**Hydrological Impact of Heinrich Events in the Subtropical Northeast Atlantic**

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Reconstructing the impact of Heinrich events outside the main belt of ice rafting is crucial to understanding the underlying causes of these abrupt climatic events. A high-resolution study of a marine sediment core from the Iberian margin demonstrates that this midlatitude area was strongly affected both by cooling and advection of low-salinity arctic water masses during the last three Heinrich events. These paleoclimatic time series reveal the internal complexity of each of the last three Heinrich events and illustrate the value of parallel studies of the organic and inorganic fractions of the sediments.

The influence of Heinrich events has sometimes been invoked to explain unusual high-frequency climatic events at low latitudes [e.g., (11)]. Abrupt decreases of sea surface temperature (SST) in phase with Heinrich events were detected in sediments of the Bermuda Rise (12) and the Mediterranean Sea (13). Further south, the tropical western Atlantic apparently warmed during H1 and the Younger Dryas (YD) (14). The strong, direct effect of melting icebergs is generally thought to be restricted to a North Atlantic belt between 40°N and 55°N, where IRD forms distinct layers in the sediments (15). The occurrence and climatic impact of H events are still poorly documented in the northeast Atlantic, especially at subtropical latitudes.

To reveal the impact of H events on the northeast Atlantic, we focused our study on the paleoceanographic variability in a mid-latitude core from the Iberian margin (SUB118 located at 37°46′N, 10°11′W and 3135 m depth) (Fig. 1). One of the main advantages of using SUB118 is that it is one of the best-dated cores available for the last deglaciation (16). These sediments are characterized by a high sedimentation rate (>20 cm/1000 years during the glacial and deglacial sections) which has been constrained by numerous 14C accelerator mass spectrometry (AMS) ages and stable isotope records (17).

SST changes were reconstructed with the alkenone unsaturation ratios (Fig. 2B and Web table 1) (18, 19), and counts of IRD (Fig. 2B and Web table 1) (18, 20) and magnetic susceptibility (MS; Fig. 2B) (21) were used to identify transported sediments. The alkenone temperature estimates are on the order of 18°C during the last 5000 years, which is between the modern annual mean (17.5°C) and the SST during summer months (19°C) when most of the local primary productivity takes place. With an average sampling resolution of ∼250 years, the alkenone-SST record shows the classical climate history of the Late Glacial: the Holocene starts at 11,500 calendar years before present (cal yr B.P.), the YD event is centered at about 12,000 cal yr B.P., and the Allerød-Bølling interstadial occurs between 13,000 and 15,000 cal yr B.P. Interestingly, the LGM in the strictest sense (21,000 ± 2000 cal yr B.P.) is a rather mild period, with SST on the order of 13°C, i.e., about 5°C lower than modern SST. In addition, the glacial period is characterized by a rather large variability with abrupt cold spells centered at about 16,000, 23,500, 26,000, and 31,000 cal yr B.P.

Figure 2B shows the IRD counts and the MS record which can be used to identify detrital material usually attributed to H events. These are clearly expressed in both records between 18,000 and 15,500 cal yr B.P. for H1 and between 26,000 and 23,000 cal yr B.P. for H2. The MS and mineralogical records (20) also suggest that each of these two events were complex and characterized by two depositional phases centered at 16,000 (H1a) and 17,500 (H1b) cal yr B.P. for H1 and at 23,500 (H2a) and 25,000 (H2b) cal yr B.P. for H2. Our results

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C37:4 peaks is obviously not accidental and

strengthen earlier suggestions of twinned IRD
peaks in some cores of the Portuguese margin (22). Interestingly, only the late depositional phases are well expressed in the IRD records: there is a lack of IRD at about 25,000 cal yr B.P. and only a slight increase around 17,500 cal yr B.P. An alternative explanation of the multiple peaks is that they belong to the pervasive millennial-scale cycle that consistently punctuates the intervals between H events and the Holocene period (2). Furthermore, the alkenone-SST record is also characterized by small shifts at about 21,500 and 29,000 cal yr B.P. (Fig. 2A) which may be explained by the same cyclicity (the latter cooling is even associated with an MS peak).

H3 may be only partly expressed in core
SU8118, because the oldest sediment in this core is about 31,500 cal yr B.P. However, it is clear that the SST decrease and MS increase measured in the lowermost section do indeed correspond to H3 even though there is no IRD increase in the same sediment levels. Low IRD concentrations during H3 have already been described in sediments of the main IRD belt (3), north of the Azores (23), and off Portugal (24) [although a small IRD peak was detected farther offshore (22)]. The sole presence of an MS signal could be accounted for if the material transported by icebergs was all finer than 150 µm.

