Supporting Information for

Anatomy of Heinrich Layer 1 and its Role in the Last Deglaciation

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Introduction

The supplementary information contains details of the methods (Text S1-S8), 10 supplementary figures (Figures S1-S8) and 4 tables (Tables S1-S4) to support the paper. Visualization of the X-ray CT scans are provided by two movies (Movie S1-S2) of false-color density from the CT scans for Heinrich Event 1 in Holes U1308A and U1308B. Visualization of the sediment coarse fraction (>150 µm) for the interval from 78 to 91 cm in Section U1308A-1H-1 is provided through a series of digital microscope images at 10x, 60x and 100x (Data Sets S1-S3). All data are archived with Pangaea (https://www.pangaea.de/) and NOAA (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data) information systems.

Text S1.

X-ray Fluorescence Core Scanning: XRF Core Scanner data were collected every millimeter down-core with a slit size of 1mm x 12mm using generator settings of 10 kV and 30kV, a current of 1 mA (0.25mA at 5mm/10kV run), and a sampling time of 30 seconds directly at the split core surface of the archive half with Avaatech XRF Core Scanner III at the MARUM - Center for Marine Environmental Sciences, University of Bremen. The split core surface was covered with a 4 micron thin SPEX Certi Prep UltraleneI foil to avoid contamination of the XRF measurement unit and desiccation of the sediment. The data reported here were acquired by a Canberra X-PIPS Silicon Drift Detector (SDD; Model SXD 15C-150-500) with 150eV X-ray resolution, the Canberra Digital Spectrum Analyzer DAS 1000 and an Oxford Instruments 100W Neptune X-ray tube with rhodium (Rh) target material. Raw data spectra were processed by the Analysis of X-ray spectra by Iterative Least square software (WIN AXIL) package from Canberra Eurisys.

Text S2.

X-ray Diffraction (XRD): Samples for XRD were ground manually to a powder with a mortar and pestle. A small quantity was placed on a level glass plate and acetone was added to level the surface before drying, and placing in a level jig in the x-ray diffractometer. Data were collected in Bragg-Brentano geometry on a D8 Bruker diffractometer equipped with primary Gobbel mirrors for parallel Cu Ka X-rays and a Vantec position sensitive linear detector at the University of Cambridge. Collection conditions were: 10-70° in 2θ, 0.02 step size, 450 seconds/step, divergence slit 0.2 mm. Rietveld refinements were performed with software Topas 4.0 (Cohelo, 2007) to estimate relative abundances of quartz, orthoclase, albite, calcite, dolomite and halite. Crystal structures of all phases were retrieved from the ICSD (Allmann and Hinek, 2007). Rietveld analysis is considered unreliable for minor phases (<5 wt %), with an accuracy of ±1-2% for major phases for the model used here (Madsen and Scarlett, 2008).

Text S3.

X-ray computerized tomography (CT) scanning and Image Processing: X-ray CT images were acquired with the “General Electric CT Prospeed SX” CT scanner at the MARUM - Center for Marine
Environmental Sciences, University of Bremen. Overview (scout) scans were processed over a 50-cm interval using 51.2 x 51.2 cm field of view (FOV) and generator settings of 120 kV and a current of 80 mA for the tube power (Fig. S1). To enable a complete 3D visualization 1 mm thick slice images with a FOV of 12 x 12 cm have been obtained in 1 mm down-core resolution using 120 kV and 100 mA to ensure maximum quality of the images. Images were saved as greyscale DICOM (Digital Imaging and Communication in Medicine) files, in sets of 50 images (50-mm sections of core).

The resulting images were processed with the open source image processing package FIJI that was employed for visualization and quantification of the CT scans of the sediment cores. In order to calculate both particle statistics as well as average core density, the x-ray tomographic volume data was segmented to identify and label pixels as either high-density IRD grains or as low-density background sediment. The first step in the segmentation process creates a mask to isolate the sediment material from the core liner running the length of the core. Once the core liner has been removed, we use the absorption intensity as a proxy for density measurements. We determine the average density of the core by averaging the pixel intensity for each 1-mm slice of the reconstructed volume, removing the background and cracks. We scale each slice density tomogram to the overall mean IRD, which produces the density curve shown in Fig. 4.

Movies of the CT X-ray scans of the two cores were generated by loading x-ray reconstruction image stacks into the open-source, multi-platform data analysis and visualization application, Paraview (Fig. S2 and S3 and Movies S1 and S2). The resulting volume render of the recognition is made using color transfer map based on the normalized x-ray absorption intensity. This gives us a relative density map, with higher density being assigned a low transparency by the color transfer function. Using the animation tools in Paraview we are then able to record a camera orbit around the cores.

