Regional and global changes during Heinrich Event 1 affecting macrobenthic habitat: ichnological evidence of sea-bottom conditions at the Galicia Interior Basin

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Abstract

Heinrich events (HEs) are climatic changes, occurring during the Pleistocene, related to massive discharge of freshwater from the Laurentide Ice Sheet, through the Hudson Strait, recognized in the sedimentary record through distinctive layers of ice-rafted detritus (IRD), the so-called Heinrich layers (HLs). Environmental changes during HEs influence significantly in marine biota (i.e. modifications in composition and abundance of assemblages), with ecological and evolutionary consequences. This point has been only partially addressed in particular groups (e.g. microorganisms), whereas interactions with other groups remain understudied. Here, we analyse ichnological features of the Heinrich layer 1, associated to Heinrich Event 1 (HE1), from several gravity cores at the Galicia

Interior Basin (NW Iberian Peninsula) to test the influence of this HE1 on environmental parameters, such as bottom and pore-water oxygenation, as well as benthic food availability, conforming the macrobenthic habitat. Freshwater input during the first phase of the HE1 caused unfavorable conditions (probably highly dysoxic to anoxic) for tracemakers, as revealed by the absence of both discrete traces and a well-developed mottled background. However, the tracemaker community was reestablished shortly after deposition of the ice-rafted detritus layer (Heinrich layer) of HE1, as reflected by the significant increase in diversity and abundance of traces (*Planolites*, *Thalassinoides*, *Thalassinoides*-like, *Chondrites*, and *Zoophycos*), revealing a major shift to oxic bottom and pore waters and likely benthic food. This global/general pattern, though, is affected by the regional setting and by the associated predominant sedimentation processes, leading to a variable incidence of paleoenvironmental changes associated with HE1. The ecological impact on macrobenthic biota, in term of changes in diversity and abundance of tracemakers, by HE1 soon attenuates, resulting in a negligible evolutionary impact.

Keywords: Heinrich Event 1; Iberian margin; Gravity cores; Ichnology; Palaeoenvironmental conditions; Oxygenation.

1. Introduction

Heinrich events (HEs) are climatic occurrences triggered by massive discharge of freshwater from the Laurentide Ice Sheet, through the Hudson Strait into the North Atlantic Ocean, occurring during the Pleistocene, recognized in the sedimentary record through distinctive layers of ice-rafted detritus (IRD), the so-called Heinrich layers (HLs) (Heinrich, 1988; Hemming, 2004; Hodell et al., 2008). These events were assumed to cause major disruptions in the Atlantic Meridional Overturning Circulation (AMOC) and North Atlantic Deep Water (NADW) formation. However, in recent years, paleoclimatologists have revealed weaknesses in this relationship, and the initial AMOC reduction could not be caused by the Heinrich events themselves. Thus alternative driving mechanisms have been proposed (Álvares-Solas et al., 2011). Subsequently, these events have been examined intensely (Hemming, 2004), yet some aspects are still poorly understood (Bassis et al., 2017), and the interpretation of paleoenvironmental conditions and changes associated with these events poses a challenge. Ichnology is a tool in paleoenvironmental studies, including paleoceanography and paleoclimatology, which provide data useful for the interpretation of parameters such as hydrodynamic energy, oxygenation, sedimentation rate or nutrient availability (Buatois and Mángano, 2011; Knaust and Bromley, 2012). Nevertheless, few ichnological studies have focused on Heinrich events. Changes in ichnological features associated to Heinrich layers may be related to the effects of the Heinrich events on the macrobenthic tracemaker community, based on the influence of paleoenvironmental conditions on the behavior of producers (i.e., Baas et al., 1997, 1998; Löwemark et al., 2004; Rodríguez-Tovar et al., 2015a,b). Recently, a detailed ichnological analysis, conducted on cores from the IODP Site U1308, located within the ice-rafted detritus belt of the North Atlantic, has revealed the complex relationship between nutrient availability and oxygen conditions during Heinrich Event 1 (Hodell et al., 2017; Rodríguez-Tovar et al., 2019).

The Galicia Interior Basin (GIB), is a narrow marginal basin (100 km wide, 2500–3000m deep), located between the western Iberian continental margin and the Galicia Bank at the northwestern Iberian Peninsula (Fig. 1). The GIB serves as a natural laboratory to study paleoceanographic dynamics, given the location near a critical transition between the subtropical (temperate) and subpolar (cold) gyres of the North Atlantic. In 2009, five gravity cores, covering the last 63 ka (Mena, 2014) were retrieved along a latitudinal transect traversing the GIB (Fig. 1). The cores provided conspicuous sedimentary evidence of Heinrich events (HEs), showing significant lateral variation in facies as indicated by the changes registered in the stratigraphic intervals associated with HEs (Mena, 2014; Mena et al., 2015, 2018) (Fig. 2). The data compiled support the characterization of HE1 as the most pronounced cold event recorded in GIB over the last 60 ka.