From Fig. 2, A and B, it is clear that strong and sharp cooling events coincide with all phases of H events H1a and H1b, H2a and H2b, and H3. It is worth noting that Zhao et al. (25) observed alkenone-SST drops off Mauritania roughly synchronous with H events, although the tentative chronology of their cores was not directly based on 

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Collectively, the observations based on alkenones indicate a significant increase (+3°C) in the east-west gradient of SST of the low-latitude North Atlantic during these two recent climatic events.

A by-product of the alkenone analyses in SU8118 is the discovery of large and systematic variations of the abundance of tetra-unsaturated C37:4 alkenones (C37:4, molecular mass of 526). Percentages higher than 5% of the total C37:4 alkenones are restricted to very distinct periods centered around 31,000, 23,500, and 16,000 cal yr B.P. (Fig. 2C). These distinct C37:4 peaks are clearly synchronous with H2a, H2b, H1a, and H1b. We also note an absence of such a peak during event H2b and a rather weak signal during the YD event.

Although the abundance of C37:4 alkene was originally used for paleothermometry (26, 27), Sikes et al. (28) analyzed core-tops from the Southern ocean and suggested that this compound may not actually be linked to SST. Subsequently, Rosell-Melé (29) proposed that this particular alkenone is linked to low-salinity water masses and that a C37:4 increase of about 5 to 10% corresponds to a freshening of one practical salinity unit (PSU). Further research is still needed to decipher if indeed salinity has a direct effect on the C37:4 biosynthesis or if the observed pattern is due to a metabolic difference of coccolithophorids endemic of arctic or coastal water masses (30). Even if this latter hypothesis is confirmed, the C37:4 abundances may still be used to study the surface advection of iceberg-bearing water masses together with their living arctic alkenone producers. In any case, C37:4 levels in SU8118 are similar during the LGM and the Holocene, which indicates that this molecule is not simply correlated to SST because it behaves differently than the more abundant di- (C37:2) and tri-unsaturated (C37:3) methyl ketones used in the U37O index.

Applying the Rosell-Melé (29) calibration to our C37:4 record leads to the conclusion that the salinity dropped by 1 to 2 PSU off Portugal during the last of the H events. This is in agreement with a salinity decrease of 2 to 3 PSU inferred for H1 which was based on 

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Several authors recognized that H3 presents some unusual features compared to other H events (1–4, 33). Gwiazda et al. (33) even proposed that, when it is present, the IRD concentration peak could be due to a lack of foraminifera caused either by dissolution or low primary productivity, and they concluded that the iceberg discharge melted mostly in the western basin of the North Atlantic.

The absence in core SU8118 of an IRD peak during H3 would be compatible with this theory, but the C37:4 SST, and MS records strongly suggest that meltwater reached the eastern basin of the North Atlantic during this period. Independent evidence of salinity changes may also be possible from the simultaneous analyses of Mg/Ca and 

18O in the same shells of planktonic foraminifera (34).
New paleoclimatic records measured in core SU8118 represented versus calendar age based on the 14C-dated tie points shown as triangles in (C) [see (16) for details]. Climatic events are abbreviated as follows: Holocene; YD, Younger Dryas; A-B, Allerød-Bølling; H1, Heinrich 1; and LGM, Last Glacial Maximum. (A) The three curves represent the C37 alkene unsaturation data converted in terms of SST by using three different calibrations titled the Holocene, --1°C during the Allerød-Bølling and the Last Glacial Maximum (LGM), but usually more than 2°C only during the last three H events. These results agree with a study of high-latitude (>65°N) sediments (43) suggesting that low alkenone-SSTs are more uncertain, especially when associated with IRD injections. One possible problem sometimes encountered in sediments from the northern North Atlantic is the rather low concentration of alkenones, which makes them more susceptible to contamination by reworked sediment transport. Indeed, Weaver et al. (42) measured extremely low concentrations of alkenones (<0.001 µg/g) in the glacial section of a core and suggested a contribution by older reworked alkenones. As shown in Web table 1, the C37 alkene concentrations in the glacial section of core SU8118 are always rather high (>0.4 µg/g), making this problem rather unlikely. A further argument considers deep-sea currents. The modern deep circulation off Portugal is characterized by northward advection of Mediterranean outflow water (MOW) and Antarctic bottom water (AABW) bracketing the southward flow of North Atlantic deep water (NADW) which bathes the location of SU8118. During the LGM and H events, it has been shown that the NADW flow was weaker about 400 years (44, 45) and that the boundary between MOW and NADW was deeper (44, 45) at about 37°N latitude, the 14C reservoir age probably has remained constant through time at about 400 years (37). By contrast, sites located farther north in the Atlantic may have experienced abrupt changes in their 14C reservoir ages (37, 38).