IRD particle sizes are determined by segmenting the Heinrich core tomogram for the high density voxels. The exact value of the pixel intensity that corresponds to IRD varies slightly from hole to hole as well as within the core. For analysis, we selected pixel intensities that would extract the largest grains in the Heinrich layers. This allows us to determine how these IRD grains relate to the event at the expense of high spatial resolution of the smallest particles. Owing to the large amount of high-density material in the Heinrich layers, it is a non-trivial task to segment with a single grey scale within and outside of the layer. Moreover as particle size becomes smaller, particles of the same material will absorb less. Advanced image processing methods potentially would allow for the segmentation of small particles within the Heinrich event as well as in sediments on either side of the layer. The resulting binary tomogram of the stack represents the largest most absorbing particles in the core. Using BoneJ we were able to obtain particle volume and orientation information for every particle that it labels [Doube et al., 2010]. For orientation information we use the best-fit ellipsoid unit vectors. The orientation of the ellipsoid axes indicate that the
majority of the IRD grains are oriented with their major and intermediate axes parallel to the sea floor and their minor axes vertically upwards (Figs. S4, S4, S6).

**Text S4.**

*Core Sampling and IRD Point Counting:* Discrete sampling of the core was carried out at 0.5-cm intervals over the interval of Heinrich Event 1 in Hole U1308A. Samples were taken from the working half of the core, the same half of core that was used for XRF measurements, in order to better correlate the sample measurements and XRF data. Point counting of IRD was carried out using an optical binocular microscope. Samples were sieved and the >150µm size fraction was split into subsamples of at least 300 grains. Data are expressed as %IRD and % detrital carbonate, where % IRD includes all lithics including detrital carbonate.

**Text S5.**

*Planktonic foraminifera assemblages:* We used a standard method for counting foraminifera (Vautravers et al., 2004; Vautravers and Shackleton, 2006). The size fraction >150 µm was subsampled using a micro-splitter until 1/32 of the original sample remained. This yielded between 300 and 600 grains. Each split-sample was spread on a gridded tray for identification and enumeration of planktonic foraminifera (Table S1). Particles were identified as planktonic foraminifera following the taxonomy of Kennett and Srinivasan (1983), planktonic foraminifer fragments, benthic foraminifera and ostracods, radiolarian, and ice-rafted detritus (undifferentiated).

**Text S6.**

*Stable isotopes:* Oxygen and carbon isotopes were measured on the planktonic foraminifer *N. pachyderma* (sin). Prior to analysis, foraminifer specimens were meticulously cleaned to remove any fine detrital carbonate from the test, which has been shown to have very low δ¹⁸O values (Hodell and Curtis, 2008). The samples were crushed between two glass plates to break the foraminifer tests, and any obvious detrital material was removed. To remove organic matter, foraminifer tests were either crushed and soaked in a solution of 1% hydrogen peroxide for 30 min in individual vials or roasted in vacuo in an oven for 1 hour at 400°C. The samples were then rinsed with UHQ H₂O and fine particles were suspended by ultrasonication, before being pipetted off. Acetone was added and the samples placed in an ultra-sonic bath for 10 s, after which the liquid was carefully decanted to remove any contaminants. The samples were dried in an oven at 50°C overnight.

For benthic foraminifer, *Cibicidoides wuellerstorfi, Cibicidoides kullenbergi,* and *Uvigerina peregrina* were picked from the >150µm fraction. Oxygen isotopes of *Cibicidoides* were corrected to *Uvigerina* by adding 0.64‰ (Fig. 10). Carbon isotopes of *Uvigerina* were disregarded as they reflect pore-water
values owing to the shallow infaunal habitat of this species. Isotopic ratios of foraminifer calcite were measured using a ThermoScientific MAT253 mass spectrometer fitted with a Kiel device. Analytical precision is estimated to be ±0.08‰ for δ18O and ±0.06‰ for δ13C, respectively.

Oxygen isotopes of bulk carbonate were measured using a ThermoScientific GasBench II, equipped with a CTC autosampler coupled to a DeltaV mass spectrometer (Spötl and Vennemann, 2003). Analytical precision is estimated to be ±0.1‰ for δ18O by repeated analysis of the Carrara Marble standard. All isotope measurements were made in the Godwin Laboratory, University of Cambridge, are reported relative to Vienna Pee Dee Belemnite (VPDB).

