Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean

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During the last ice age, the Indian Ocean southwest monsoon exhibited abrupt changes that were closely correlated with millennial-scale climate events in the North Atlantic region[1–3], suggesting a mechanistic link. In the Holocene epoch, which had a more stable climate, the amplitude of abrupt changes in North Atlantic climate was much smaller, and it has been unclear whether these changes are related to monsoon variability. Here we present a continuous record of centennial-scale monsoon variability throughout the Holocene from rapidly accumulating and minimally bioturbated sediments in the anoxic Arabian Sea. Our monsoon proxy record reveals several intervals of weak summer monsoon that coincide with cold periods documented in the North Atlantic region[4]—including the most recent climate changes from the Medieval Warm Period to the Little Ice Age and then to the present. We therefore suggest that the link between North Atlantic climate and the Asian monsoon is a persistent aspect of global climate.

Abrupt changes in climate are apparent in the geologic record of climate over various timescales. Examples of large millennial-scale abrupt events in the North Atlantic include the Dansgaard–Oeschger cycles of the last glacial, and the Younger Dryas event that occurred at the end of that glacial. Because these North Atlantic warm/cold cycles correlate with monsoon variations[2,3,5], a question relevant to future climate change and prediction efforts is whether the smaller abrupt changes that have occurred in the North Atlantic during the present Holocene interglacial period are also reflected in the monsoon. The Indian Ocean monsoon system is an important component of the global climate, and has a significant role in the socio-economic life of people of the Indian subcontinent. Seasonal reversals in the Indian monsoons, the southwest (or 'summer') and northeast (or 'winter') monsoon, influence weather and climate between 30° N and 30° S over African, Indian and Asian landmasses. Although evidence of the monsoon can be found across the region in various proxies, arguably the most consistent continuous record of the monsoon comes from the floor of the Arabian Sea.

Each summer adjacent to the Oman margin, the seasonal reversal in the winds causes southwest winds to blow across the Arabian Sea (Fig. 1). Cooling of the sea surface associated with coastal and open-ocean upwelling promotes the blooming of distinct fauna and flora[6–8]. The biological response to the monsoonal activity in the surface water column is preserved as increased abundance of the planktic foraminifer *Globigerina bulloides*. The *G. bulloides* proxy has been calibrated using modern sea-floor samples[6] and sediment-trap time series[9], and has been tested over a range of timescales. Advantages of this proxy are (1) its unique association with the summer monsoon (*G. bulloides* has a subpolar habitat and would be absent in the tropics except for wind-driven upwelling), (2) linear correlation with the surface cooling due to upwelling, apparently unbiased by other influences, and (3) strong sensitivity to wind speed and the monsoonal atmospheric pressure gradient (the wind

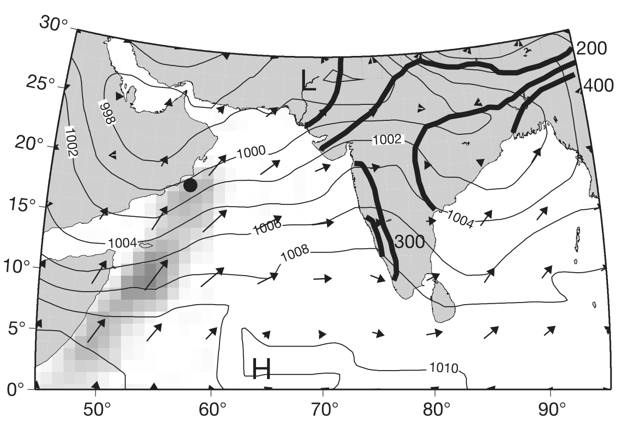

Figure 1 July sea-level pressure (mbar, thin contours), wind direction[27], cooling of the Arabian Sea due to upwelling[28], and precipitation over Asia[29] (mm month^{-1}, thick contours). Site 723 and box core RC2730 are located at 18° N, 58° E (circle). H, high pressure; L, low pressure.

