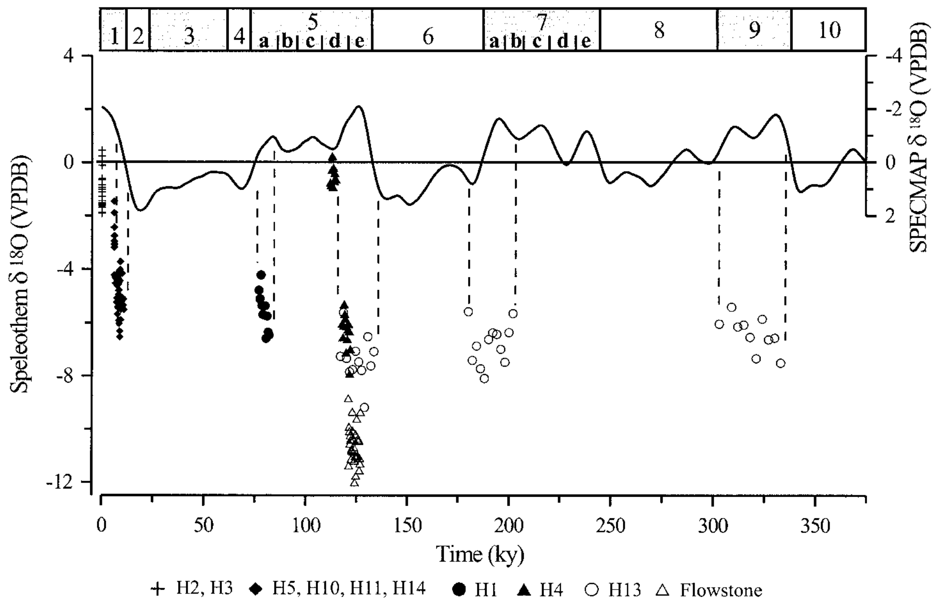

Figure 2. Composite record of speleothem growth periods and oxygen isotope ratios for Hoti Cave. Samples H2 and H3 are modern; all other ages are based on U/Th data (see footnote 1). Also shown is SPECMAP (Imbrie et al., 1990) marine oxygen isotope curve and marine oxygen isotope stage numbers.

RESULTS

Active stalagmites in Hoti Cave are small in comparison to fossil stalagmites and have $\delta^{18}O$ values that range from about −1‰ to −3‰ (Fig. 2). Measured $\delta^{18}O$ values of drip waters associated with growing stalagmites vary mainly between 0‰ and −2‰, very similar to rainfall $\delta^{18}O$ values in the region of the cave despite high evaporation rates in arid climates. For the measured cave temperatures of 25–27 °C, the modern speleothem $\delta^{18}O$ values are, thus, very close to expected equilibrium calcite values and well reflect modern rainfall in the area. Transects of stable isotopic measurements along growth lines of older stalagmites show no evaporative effect, suggesting that they too precipitated calcite close to isotopic equilibrium.

With one exception, large stalagmites in Hoti Cave are no longer actively growing. Age determinations on large stalagmites show that they grew during discrete periods. The most recent growth period of large stalagmites in Hoti Cave occurred during the early to middle Holocene; four different stalagmites yielded ages between 6.2 and 10.5 ka. Prior periods of growth of large speleothems took place during the intervals 78–82 ka B.P., 117–130 ka B.P., 180–210 ka B.P., and 300–325 ka B.P. (Fig. 2). An important feature of one sample, stalagmite H-13, is that it records three separate growth periods. As shown on the age versus depth plot in Figure 3, the stalagmite grew rapidly during three relatively short periods of about 10–30 k.y.; intervening long periods of nondeposition are marked by thin, reddish, clay mineral–rich layers. Growth phases occurred during times equivalent to MIS (marine [oxygen] isotope stages) 5e, 7a, and 9. Note that although two samples from the last growth period in H-13 date beyond MIS 9, the ages of these samples have large errors and are bracketed above and below by better-determined ages (Fig. 3). Because growth was reactivated multiple times within a single sample, the intervening hiatuses are taken to have been continually dry. Each of the growth periods of large stalagmites is coincident with an interglacial stage of the marine isotope record; growth took place during times equivalent to MIS 1, 5a, 5e, 7a, and 9 (Fig. 2). During each phase of rapid speleothem growth, the $\delta^{18}O$ values of speleothem carbonate are much more negative than those measured in modern, active speleothems. For the early to middle Holocene and MIS 5a, speleothem carbonate $\delta^{18}O$ values generally range from −4‰ to −6‰. For the periods associated with the interglacial periods of MIS 5e, 7a, and 9, the $\delta^{18}O$ values from stalagmites are even more negative, ranging mainly from