Here, we examine, for the first time, ichnological features of the Heinrich Layer 1 from several cores at the Galicia Interior Basin, a setting of special interest for paleoceanographic studies due to the particular location, to assess how global and regional changes related to Heinrich Event 1 exert an impact on the macrobenthic habitat, as well as to improve knowledge of the incidence of HE1 on sea-bottom conditions as bottom and pore-water oxygenation and benthic food availability.

2. Methods

Five gravity cores, FSG09-10 (230 cm thick), FSG09-16 (390 cm thick), FSG09-09 (342 cm thick), FSG09-07 (335 cm thick) and FSG09-17 (329 cm thick), collected in the Galicia Interior Basin (GIB) during the ForSaGal 09 (R/V Sarmiento de Gamboa in 2009) research cruises were studied (Mena et al., 2015, 2018). These cores, covering the last 63 ka, traverse an E-W transect of the GIB at depths between 2150 and 2780 m (Mena, 2014; Mena et al., 2015, 2018). In previous studies, cores were subjected to CT-scan and logging procedures which provided sediment radiodensities and allowed a detailed facies analysis (Mena et al., 2015). Moreover, each core was analyzed using an X-ray fluorescence (XRF) core scanner (Avaatech; available through the University of Barcelona) to measure the semi-quantitative abundance of Ca, Fe, and other elements. Following the scanning of the core, high-resolution sediment sampling was performed for the micropaleontological study (Mena, 2014). An age model was established based on 18 new AMS-^{14}C dates (measured at the Center for Applied Isotopes Studies, University of Georgia, USA) determined from monospecific handpicked samples of the planktonic foraminifera *G. bulloides* (Mena et al., 2018). Terrigenous elements (Fe, Ti, K) and Ca/Sr and Zr/Sr ratios were quantified for additional information on facies related to HEs (Mena, 2014; Mena et al., 2015, 2018).

We conducted a continuous analysis of the ichnological features, including ichnofabrics, of the stratigraphic interval spanning the HE1 in these five cores. Ichnological research was supported by digital image analysis (Dorador and Rodríguez-Tovar, 2014, 2018; Dorador et al., 2014a,b; Rodríguez-Tovar and Dorador, 2015), applied to the high-resolution images made from the five cores studied (FSG09-10, FSG09-16, FSG09-09, FSG09-07 and FSG09-17). The technique is based on image adjustment modifications to enhance visibility and characterization of ichnological features. Three adjustment modifications (levels, brightness and vibrance) were applied using Adobe Photoshop CS6 software®. The digital treatment of high-resolution images was conducted at the Department of Stratigraphy and Paleontology at the University of Granada (Spain). Digital image analysis enables: a) differentiation between trace fossils (i.e. bioturbational sedimentary structures with sharp outlines and a characteristic recurrent geometry) and biodeformational structures (i.e. with no distinct outlines and no recurrent geometry determining a mottled background); b) ichnotaxonomy; c) relative abundance; d) cross-cutting relationships; e) percentage of bioturbation; and f) characterization of ichnofabrics (Dorador and Rodríguez-Tovar, 2014, 2018; Dorador et al., 2014a,b; Rodríguez-Tovar and Dorador, 2015). As usually occurs with core analysis, ichnotaxonomic identification was limited, in most cases, to the ichnogenus level. The sections studied correspond to the uppermost 150 cm of each core, including the ice-rafted detritus layer of HE1, and the sediments directly below and above (Fig. 2).

3. Results

Figure 3 shows the distribution of differentiated ichnogenera through the sections of the cores. Differentiated ichnotaxa are indicated, corresponding to: *Ch*=*Chondrites*, *Pl*=*Planolites*, *Th*=*Thalassinoides*, *Th*-l=*Thalassinoides*-like, and *Zo*=*Zoophycos*, as well as Mottled background. Cross-cutting relationships were indicated when detected. In any of the sections, five intervals were studied for a more detailed ichnological analysis, corresponding to sediments pre-IRD layer of HE1 (intervals 1-2), IRD layer (interval 3), and post-IRD layer (intervals 4-5). Figure 4 shows the intervals studied (1 to 5) in all the cores showing ichnogenera and the corresponding percentage of bioturbated surface by ichnotaxa. Table 1 includes, for each interval studied, data of the percentage of bioturbated surface by ichnotaxa, and the total bioturbated surface.