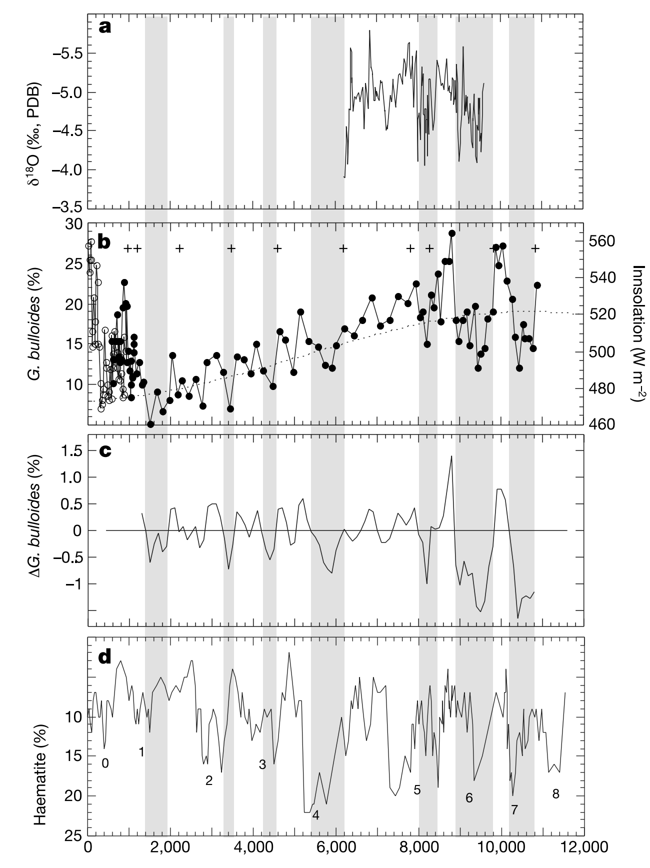

Figure 2 Southwest monsoon proxy record from the Arabian Sea Site 723A and box core RC2730 combined with Oman cave stalagmite $\delta^{18}O$ and North Atlantic haematite percentage. Time series of **a**, cave stalagmite $\delta^{18}O$ from ref. 16, **b**, *G. bulloides* percentage in Hole 723A (filled circles) and box core RC2730 (open circles) from the Arabian Sea (detail in Fig. 3), and July insolation at 65° N (ref. 18, shown by dotted line; radiocarbon-dated intervals shown by crosses), **c**, change in *G. bulloides* percentage (normalized by removing the trend related to insolation), and **d**, haematite percentage in core MC52 -VM29-191 from the North Atlantic, and events labelled 0–8 in ref. 4. The vertical grey bars indicate intervals of weak Asian SW monsoon.

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Table 1 **Radicarbon ages determined by accelerator mass spectrometry**

NOSAMS* lab. Code	Species	Depth (m.b.s.f.)†	Radiocarbon age‡ (yr BP)	Calendar age (years before 1950)	1 s.d. (yr)
34259	Mixed planktics	0.16	1,680	1,005	35
34260	*G. bulloides* & *N. dutertrei*	0.39	2,010	1,330	45
34261	*G. bulloides* & *N. dutertrei*	0.64	2,760	2,254	30
34262	*G. bulloides* & *N. dutertrei*	0.96	3,890	3,587	45
34263	*G. bulloides*	1.21	4,670	4,622	40
34264	*G. bulloides*	1.54	6,000	6,202	30
34265	*G. bulloides*	1.54	6,070	6,276	30
34266	*G. bulloides*	1.86	7,700	7,938	45
34267	*G. bulloides*	2.18	8,110	8,359	40
34268	*G. bulloides*	2.74	9,510	9,854	40
34269	*G. bulloides*	3.16	10,500	10,877	40

*NOSAMS, National Ocean Sciences Accelerator Mass Spectrometer Facility.
†Metres below sea floor.
‡Calibrated to calendar year before present (1950) using the marine98 calibration data[30].

stress that drives upwelling is proportional to the square of the wind speed).