[1]GSA Data Repository item 2001069, Table 1, Details of U-Th chemistry, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

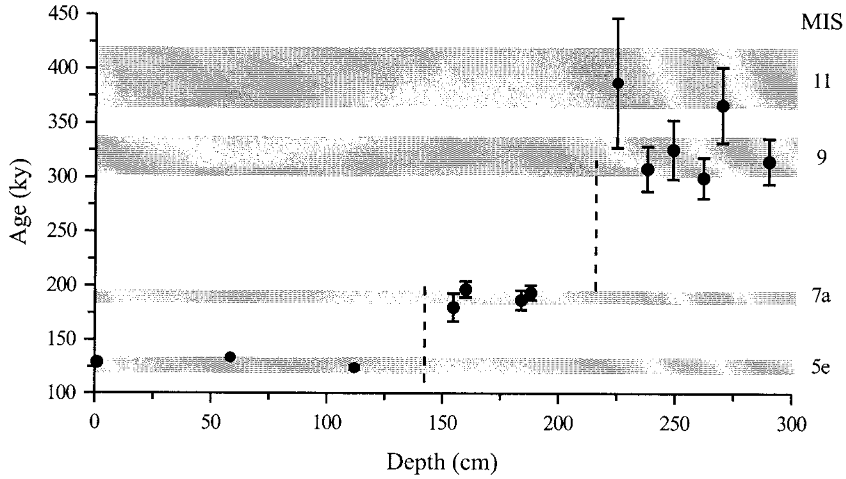

Figure 3. Ages, with associated error bars, vs. sample depth for stalagmite H-13. Stalagmite grew rapidly during each of three peak interglacial periods, equivalent to marine (oxygen) isotope stages (MIS) 5e, 7a, and 9. No growth took place during intervening times.

−6‰ to −8‰. The most negative $\delta^{18}O$ values, from −9‰ to −12‰ were measured in samples from the flowstone deposited during MIS 5e.

DISCUSSION

The highly negative $\delta^{18}O$ values that characterize carbonate deposited during the pluvial periods as compared to modern speleothems cannot be due to higher temperatures in the past. Even a 1‰ decrease in carbonate $\delta^{18}O$ would require a 4.5 °C temperature increase, and marine oxygen isotope records from the Arabian Sea (e.g., Murray and Prell, 1992) demonstrate that temperatures during the early Holocene and past interglacial were within 1–2 °C of recent temperatures. Rather, the negative isotopic values of speleothem carbonate reflect isotopic depletion of rainfall and groundwaters during these periods. If we assume that cave temperatures during the periods of speleothem growth were within 1–2 °C of modern cave temperatures, then the stalagmite calcite $\delta^{18}O$ values yield calculated $\delta^{18}O_{VSMOW}$ values for rainfall of about −4‰ for the early to middle Holocene and MIS 5a, and −5‰ for MIS 5e, 7a, and 9. The flowstone $\delta^{18}O$ values suggest that rainfall values averaged about −7‰ (VSMOW), during its deposition.