Ichnological data reveal a similar general pattern in all the cores studied for the IRD layer as well as for sediments below and above, even with some differences according to the particular cores. In this context, core FSG09-10, to the west of the GIB shows a sparse ichnological record, in sharp contrast to the rest of cores (Fig. 3). As observed in the general stratigraphic distribution through the cores (Fig. 3), and in detailed analysis of selected intervals (Fig. 4 and Table 1), the general pattern is as follows:

- Sediments below the IRD layer of HE1 (intervals 1 and 2) show scarcity (interval 1; 8-9% of bioturbated surface) or absence (interval 2; 0%) of discrete trace fossils, but the presence of a relatively well-developed mottled background (Fig. 4, Table 1). In western cores (FSG09-16, FSG09-09), the mottled-background interval is interrupted by the presence of discrete trace fossils, including *Planolites*, *Thalassinoides*, and *Chondrites*, whereas in the eastern cores (FSG09-07, FSG09-17) this mottled-background interval is thicker and continuous (Fig. 3).

- Sediments corresponding to the IRD layer (interval 3) show the record of scarce discrete traces (mainly *Planolites*), especially in the east (Fig. 3). The percentage of bioturbated section-surface is low, between 0 and 13% (Table 1).

- Sediments above the IRD layer (intervals 4 and 5) show significantly greater diversity and abundance of traces bearing *Planolites*, *Thalassinoides*, *Thalassinoides*-like, *Chondrites*, and *Zoophycos* (Fig. 3). The percentage of bioturbated surface increases from just above the IRD layer (interval 4; between 0 to 17%) to the sediment above (interval 5, between 5 to 25%) (Table 1). This increase is especially marked and rapid in the eastern cores (Fig. 4).

In the context of the observed similar pattern in the stratigraphic distribution of ichnological data through the studied cores, lateral changes in ichnological features have been recognized (Figs. 3, 4, Table 1). From the west (FSG09-10) to the east (FSG09-7 and FSG09-17) ichnodiversity and abundance clearly increase in the IRD layer of HE1 as well as in the sediments above (Fig. 3, Table 1). FSG09-10 to the west shows a distinctly different record with respect to the other cores, with the near absence of discrete traces at the IRD layer of HE1 as well as in the sediments above (Fig. 3). In the center of the transect, cores FSG09-16 and FSG09-9 are very similar, with the record of several traces in the IRD layer (*Planolites* and *Chondrites*). Then, after the IRD layer, the abundance and diversity gradually and steadily increase with the record of *Planolites*, *Thalassinoides*, *Thalassinoides*-like, and *Chondrites* (Fig. 3). The percentage of bioturbated surface for intervals 3 to 5 is between 16% (FSG09-16) and 24% (FSG09-09) (Table 1). In the east, cores FSG09-07 and FSG09-17 are quite similar, registering the highest values in abundance and diversity (Fig. 3, Table 1). The IRD layer consists of dominant *Planolites*, and then abundance and diversity rapidly changes with the presence of *Planolites*, *Thalassinoides*, and *Chondrites*, as well as *Zoophycos* and *Scolicia*. The percentage of bioturbated surface for intervals 3 to 5 reaches 43% (FSG09-07) and 49% (FSG09-17) (Fig. 3, Table 1).

4. Discussion

4.1. Heinrich events, paleoenvironmental conditions and macrobenthic tracemaker community

Global paleoenvironmental changes appear during Heinrich events, with dramatic reductions in both temperature and salinity being the most commonly reported features, attributable to the amount of ice melting (Hemming, 2004). However, the incidence of other conditions, such as oxygenation or nutrient availability, has not been sufficiently considered. Large freshwater discharges in relation to iceberg surges may have caused a temporary stratification of the water column and then dysaerobic conditions at the sea bottom during Heinrich events (Tamburini et al., 2002). This decrease in bottom-water oxygenation during HEs has been identified by productivity changes during North Atlantic Heinrich events (Hoogakker et al., 2016). As usually interpreted, bottom and pore-water oxygenation as well as benthic food availability constitute major limiting conditions for the tracemaker community living in deep-sea marine environments, making ichnological information a valuable tool to explain changes in these parameters (Rodríguez-Tovar et al., 2015a,b). The influence of bottom-water oxygen conditions and food availability on the macrobenthic tracemaker community has been sometimes previously assessed for HE1. Concentrations of *Chondrites* immediately below Heinrich layers can be used as a proxy for bottom-water stagnation and low-oxic bottom-water conditions during Heinrich events (Baas et al., 1997, 1998). The presence of a short interval with *Chondrites*, in coincidence with the occurrence of IRD associated with HE1, was interpreted as possibly caused by a greater influence of oxygen-depleted deep-water masses (Baas et al., 1997, 1998). An increase in freshwater input associated with the HE1 led to diminishing oxygenation in bottom-water conditions and thus to an increase in the abundance of *Chondrites* (Baas et al., 1997; Löwemark et al., 2004). Recently, a detailed ichnofabric analysis throughout the HE1 interval recorded in North