Like other major components of climate, the summer monsoon wind has varied at orbital[7,10–12] and longer timescales in response to known external forcing. More remarkable are the abrupt changes that have occurred in the absence of known forcing over suborbital or millennial scales[1,5,8]. Millennial-scale abrupt monsoon events have been attributed to changes in the North Atlantic and downstream over Europe and Eurasia, according to the hypothesis that increased winter snowfall weakens the monsoon the following summer, observed in numerical simulations and observation-based studies[1,13,14]. The recent discovery that the Holocene North Atlantic is also marked by repeating, but less severe, cold spells[4,15] (the most recent being the Medieval Warm Period and subsequent Little Ice Age) begs the question: were the small-amplitude changes in the North Atlantic during the Holocene also accompanied by changes in the Asian southwest monsoon? Pioneering studies have suggested such a link for the Asian southwest monsoon[16] and the East Asian monsoon[17], but more records are needed, given the uncertainty in radiocarbon dating (±100 yr), the effect of bioturbation on marine sediments, the generally noisy character of most proxies, and the small amplitude of the expected signal (barely above the uncertainty). To determine whether the Little Ice Age, Medieval Warm Period and other Holocene events were accompanied by changes in the Asian southwest monsoon, we examined one of the most extensively tested proxies of the Asian southwest monsoon, the record of *G. bulloides* shells in sediments from the Oman margin.

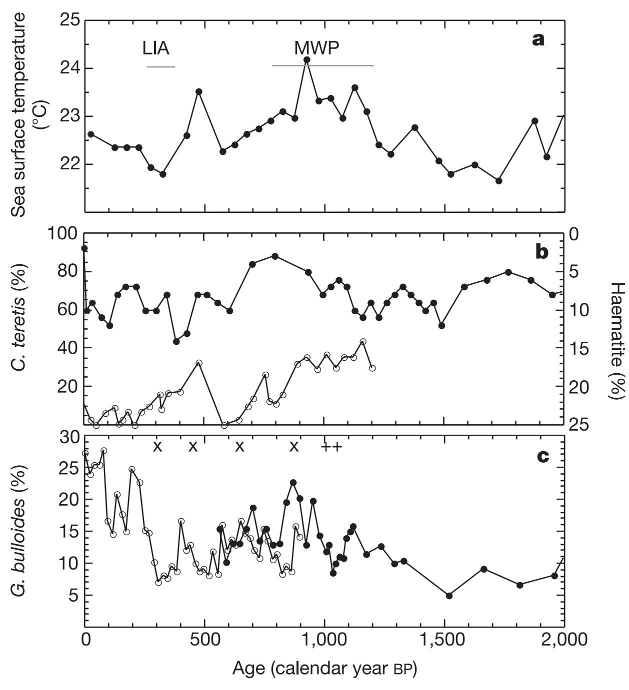

Figure 3 Southwest monsoon proxy record from the Arabian Sea Site 723A and box core RC2730 combined with North Atlantic percentage *Cassidulina teretis*, haematite and SST. Time series of **a**, temperature (inferred from $\delta^{18}O$ variation)[23] and ice rafting events[4] in North Atlantic sediments, **b**, *C. teretis* abundance from an east Greenland fjord[24], and **c**, *G. bulloides* percentage in Hole 723A (filled circles) and box core RC2730 (open circles), showing also dated depths in 723A (plus signs) and RC2730 (crosses). The North Atlantic Medieval Warm Period (MWP) and Little Ice Age (LIA) extents are based on the records shown here.

We produced a record of *G. bulloides* covering 10,877 calendar years by sampling cores from Ocean Drilling Program (ODP) Site 723, Hole A, every 1 cm (0–0.25 m), and every 4 cm (0.25–3.16 m) (see Supplementary Information). Site 723A is located on the continental margin of Oman, Arabian Sea (18° 03.079′ N, 57° 36.561′ E; water depth 807.8 m) in the centre of an oxygen-minimum zone, and provides a high-resolution sedimentary record of biotic variations linked with the intense southwest monsoon upwelling (Fig. 1). The bioturbation smoothing that would normally affect fine-scale variability is minimal at this site owing to the strong oxygen-minimum zone that exists in the Oman margin. The average age interval per sample is ~133 yr (ranging from 53 to 166 yr) based on linear interpolation of ten AMS ^{14}C calibrated dates (Table 1; also see Supplementary Information). Although the radiocarbon measurement error (1 s.d.) is less than 50 yr, including the uncertainty in reservoir age and stratigraphic interpolation increases the uncertainty to about ±100 yr. To determine the age of the uppermost sample, we correlated the top of our record with a well-dated Oman margin box core (RC2730), finding an age of ~560 yr, suggesting that the top few centimetres were lost at the time of drilling. The percentages of *G. bulloides* were calculated from an aliquot of ~300 specimens of planktic foraminifera from the >150-μm size fraction from each sample. The *G. bulloides* percentage data are compared with the 65° N July solar insolation[18] and with data on the percentage of haematite-stained grains from the North Atlantic[4] (Fig. 2).