16. Supplementary table is available at www.sciencemag.org/feature/data/1050685.shl

19. Analytical techniques used for alkenones at CEREGE are described elsewhere (39). The relative degree of unsaturation are expressed by the U37K index ([C37:2]/[C37:3 + C37:4]) or the index ([C37:4 - C37:2]/[C37:2 + C37:4 + C37:9]) and the alkene total concentration ([C37:4 + C37:2 + C37:9]) is given in µg of dry weight sediment. The precision of U37K measurements is about 0.01 unit (i.e., −0.3°C) and about 20% for alkene concentrations. Figure 2A shows the temperature estimates based on a culture calibration [T = (U37K - 0.093)/0.026]. (2) in Web table 1 based on U37K measured in modern sediments from the northeast Atlantic (26). The dotted curve (3) in Web table 1 uses the North Atlantic calibration, T = (U37K - 0.093)/0.003, based on the original definition of the U37K index. (26). The maximum SST difference is <1°C during the Holocene, --1°C during the Allerød-Bølling and the Last Glacial Maximum (LGM), but usually more than 2°C only during the last three H events. These results agree with a study of high-latitude (>65°N) sediments (43) suggesting that low alkenone-SSTs are more uncertain, especially when associated with IRD injections. One possible problem sometimes encountered in sediments from the northern North Atlantic is the rather low concentration of alkenones, which makes them more susceptible to contamination by reworked sediment transport. Indeed, Weaver et al. (42) measured extremely low concentrations of alkenones (<0.001 µg/g) in the glacial section of a core and suggested a contribution by older reworked alkenones. As shown in Web table 1, the C37 alkene concentrations in the glacial section of core SU8118 are always rather high (>0.4 µg/g), making this problem rather unlikely. A further argument considers deep-sea currents. The modern deep circulation off Portugal is characterized by northward advection of Mediterranean outflow water (MOW) and Antarctic bottom water (AABW) bracketing the southward flow of North Atlantic deep water (NADW) which bathes the location of SU8118. During the LGM and H events, it has been shown that the NADW flow was weaker (44, 45) and that the boundary between MOW and NADW was deeper (44). Contribution of detrital

References and Notes

16. The time scale of core SU8118 used in this study is based on translating the original AMS 14C ages (17) into calendar ages by means of the most recent 14C calibrations (35, 36). Beyond 20,000 cal yr B.P., we also used the 14C ages measured on a nearby core, MD952039, which is precisely tied to SU8118 through correlation of magnetic properties records (27). The 14C control points used to derive the final chronology are shown as triangles on Fig. 2C. Because the total length of the core is limited to 7 m, the Late Glacial section of core SU8118 is probably free of stretching, which can occur in giant piston cores (27). In addition, at about 37°N latitude, the 14C reservoir age probably has remained constant through time at about 400 years (37). By contrast, sites located farther north in the Atlantic may have experienced abrupt changes in their 14C reservoir ages (37, 38).

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19. Analytical techniques used for alkenones at CEREGE are described elsewhere (39). The relative degree of unsaturation are expressed by the U37K index ([C37:2]/[C37:2 + C37:3]) or the index ([C37:4 - C37:2]/[C37:2 + C37:4 + C37:9]) and the alkene total concentration ([C37:4 + C37:2 + C37:9]) is given in µg of dry weight sediment. The precision of U37K measurements is about 0.01 unit (i.e., −0.3°C) and about 20% for alkene concentrations. Figure 2A shows the temperature estimates based on a culture calibration [T = (U37K - 0.093)/0.026]. (2) in Web table 1 based on U37K measured in modern sediments from the northeast Atlantic (26). The dotted curve (3) in Web table 1 uses the North Atlantic calibration, T = (U37K - 0.093)/0.003, based on the original definition of the U37K index. (26). The maximum SST difference is <1°C during the Holocene, −1°C during the Allerød-Bølling and the Last Glacial Maximum (LGM), but usually more than 2°C only during the last three H events. These results agree with a study of high-latitude (>65°N) sediments (43) suggesting that low alkenone-SSTs are more uncertain, especially when associated with IRD injections. One possible problem sometimes encountered in sediments from the northern North Atlantic is the rather low concentration of alkenones, which makes them more susceptible to contamination by reworked sediment transport. Indeed, Weaver et al. (42) measured extremely low concentrations of alkenones (<0.001 µg/g) in the glacial section of a core and suggested a contribution by older reworked alkenones. As shown in Web table 1, the C37 alkene concentrations in the glacial section of core SU8118 are always rather high (>0.4 µg/g), making this problem rather unlikely. A further argument considers deep-sea currents. The modern deep circulation off Portugal is characterized by northward advection of Mediterranean outflow water (MOW) and Antarctic bottom water (AABW) bracketing the southward flow of North Atlantic deep water (NADW) which bathes the location of SU8118. During the LGM and H events, it has been shown that the NADW flow was weaker (44, 45) and that the boundary between MOW and NADW was deeper (44). Contribution of detrital
alkenones advected by deep waters originating from high northern latitudes is thus very unlikely. A similar argument can be made against a significant contribution of NADW to the concentration of fine-grained magmatic as could occur in sediments farther north ([66]).