Atlantic (Site U1308, close to the mouth of Hudson Strait) revealed differences between the two different stages of HE1 (i.e. HE1.1 and HE1.2) and the interval in between (Rodríguez-Tovar et al., 2019). At the beginning of HE1.1, a dominance of *Chondrites* suggests highly dysoxic conditions. By contrast, above, a greater diversity of trace fossils (*Planolites*/*Thalassinoides*), and the disappearance of *Chondrites*, reveals oxygen (pore and bottom water) amelioration and more available benthic food content for larger tracemakers. Conditions abruptly changed (between HE1.1 and HE1.2); the absence of bioturbation structures reveals falling oxygen levels to dysoxic/anoxic conditions. Finally, during the development of HE1.2, conditions again improved, as supported the record of *Planolites*. These changes in paleoenvironmental conditions were related to the dynamics of the Atlantic Meridional Overturning Circulation, affecting deep-water circulation (Rodríguez-Tovar et al., 2019).

4.2. Ichnological features through HE1 at the Galicia Interior Basin

HE1 presents the same configuration in all cores, with high radio-density particles of diverse sizes embedded in a low-density muddy matrix (Mena, 2014; Mena et al., 2015, 2018). The base of the IRD layer of HE1 usually has very low radiodensity, diffuse lamination, and profuse bioturbation. The low radiodensity values of the mud matrix are consistent with higher abundance of terrigenous material from the greater continental input during the HE (Wilson and Austin, 2002; Sierro et al., 2009; Mena, 2014).

The HE1 signal at the Galicia Interior Basin (GIB; NW Iberian Peninsula) shows a generally similar ichnological pattern before, during, and after the Heinrich Event 1, in all the cores studied (Fig. 5). The near absence of discrete traces, but the presence of a relatively well-developed mottled background immediately below IRD layers may be related to general low oxygenation in bottom and pore water prior to the Heinrich Event 1. Dysoxic conditions probably allow the bioturbation of only the first centimeters of the sediments by microtracemakers, but any activity of larger producers is nearly absent (Fig. 3). Later, associated with freshwater input during the first phase of the Heinrich Event 1, oxygen conditions are less favorable, apparently highly dysoxic to anoxic, even leading to the absence of a well-developed mottled background (Fig. 5). These unfavorable conditions start to improve during the final deposition of the IRD layer, as revealed by the meager presence of discrete traces (i.e. *Planolites*). Shortly after deposition of the IRD layer, a major shift to oxic bottom and pore waters is interpreted, probably related to the mixing of bottom water after stagnation and restoration of background paleoclimatic/paleoceanographic conditions, as reflected by the significant surge in diversity and abundance of traces (*Planolites*, *Thalassinoides*, *Thalassinoides*-like, *Chondrites*, and *Zoophycos*) (Fig. 5). Thus, a general trend in oxygen conditions was from dysoxic to highly dysoxic/anoxic and finally oxic, caused a comparable global/general response of the macrobenthic tracemaker community in all the cores studied.

4.3. Lateral variability of Heinrich Event 1

Within the Galicia Interior Basin, facies associations indicate three spatiotemporal domains with different predominant sedimentation processes during glacial events (Mena, 2014; Mena et al., 2015, 2018). These include (from the west): the area close to the Galicia Bank, where the GIB consists of turbidites and hemipelagic sediments; the center of the GIB, where only Pre-Holocene pelagic sediments (PelC) were formed; and the eastern area, near the continental slope where hemipelagic and contouritic facies developed. According to this scheme, the stratigraphic intervals associated with any of the recorded HEs also show significant lateral variation. This lateral facies change was interpreted as having been caused by the development of an oceanographic boundary between surface water masses with different temperatures and salinity parameters or changes in surface currents which may have channeled relatively warmer water into the GIB during the last glacial period (Mena et al., 2018). Our ichnological data from the cores studied also support the idea of this regional/lateral variation in HE1 (Figs. 3, 4, Table 1).