We identified seven discrete intervals of weak summer monsoon (grey bars, Fig. 2b) during the Holocene that, although small in amplitude, can be correlated within the radiocarbon age uncertainties to the millennial-scale events (cold spells numbered 0–8, Fig. 2d) in the North Atlantic[4,15] (plotted so that cooling and monsoon weakening are downward in Fig. 2). Monsoon maxima have occurred in several pulses while the North Atlantic was warmest (low haematite). We defined monsoon events as the departures from the Holocene mean (Fig. 2c), removing the variation associated with the slow Holocene change in summer insolation by subtracting the standardized insolation series from the standardized

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G. bulloides series. Weak monsoon events were defined as runs in the data exceeding 0.5 s.d. The four oldest events have the largest amplitude, and have readily identifiable counterparts (numbered 7, 6, 5 and 4) in the haematite record. Correlating the weak monsoon events to a record of oxygen isotope enrichment in an Oman cave stalagmite[16] (Fig. 2a), we observe enriched $\delta^{18}O$ (weaker monsoon/intertropical convergence zone precipitation) accompanying times of weaker winds, as expected. The cool event at 8,200 yr before present (BP), now well-documented in the North Atlantic[19], appears prominent in the cave stalagmite record as well as our monsoon record.

The identification of events in the younger part (5,000 yr BP to present) is more difficult to establish because the events are of short duration and barely exceed 0.5 s.d. Nevertheless, we made tentative correlations with North Atlantic Bond events 3, 2 and 1 (as well as event 0, see Fig. 2b). Potential problems with our data include double-peak event 5 (less prominent in our data), the low amplitude of variability during 2–6,000 yr BP, and the observation that almost all correlations could be improved by small age adjustments. It is important to point out that in addition to the radiocarbon measurement uncertainty (Table 1), the largest source of age error is probably related to small unknown variations in the surface-ocean reservoir age in both the Atlantic Ocean and the Arabian Sea during the Holocene. Despite these problems, the observations provide strong support for the view that throughout the Holocene, cool episodes in the North Atlantic are accompanied by weakening of the Asian southwest monsoon wind, just as they are for the larger, more readily observable Dansgaard–Oeschger cycles of the last glacial.

Variations in solar output have been suggested as the driver of both the North Atlantic cycles[4] and the variations in Oman precipitation[16]. Solar variations could influence the monsoon regime indirectly, perhaps amplified by the North Atlantic teleconnection, on the basis of numerical simulations of North Atlantic cooling[1,20]. Alternately, solar variations could directly affect the land–sea contrast that drives the monsoon, on the basis of numerical simulations with reduced solar output during the Maunder minimum[21]. These papers[1,20,21] indicate that the monsoon could be sensitive to relatively small changes in forcing (0.25% change in solar output, or a 2 °C change in sea surface temperature). Internal forcing caused by oscillations in North Atlantic northward heat transport/deep-water production are an alternative explanation that excludes the role of insolation. To discriminate among these hypotheses more records are needed, particularly those that quantify the magnitude of sea surface temperature change in the North Atlantic and the magnitude of change in the monsoon.

The North Atlantic Medieval Warm Period and Little Ice Age can be considered to be the most recent in a seemingly persistent series of small-amplitude changes in the Holocene climate of the North Atlantic region. Splicing previously studied box core RC 2730[22] with the Site 723 record allows us to examine the last 2,000 yr in greater detail (Fig. 3). We find a broad increase in *G. bulloides* at 600–1,200 yr BP that correlates with a minimum in haematite and with warmer sea surface temperature at the Bermuda rise, North Atlantic[23] (labelled MWP—'Medieval Warm Period'—in Fig. 3a), and a minimum in *G. bulloides* at approximately 300–400 yr BP that correlates with a brief maximum in haematite and with cooling at Bermuda rise during the Little Ice Age (LIA in Fig. 3a). The monsoon record also correlates with the Medieval Warm Period along the east Greenland margin indicated by increased abundance of *Cassidulina teretis*[24] (Fig. 3b). Although not exact, the correlations are unambiguous and allow us to conclude that as for the entire Holocene, the most recent cycles in the North Atlantic have counterparts in the Asian southwest monsoon (Fig. 3c).