The most likely source for rainfall with such negative $\delta^{18}O$ values is the Indian Ocean summer monsoon. The strong convection associated with monsoonal circulation results in rainfall highly depleted in ^{18}O. For example, the weighted mean $\delta^{18}O$ rainfall value for New Delhi, India, is −5.81‰ (International Atomic Energy Agency, 1992), reflecting the dominance of the summer monsoon rainfall. The composite record of speleothem growth periods from Hoti Cave shows that periods of rapid speleothem growth, marked by very negative $\delta^{18}O$ values for speleothem calcite, are separated by hiatuses marking periods of little or no speleothem growth, with much less negative calcite $\delta^{18}O$ values. The periods of rapid growth are interpreted to mark climate periods much wetter than at present, periods during which the intertropical convergence zone and limit of monsoon rainfall were shifted far north of their present location and brought monsoon rainfall to the region of Hoti Cave. The growth hiatuses occurred during arid periods similar to the present climate, when the summer intertropical convergence zone was generally south of the Arabian Peninsula.

For the most recent speleothem growth period, the early to middle Holocene, a pluvial period is also recorded in continental paleoclimate records from across northern Africa, the Arabian Peninsula, and into India. In particular, lacustrine sediments in these regions show high lake-level stands during the early to middle Holocene (Gasse and Street, 1978; Ritchie et al., 1985; Bryson and Swain, 1981). Pollen data from marine sediments in the Indian Ocean (Van Campo et al., 1982; Prell and Van Campo, 1986) and the continental margin of equatorial west Africa (Dupont et al., 2000) also show a pattern of continental wetness remarkably similar to our speleothem record. Studies of pollen contained in cores from both areas show peaks in species indicative of tropical humid conditions during the early Holocene and in sediments deposited during MIS 5a and 5e (Van Campo et al., 1982; Prell and Van Campo, 1986; Dupont et al., 2000). During the period between the end of MIS 5a and the early Holocene, pollen indicative of more arid conditions dominated. Our speleothem data extend the record of continental climate over the past four of Earth's glacial cycles. For each of these cycles, the peak interglacial periods, equivalent in time to MIS 5a, 5e, 7, and 9, are marked by a continental pluvial phase. This association strongly suggests that periods of continental wetness are controlled by some aspect of glacial boundary conditions. Whether the most important of these might be sea-surface temperatures in the Indian Ocean, snow cover on the Himalayan plateau, atmospheric CO_2 concentrations, or even conditions far afield from the Indian Ocean cannot be interpreted from our data.

Perhaps the primary source of information on changes in the Indian Ocean monsoon system is marine sediments in the Arabian Sea and Indian Ocean. For nearly all of these records, the proxies for variation in monsoon winds are based on indicators of wind strength or wind-driven upwelling—for example, lithogenic grain size, carbon mass-accumulation rates, or relative percentages of foraminifera or coccolithophores. In some cases, the upwelling is driven by the southwest summer monsoon; in others, upwelling is a response to the northeast, or winter, monsoon winds. Several important differences exist between these marine, upwelling-based records and those based on studies of continental pluviality. First, on glacial-interglacial time scales, the majority of these records vary primarily with a periodicity of ~20 k.y., close to the precessional cycle in Earth's orbit records (Anderson and Prell, 1993; Rosteck et al., 1997; Clemens and Prell, 1990; Reichart et al., 1997). This is true regardless of whether the upwelling region in question is summer or winter monsoon driven, although these two types of upwelling do not vary in phase. Nearly all of these records have been interpreted as indicating that the dominant control on monsoon intensity is solar insolation and that glacial boundary conditions play a much subordinate role (Anderson and Prell, 1993; Rosteck et al., 1997; Clemens and Prell, 1990; Reichart et al., 1997).

Second, there are specific time periods during which marine upwelling indicators suggest intensified monsoon winds, yet the continental records of climate indicate dryness. For example, during MIS 3, we have thus far found no evidence of speleothem growth in Hoti Cave, and pollen studies indicate that arid conditions dominated eastern Africa (Van Campo et al., 1982; Prell and Van Campo, 1986; Dupont et al., 2000). In contrast, a variety of marine indicators of the intensity of monsoon-wind–driven upwelling along the Oman margin suggest intensified monsoon winds. In fact, the marine indicators of monsoon wind intensity during MIS 3 are often much higher than those during the early Holocene (Hermelin and Shimmield, 1995; Rosteck et al., 1997; Reichart et al., 1998). The differences between the marine and continental records of the monsoon suggest that although wind intensity may indeed be tied to solar forcing, changes in wind strength will not necessarily lead to increased continental wetness. The latter appears to be more closely tied to control by the glacial boundary condition on the location of the intertropical convergence zone during Northern Hemisphere summers. In any case, increases in monsoon wind strength appear to not always result in increased continental wetness.