20. The IRD studied at DGO (Talence, France) are expressed in number per gram for the size fraction greater than 150 μm (sample size for counting is 10 g of dry sediments). The complexity of H1 and H2 is further demonstrated by their mineralogical composition: The H2a IRD peak centered at 23,000 cal yr B.P. is characterized by a dominance of quartz (84%), with a presence of feldspars (5%), detrital carbonates (3%), and hematite-coated grains (2%). Broadly similar, the H1a IRD peak at 16,000 cal yr B.P. is dominated by grains of quartz (76%) and feldspars (14%), with small percentages of hematite-coated grains (3%), glauconite (3%), volcanic shards (1%), and an almost complete lack of detrital carbonate. By contrast, the smaller IRD peak at 17,500 cal yr B.P. (H1b) is composed mainly of detrital carbonates (80%), with secondary contributions of quartz (16%) and feldspar (3%).


42. P. P. E. Weaver et al., Paleogeography 14, 336 (1999).


We acknowledge helpful discussions or reviews by G. C. Bond, C. De La Rocha, R. Rickaby, A. Rosell-Melé, E. L. Sikes, N. Thouveny, and anonymous referees. We thank J.-S. Motte for drawing Fig. 1. This work is supported by CNRS Programme National d’Etudes de la Dynamique et du Climat and the European Community (projects ENV4-CT97-0564, FMRX-CT96-0046, and ENV4-CT97-0639).

22 March 2000; accepted 16 June 2000

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**REPORTS**

**Discrete Atom Imaging of One-Dimensional Crystals Formed Within Single-Walled Carbon Nanotubes**


The complete crystallography of a one-dimensional crystal of potassium iodide encapsulated within a 1.6-nanometer-diameter single-walled carbon nanotube has been determined with high-resolution transmission electron microscopy. Individual atoms of potassium and iodine within the crystal were identified from a phase image that was reconstructed with a modified focal series restoration approach. The lattice spacings within the crystal are substantially different from those in bulk potassium iodide. This is attributed to the reduced coordination of the surface atoms of the crystal and the close proximity of the van der Waals surface of the confining nanotube.

The synthesis and characterization of one-dimensional (1D) crystals that have a well-specified chemistry, size, and crystal structure have presented a formidable challenge for materials chemistry and analysis. Here, we show that both the widths and the lattice spacings of 1D crystals can be tailored by encapsulating them within single-walled carbon nanotubes (SWNTs) (7). The resulting crystals can be tens of micrometers in length yet only two or three atoms in width. We illustrate our results for a <110> projection of a discrete KI crystal that is three atomic layers thick and formed within a SWNT, in which the crystal thickness varies in a strictly integral fashion on an atomic scale.

Conventional high-resolution transmission electron microscopy (HRTEM) has previously been used to image single heavy atoms on crystal surfaces and amorphous support films (2–6). The technique can be applied in the same way to provide structural information about a crystal incorporated within a SWNT. However, the image contrast is weak and noisy, and it is, in general, only possible to identify strongly scattering species such as K in an encapsulated KI crystal (see below). A single HRTEM image is also subject to artifacts due to lens aberrations such as defocus, astigmatism, and beam tilt, particularly near the edge of a crystal. These problems can be overcome by recovering the amplitude and phase of the electron wave function at the exit surface of a sample from either a focal (7–9) or a tilt azimuth (10, 11) series of images. The procedure involves the determination of the lens aberrations and a numerical reconstruction of the exit plane wave function by using a Wiener filter. The restored wave function can then be used to calculate the high-spatial-frequency components of the phase shift of the electron wave as it leaves the sample. This phase image is free of artifacts introduced by objective lens aberrations and is higher in resolution and less noisy than an individual HRTEM image. It is also less noisy than an equivalent atomic resolution phase image obtained by electron holography (12). For a sufficiently thin crystal, the recorded phase can be interpreted intuitively because it is directly proportional to the projected potential of the sample integrated in the incident beam direction (13). However, the technique imposes strict requirements on specimen and instrumental stability and must be applied with great care to SWNTs, which are damaged readily by over-exposure to a high-energy electron beam.

SWNTs were synthesized with a modified high-yield arc synthesis technique (14) and filled with highly pure KI (99.99%) (Aldrich) through a capillary filling method (1, 15). The specimen was characterized at 300 kV in a Japan Electron Optics Laboratory (JEOL) JEM-3000F field emission gun transmission electron microscope (16–18). Figure 1A shows a phase image reconstructed from a 20-member focal series of a 1.6-nanometer diameter SWNT containing a KI single crystal (19). In cross section, the encapsulated crystal can be regarded as a single KI unit cell viewed along