The significance of our results lies in demonstrating a pattern of persistent variability in the monsoon throughout the Holocene that may be linked with episodic warming/cooling of the North Atlantic. These results indicate that subtle interglacial changes in the North Atlantic, and not just large glacial changes, may have a significant effect on the strength of the Asian monsoon system. Our results highlight the need to improve our understanding of abrupt (and difficult to predict) weakening in monsoon strength that could accompany abrupt climate shifts in the North Atlantic that may occur in the future[25,26], further complicating efforts to plan for the future in the world's most populous region. □

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1. Overpeck, J. T., Anderson, D. M., Trumbore, S. & Prell, W. L. The Southwest Monsoon over the last 18,000 years. *Clim. Dyn.* **12,** 213–225 (1996).
2. Schulz, H., Rad, U. & Erlenkeuser, H. Correlations between Arabian Sea and Greenland climate oscillations of the past 110,00 years. *Nature* **393,** 54–57 (1998).
3. Altabet, M. A., Higginson, M. J. & Murray, D. W. The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric CO_2. *Nature* **415,** 159–162 (2002).
4. Bond, G. *et al.* Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294,** 2130–2136 (2001).
5. Sirocko, F., Leuschner, D., Staubwasser, M., Maley, J. & Heusser, L. in *Mechanisms of Global Climate Change at Millennial Time Scales* (eds Clark, P., Webb, R. S. & Keigwin, L. D.) 113–126 (American Geophysical Union, Washington DC, 1999).
6. Prell, W. L. in *Climate Processes and Climate Sensitivity* (eds Hansen, J. E. & Takahashi, T.) 48–57 (American Geophysical Union, Washington DC, 1984).
7. Anderson, D. M. & Prell, W. L. A 300 kyr record of upwelling off Oman during the late Quaternary: Evidence of the Asian Southwest Monsoon. *Paleoceanography* **8,** 193–208 (1993).
8. Naidu, P. D. & Malmgren, B. J. A high resolution record of late Quaternary upwelling along the Oman Margin, Arabian Sea based on planktonic foraminifera. *Paleoceanography* **11,** 129–140 (1996).
9. Curry, W. B., Ostermann, D. R., Guptha, M. V. S. & Ittekkot, V. in *Upwelling Systems: Evolution since the Early Miocene* (eds Summerhayes, C. P., Prell, W. L. & Emeis, K. C.) 93–106 (The Geological Society, London, 1992).
10. Prell, W. L. & Campo, E. V. Coherent response of Arabian Sea upwelling and pollen transport to late Quarternary monsoonal winds. *Nature* **323,** 526–528 (1986).
11. Clemens, S. C., Prell, W. L., Murray, D. W., Shimmield, G. & Weedon, G. Forcing mechanisms of the Indian Ocean monsoon. *Nature* **353,** 720–725 (1991).
12. Gupta, A. K., Dhingra, H., Melice, J.-C & Anderson, D. M. Earth's eccentricity cycles and Indian Summer Monsoon variability over the past 2 million years: evidence from deep sea benthic foraminifer. *Geophys. Res. Lett.* **28,** 4131–4134 (2001).
13. Barnett, T. P., Dumenil, L., Schlese, U., Roeckner, E. & Latif, M. The effect of Eurasian snow cover on regional and global climate variations. *J. Atmos. Sci.* **46,** 661–684 (1989).
14. Meehl, G. A. Influence of the land surface on the Asian summer monsoon, external conditions versus internal feedbacks. *J. Clim.* **7,** 1033–1049 (1994).
15. Bond, G. *et al.* A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. *Science* **278,** 1257–1266 (1997).
16. Neff, U. *et al.* Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature* **411,** 290–293 (2001).
17. Wang, L. *et al.* Holocene variations in Asian monsoon moisture: a bidecadal sediment record from the South China Sea. *Geophys. Res. Lett.* **26,** 2889–2892 (1999).
18. Berger, A. L. Long-term variations of daily insolation and Quaternary climatic changes. *J. Atmos. Sci.* **35,** 2362–2367 (1978).
19. Alley, R. B. *et al.* Holocene climatic instability: a prominent, widespread event 8200 years ago. *Geology* **25,** 483–486 (1997).
20. Rind, D. J. & Overpeck, J. T. Hypothesized causes of decade- to century-scale climatic variability: climate model results. *Quat. Sci. Rev.* **12,** 357–374 (1993).
21. Shindell, D. T. *et al.* Solar forcing of regional climate change during the Maunder minimum. *Science* **294,** 2149–2152 (2001).
22. Anderson, D. M., Overpeck, J. T. & Gupta, A. K. Increase in the Asian SW monsoon during the past four centuries. *Science* **297,** 596–599 (2002).
23. Keigwin, L. D. The little ice age and medieval warm period in the Sargasso Sea. *Science* **274,** 1504–1508 (1996).
24. Jennings, A. J. & Weiner, N. J. Environmental change in eastern Greenland during the last 1300 years: evidence from foraminifera and lithofacies in Nansen fjord, 68°N. *Holocene* **6,** 179–191 (1996).
25. Manabe, S. & Stouffer, R. J. Century-scale effects of increased atmospheric CO_2 on the ocean-atmosphere system. *Nature* **364,** 215–218 (1993).
26. Houghton, J. T *et al.* (eds) *Climate Change 2001: The Scientific Basis* (Cambridge Univ. Press, New York, 2001).
27. Trenberth, K., Olson, J. & Large, W. A global ocean wind stress climatology based on ECMWF analyses. Technical Note NCAR/TN-388 + STR, 1–93 (National Center for Atmospheric Research, Colorado, Boulder, 1989).
28. Reynolds, R. W. & Smith, T. M. A high-resolution global sea surface temperature climatology. *J. Clim.* **8,** 1571–1583 (1995).
29. Janowiak, J. & Xie, P. CAMS-OPI: A global satellite-rain gauge merged product for real-time precipitation monitoring applications. *J. Clim.* **12,** 3335–3342 (1999).
30. Stuiver, M. & Reimer, P. J. Extended ^{14}C data base and revised radiocarbon age calibration program. *Radiocarbon* **35,** 215–230 (1993).