Why might moisture transport and resulting continental wetness respond to elements of overall climate forcing different from monsoon wind strength? Today, by far the principal moisture source for Indian monsoon rainfall is the tropical Indian Ocean in the Southern Hemisphere (Hastenrath, 1985). This moisture is carried by the low-level monsoon winds across the Arabian Sea with little further addition of water vapor. Changes in the amount of precipitation in the Northern Hemisphere during the monsoon should, therefore, be primarily controlled by changes in the amount of moisture input to the system during the Southern Hemisphere winter. The changes in incoming solar radiation at 20°S during the months of June–August are approximately one-half of those at 20°N for the same months (Berger and Loutre, 1991). Thus, precessional cycle forcing is considerably weaker in the moisture source area than in the Northern Hemisphere, where it controls zonal wind strength (Beaufort et al., 1997). The water-vapor content of the atmosphere is also highly and nonlinearly dependent on temperature. Thus, it might be expected that sea surface temperatures, more closely tied to glacial boundary conditions than to solar forcing, would be a major control on the total water-vapor content of low-level air masses originating in the southern tropical Indian Ocean.

REFERENCES CITED

Anderson, D.M., and Prell, W.L., 1993, A 300 kyr record of the upwelling off Oman during the Late Quaternary: Evidence of the Asian southwest monsoon: Paleoceanography, v. 8, p. 193–208.

Bar-Matthews, M., Ayalon, A., and Kaufman, A., 2000, Timing and hydrological conditions of sapropel events in the Eastern Mediterranean, evidence from speleothems, Soreq Cave: Chemical Geology, v. 169, p. 145–156.

Beaufort, L., Lancelot, Y., Camberlin, P., Cayre, O., Vincent, E., Bassinot, F., and Labeyrie, L., 1997, Insolation cycles as a major control of equatorial Indian Ocean primary production: Science, v. 278, p. 1451–1454.

Berger, A., and Loutre, M.F., 1991, Insolation values for climate of the last 10 million years: Quaternary Science Reviews, v. 10, p. 297–317.

Bryson, R.A., and Swain, A.M., 1981, Holocene variations of monsoon rainfall in Rajasthan: Quaternary Research, v. 16, p. 135–145.

Burns, S.J., Matter, A., Frank, N., and Mangini, A., 1998, Speleothem-based paleoclimate record from northern Oman: Geology, v. 26, p. 499–502.

Clemens, S.C., and Prell, W.L., 1990, Late Pleistocene variability of Arabian Sea summer monsoon winds and continental aridity: Eolian records from the lithogenic component of deep-sea sediments: Paleoceanography, v. 5, p. 109–145.

Clemens, S.C., Prell, W.L., Murray, D., Shimmield, G., and Weedon, G., 1991, Forcing mechanisms of the Indian Ocean monsoon: Nature, v. 353, p. 720–725.

Dorale, J.A., González, L.A., Reagan, M.K., Pickett, D.A., Murrell, M.T., and Baker, R.G., 1992, A high-resolution record of Holocene climate change in speleothem calcite from Cold Water Cave, northeast Iowa: Science, v. 258, p. 1626–1630.

Dupont, L.M., Jahns, S., Marret, F., and Ning, S., 2000, Vegetation change in equatorial West Africa: Time slices for the last 150 ka: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 155, p. 95–122.

Food and Agriculture Organization, United Nations, 1987, Agroclimatological data for Asia: Plant Productivity and Protection Series, no. 25, 788 p.

Frank, N., Braun, M., Hambach, U., Mangini, A., and Wagner, G., 2000, Warm period growth of travertine during the last interglaciation in southern Germany: Quaternary Research, v. 54, p. 38–48.

Gasse, F., and Street, F.A., 1978, Late Quaternary lake-level fluctuations and environments of the northern Rift Valley and Afar region (Ethiopia and Djibouti): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 24, p. 279–325.