Text S7.  
Ichnology: Ichnological analysis was performed in Holes U1308A and U1308B in the parts of the cores that contain Heinrich Event 1, corresponding to intervals (7 to 18) in Figure 11. All CT images were analyzed in each of the intervals (12 images per interval) using established methods (Dorador and Rodriguez-Tovar, 2014; Dorador et al., 2014a, b; Rodriguez-Tovar and Dorador, 2015). Ichnological analysis included: (i) differentiation between biodeformational structures and trace fossils, (ii) ichnotaxonomical classification of the trace fossils, (iii) relative abundance, (iv) cross-cutting relationships, (v) bioturbation index (BI, according to Taylor and Goldring, 1993), and (vi) ichnofabric characterization.

Text S8.  
Radiocarbon and Age Model: Samples for dating were analyzed at the NERC radiocarbon facility in East Kilbride, Scotland (UK) and the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory in Irvine, California (USA) (Table S2). Prior to analysis, foraminiferal specimens were cleaned using a modified version of the clay- and organic removal cleaning steps described by Barker et al. (2003). This cleaning was performed to remove any organic material and, especially, to remove fine detrital carbonate that, being radiocarbon dead, would contaminate the measurements causing older ages. The samples were crushed between two glass plates to break the foraminifer tests, and any obvious detrital material was removed. The samples were then rinsed with UHQ H2O and clay minerals were suspended by ultrasonication, before being pipetted off. This step was performed five times, until the H2O in the sample vials appeared clear. The methanol cleaning step in this procedure was omitted to avoid contamination. To remove organic material, the samples were rinsed with 1% H2O2 solution and left for 10 minutes in a hot water bath with occasional agitation of the samples by ultrasonification. The liquid was then pipetted away. This step was performed twice. Samples were then dried in an oven.
The chronology for Section U1308A-1H-1 relies on eight radiocarbon dates of *N. pachyderma* (sin) from Hole U1308A (Table S2) combined with 15 radiocarbon dates from Bond et al. [1992] (Table S3). We have derived the calibrated age model using Marine13 [Reimer et al., 2013] within a Bayesian modeling (BACON) framework [Blaauw and Christen, 2011]. We used estimates of high-latitude North Atlantic reservoir ages and errors given by Stern and Lisiecki [2014]. Model parameters for BACON included an accumulation shape of 1.5, memory strength of 4, memory mean of 0.7 that were applied to 150x0.5cm sections. The age model was interpolated at 0.25 cm increments within a Monte Carlo framework and a 95% confidence interval. Samples are plotted using the weighted mean calibrated years BP (Table S4).

**References**


Dorador, J., F. J. Rodríguez-Tovar, and IODP Expedition 339 Scientists (2014a), Digital image treatment applied to ichnological analysis of marine core sediments, Facies, 60, 39-44.


Spötl, C. and T. W. Vennemann (2003), Continuous flow isotope ratio mass spectrometric analysis of carbonate minerals, Rapid Communications in Mass Spectrometry, 17 (9), 1004-1006.

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**Table S1.** Species list of planktonic foraminifera counted in Section U1308A-1H-1

- *Neogloboquadridina pachyderma (sinistral)*
- *Neogloboquadridina pachyderma (dextral)*
- *Globigerina bulloides*
- *Globorotalia inflata*
- *Globogerinita glutinata*
- *Turborotalia quinqueloba*
- *Globorotalia scitula*
- *Globigerina falconensis*
- *Glogogerina rubescens*
- *Globigerinoides ruber*
- *Globorotalia truncatulinoides*
- *Hastigerina aequilateralis*
- *Beela digitata*
**Table S2.** Radiocarbon dates in Section U1308A-1H-1.

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<th>Laboratory ID</th>
<th>Hole-Core-Section</th>
<th>Depth (cm)</th>
<th>Species</th>
<th>fraction</th>
<th>$\Delta$</th>
<th>$\Delta$C</th>
<th>14C years (uncorrected)</th>
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**Table S3.** Combined radiocarbon dates from Holes U1308A and 609. The reservoir correction is taken from Stern and Lisiecki (2014).

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<th>error</th>
<th>Reference</th>
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**Table S4.** The age model interpolated at 0.25 cm increments in Section U1308A-1H-1 derived using a Bayesian modeling (BACON) framework (Blaauw and Christen, 2011).