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Reductive dehalogenation of chlorinated dioxins by an anaerobic bacterium

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Polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDDs and PCDFs) are among the most notorious environmental pollutants. Some congeners, particularly those with lateral chlorine substitutions at positions 2, 3, 7 and 8, are extremely toxic and carcinogenic to humans[1]. One particularly promising mechanism for the detoxification of PCDDs and PCDFs is microbial reductive dechlorination. So far only a limited number of phylogenetically diverse anaerobic bacteria have been found that couple the reductive dehalogenation of chlorinated compounds—the substitution of a chlorine for a hydrogen atom—to energy conservation and growth in a process called dehalorespiration[2]. Microbial dechlorination of PCDDs occurs in sediments and anaerobic mixed cultures from sediments, but the responsible organisms have not yet been identified or isolated. Here we show the presence of a *Dehalococcoides* species in four dioxin-dechlorinating enrichment cultures from a freshwater sediment highly contaminated with PCDDs and PCDFs. We also show that the previously described chlorobenzene-dehalorespiring bacterium *Dehalococcoides* sp. strain CBDB1 (ref. 3) is able to reductively dechlorinate selected dioxin congeners. Reductive dechlorination of 1,2,3,7,8-pentachlorodibenzo-*p*-dioxin (PeCDD) demonstrates that environmentally significant dioxins are attacked by this bacterium.