Hastenrath, S., 1985, Climate and circulation of the tropics: Boston, Massachusetts, Reidel, 433 p.

Hermelin, J.O.R., and Shimmield, G., 1995, Impact of productivity events on the benthic foraminiferal fauna in the Arabian Sea over the last 150 000 years: Paleoceanography, v. 10, p. 85–116.

Imbrie, J., et al., 1990, SPECMAP Archive #1: NOAA/NGDC Paleoclimatology Program, Boulder, Colorado, IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series # 90–001.

International Atomic Energy Agency, 1992, Statistical treatment of data on environmental isotopes in precipitation: Vienna, IAEA Technical Reports Series, no. 331, 781 p.

Ivanovich, M., and Harmon, R.S., 1993, Uranium series disequilibrium: Applications to environmental problems: Oxford, UK, Clarendon Press, 541 p.

Macumber, P.G., Niwas, J.M., Al Abadi, A., and Seneviratne, R., 1997, A new isotopic water line for Northern Oman: Muscat, Sultanate of Oman, Proceedings of Third Gulf Water Conference.

McClure, H.A., 1976, Radiocarbon chronology of late Quaternary lakes in the Arabian Peninsula: Nature, v. 263, p. 755–756.

Murray, D.W., and Prell, W.L., 1992, Late Pliocene and Pleistocene climatic oscillations and monsoon upwelling recorded in sediments from the Owen Ridge, northwestern Arabia Sea, *in* Summerhayes, C.P., et al., eds., Upwelling systems: Evolution since the early Miocene: Geological Society [London] Special Publication 64, p. 301–321.

Overpeck, J., Anderson, D., Trumbore, S., and Prell, W., 1996, The southwest Indian monsoon over the last 18 000 years: Climate Dynamics, v. 12, p. 213–225.

Prell, W.L., and Van Campo, E., 1986, Coherent response of Arabian Sea upwelling and pollen transport to late Quaternary monsoonal winds: Nature, v. 323, p. 526–528.

Reichart, G.J., den Dulk, M., Visser, H.J., van der Weijden, C.H., and Zachariasse, W.J., 1997, A 225 kyr record of dust supply, paleoproductivity and the oxygen minimum zone from the Murray Ridge (northern Arabian Sea): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 134, p. 149–169.

Reichart, G.J., Lourens, L.J., and Zachariasse, W.J., 1998, Temporal variability in the northern Arabian Sea oxygen minimum zone (OMZ) during the last 225 000 years: Paleoceanography, v. 13, p. 607–621.

Ritchie, J.C., Eyles, C.H., and Haynes, C.V., 1985, Sediment and pollen evidence for an early to mid-Holocene humid period in the eastern Sahara: Nature, v. 314, p. 352–355.

Rosteck, F., Bard, E., Beaufort, L., Sonzogni, C., and Ganssen, G., 1997, Sea surface temperature and productivity records for the past 240 kyr in the Arabian Sea: Deep-Sea Research II, v. 44, p. 1461–1480.

Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M., and Duplessey, J.C., 1993, Century-scale events in monsoonal climate over the last 24 000 years: Nature, v. 364, p. 322–324.

Van Campo, E., Duplessey, J.C., and Rossignol-Strick, M., 1982, Climatic conditions deduced from a 150-kyr oxygen isotope–pollen record from the Arabian Sea: Nature, v. 296, p. 56–59.

Weyhenmeyer, C.E., Burns, S.J., Waber, H.N., Aeschbach-Hertig, W., Kipfer, R., Beyerle, R., Loosli, H., and Matter, A., 2000, Cool glacial temperatures recorded by noble gases in a groundwater study from northern Oman: Science, v. 287, p. 842–845.

Weyhenmeyer, C.E., 2000, Origin and evolution of groundwater in the alluvial aquifer of the Eastern Batinah coastal plain, Sultanate of Oman [dissertation]: Bern, Switzerland, University of Bern, 202 p.

Manuscript received October 4, 2000
Revised manuscript received March 2, 2001
Manuscript accepted March 21, 2001

Printed in USA