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<tr>
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<th>max Age (ka)</th>
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Figure S1. Overview (scout) X-ray CT scans of Section 1 in Holes U1308A and U1308B. Two distinct layers of dense sediment are visible in Hole U1308A (red arrows) whereas a single mixed layer occurs in Hole U1308B.
Figure S2. Frame shot of Movie S1 for Section U1308A-1H-1, 75-105 cm. Note the two distinct high-density layers associated with H1.1 and H1.2.
**Figure S3.** Frame shot of Movie S2 for Section U1308B-1H-1, 21-96 cm. Note that bioturbation has obliterated the internal structure of H1 in this hole.
Figure S4. Stereonet of the major ellipsoid axes of the IRD grains in the CT scan of Section U1308A-1H-1. The distribution indicates that the majority of the ellipsoid axes are oriented vertically upwards.
Figure S5. Stereonet of the intermediate ellipsoid axes of the IRD grains in the CT scan of Section U1308A-1H-1. The orientation of the intermediate ellipsoid axes indicates that most grains lie parallel to the sea floor.
Figure S6. Stereonet of the minor ellipsoid axes of the IRD grains in the CT scan of Section U1308A-1H-1. The orientation of the minor ellipsoid axes indicates that most grains lie parallel to the sea floor.
Figure S7. Core photos of Sections 609-1H-1 and 609B-1H-1 indicating the positions of radiocarbon dates (dashed lines). Yellow arrows indicate the base of Heinrich Layer 1 and green arrows the base of the Younger Dryas. The images are similar to those of Site U1308 (Fig. 2).
Figure S8 (A.) Percent detrital carbonate at Site 609 (black) [Bond et al., 1992] with position of radiocarbon dates indicated by vertical lines. (B.) Percent IRD (black) and N. pachyderma (sin) (red) in Section U1308A-1H-1 relative to the position of radiocarbon dates. The position of HL1.1 and HL 1.2 are indicated by gray shading. Note the similarity of the radiocarbon ages at the base of the two detrital carbonate peaks.
Figure S9. Calibrated radiocarbon dates (blue vertical lines) and the age-depth model using Bacon v. 2.2 versus depth (cm) in Section U1308A-1H-1. Darker greys indicate more likely calendar ages; grey stippled lines show 95% confidence intervals; red curve shows single 'best' model based on the weighted mean age for each depth.
Figure S10. Ca/Sr record for Section U1308A-1H-1 using the minimum, mean/median, and maximum ages estimated using Bacon. The mean and median ages were indistinguishable from one another and are plotted together. The ages of the peaks are given for H1.1, H1.2 and H2.
Figure S11. Ca/Sr from IODP Site U1302/03 located in a water depth of 3600m on Orphan Knoll. DC0= Detrital Carbonate Event 0 associated with the Younger Dryas. The small Ca/Sr peak between HL1.1 and DC0 might represent HL1.2.
Figure S11. Scanning electron microscopy (SEM) photomicrographs showing that both detrital and authigenic dolomite is present in Heinrich layers. (A) Particle of detrital dolomite (arrow) characterized by irregular surfaces that likely result from mechanical reworking and transport. (B) Crystal displaying a rhombohedral habit (arrow) that commonly characterizes authigenic dolomite. The preservation of the rhombohedral crystals suggests that part of the dolomite present in the sample has not been transported but, rather, precipitated in situ, contributing in the cementation of the detrital carbonate particles (Tamburini et al., 2002). (C) and (D) Energy dispersive X-ray analyses confirming the dolomitic composition of the investigated minerals. The position of the spot analysis is indicated by the white cross in (A) for spectrum (C) and by the white cross in (B) for spectrum (D). The Si peaks are likely due to the presence of small clay minerals that stick to the dolomite, contaminating the EDX signal. Pt peaks correspond to coating applied during sample preparation. Analyses were performed with a Zeiss Supra 50 VP equipped with an energy dispersive X-ray detector for element
analysis, using a secondary electron detector, applying an accelerating voltage of 15 kV, and a working distance of 7.5 mm.

**Data Set S1.** Visualization of sediment coarse fraction (>150µm) at 1-cm intervals between 78 and 91 cm in Section U1308A-1H-1 at 10X magnification.

**Data Set S2.** Visualization of sediment coarse fraction (>150µm) for 78, 82, 85, 87, and 91 cm in Section U1308A-1H-1 at 62.5X magnification.

**Data Set S3.** Visualization of sediment coarse fraction (>150µm) for 78, 82, 85, 87, and 91 cm in Section U1308A-1H-1 at 125X magnification.

**Movie S1.** Movie of Section U1308A-1H-1, 75-105 cm showing two distinct high-density layers associated with H1.1 and H1.2.

**Movie S2.** Movie for Section U1308B-1H-1, 21-96 cm. Note that bioturbation has obliterated the internal structure of H1 in this hole.