PCDDs and PCDFs are ubiquitous and recalcitrant environmental pollutants[4,5]. Continuing anthropogenic contamination with PCDDs and PCDFs, formed as unwanted by-products of manufacturing and incineration processes, is of great public concern owing to the compounds' toxicity and tendency to bioaccumulate and biomagnify in wildlife and humans. Natural sources of dioxins include volcanic activities, forest fires, production by biological systems[6,7] and as yet unknown formation processes[8,9]. Because of their high hydrophobicity, dioxins are strongly adsorbed on organic matter and they therefore accumulate in aquatic sediments and soils, where conditions might be anaerobic. The only known biological process leading to a transformation of the highly chlorinated congeners under anaerobic conditions is the microbially mediated reductive dechlorination observed in microcosms or mixed cultures[10–15]. Different sources of PCDDs and PCDFs introduce different complex mixtures of PCDD and PCDF congeners into the environment. The extent to which intrinsic microbes change these source-specific profiles *in situ* is largely unknown, although studies of sediment cores of Lake Ketelmeer, a sedimentation area of the river Rhine in The Netherlands, have shown a change of congener distribution over time[16]. This observation can be taken as an indication that highly chlorinated dioxins are subject to anaerobic dehalogenation processes *in situ*. Our knowledge of the organisms involved in PCDD dechlorination is currently very limited. Until now, no pure culture with the ability to reductively dechlorinate dioxins has been described.

We have previously examined the reductive dehalogenation of selected dioxin congeners by anaerobic mixed cultures[17]. These enrichment cultures were established with various sediment samples from the stream Spittelwasser (Bitterfeld district, Germany), which contains dioxin at concentrations of up to 120,000 pg toxicity equivalents (I-TEQ) per g dry weight. Spiked 1,2,3,4-tetrachlorodibenzo-*p*-dioxin (TeCDD) (50 μM) was converted to a mixture of 1,3- and 2,3-dichlorodibenzo-*p*-dioxin (DiCDD). In previous experiments, the transformation pathways

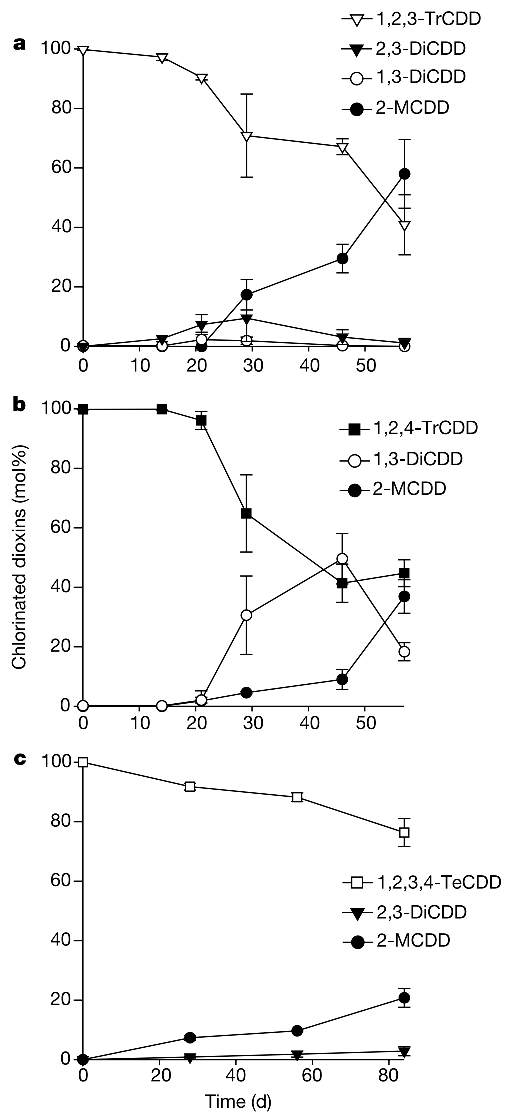

Figure 1 Time course of reductive dechlorination of 25 μM 1,2,3-TrCDD (**a**), 60 μM 1,2,4-TrCDD (**b**) and 46 μM 1,2,3,4-TeCDD (**c**) by *Dehalococcoides* sp. strain CBDB1. Molar distributions of the parent compounds and their dechlorination products are shown. Values are means and s.d. for triplicate samples. No dechlorination products were detected in sterile controls after 75 days (**a**, **b**) and 84 days (**c**).

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