The observed increase in ichnodiversity from the west (FSG09-10) to the east (FSG09-07 and FSG09-17), in the IRD layers and in the sediments above, as well as the changes in the rate of recovery, can be related to the particular spatiotemporal domain and to the associated predominant sedimentation processes determining a variable incidence of paleoenvironmental changes associated with HE1 (Fig. 5). The westernmost core FSG09-10 is from the east flank of the Galicia Bank, in the so-called Transitional Zone (Vázquez et al., 2008), a dome-like elevation dominated by bottom current activity that generates the abraded surfaces (Ercilla et al., 2011). Cores FSG09-09 and FSG09-16 are located in the central part of the basin, between the Transitional Zone (Ercilla et al., 2011) and the lower slope (Bender et al., 2012), dominated by pelagic and hemipelagic sedimentation. Core FSG09-07 and especially the easternmost core FSG09-17 corresponds mainly to a hemipelagic and contouritic depositional setting that developed on the lower continental slope (Bender et al., 2012). Thus, the near absence of discrete traces in the IRD layer of HE1 as well as in the sediments above in core FSG09-10 reveal the clear influence of the particular depositional setting in an elevated area with density current processes causing an unfavorable habitat for the macrobenthic tracemaker community, superimposed on the global HE1 phenomena (Fig. 3). In the central and eastern part of the basin, general conditions are favorable for the development of a multitiered tracemaker community typical of the *Zoophycos* ichnofacies – usually associated with fine-grained pelagic and hemipelagic sediments with abundant organic matter, in low-energy subtidal settings (Rodríguez-Tovar et al., 2015a, b) – especially when hemipelagic and bottom current deposits predominated, presumably could be related to the increase in terrigenous material and organic matter content (Fig. 5).

5. Conclusions

Although the Heinrich Event 1 has been profusely studied, some aspects are still poorly understood. Changes in the ichnological features before, during and after HE1 at the Galicia Interior Basin reveal the impact of this event on the benthic marine habitat at global and regional scales. Firstly, a marked global/general change is recorded during the development of HE1. This is indicated by the near absence of discrete traces, but the presence of a relatively well-developed mottled background, immediately below the IRD layers, the absence of trace fossils and mottled background during most of the IRD layer deposition, the scarce presence of discrete traces (i.e. *Planolites*) at the final deposition of the IRD layer, and the significant increase in diversity and abundance of traces (*Chondrites*, *Planolites*, *Thalassinoides*, *Thalassinoides*-like, and *Zoophycos*) just afterwards, evidencing the influence of the HE1 on the macrobenthic tracemaker community at a global scale. Variations in oxygen conditions from dysoxic to highly dysoxic/anoxic and finally oxic are interpreted as the main factor inducing the response of the biota. Secondly, major ichnological changes registered between the cores studied, with an increase in ichnodiversity from the west (FSG09-10) to the east (FSG09-07 and FSG09-17), demonstrate the lateral variability of the HE1 associated to variations in topography and ocean dynamics at regional scale. Changes in the input of terrigenous material and in the organic matter content at the benthic habitat could affect macrobenthic tracemaker community at a regional scale.

Acknowledgements

We thank reviewer Dr. Scott and the Global and Planetary Editor (Dr. Marret-Davies) for valuable comments and suggestions. Funding for this research was provided by Projects CGL2015-66835-P and CTM2016-75129-C3-2-R (Secretaría de Estado de I+D+I, Spain), and B-RNM-072-UGR18 (FEDER Andalucía), and Research Group RNM-178 (Junta de Andalucía). JD’s research is funded by through a European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 792314

(ICON-SE). AM’s research is funded by the I2C program of the Xunta de Galicia Postdoctoral programme (ED481B 2016/029-0).

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Figure captions

Figure 1. Location of the cores taken at the Galicia Interior Basin, with differentiation of the three main domains.

Figure 2. Synthetic columns of the cores indicating differentiated facies (Mena, 2014; Mena et al., 2015, 2018) and schematic infill of the Galicia Interior Basin with the main sedimentary facies showing IRD-1 layer and position of the cores. Modified from Mena et al. (2018).

Figure 3. Distribution of ichnotaxa through the cores studied indicating selected intervals 1 to 5. Note: Intervals 1 and 2 correspond to pre-IRD-1 layer deposits, interval 3 to IRD-1 layer, and intervals 4 and 5 to post-IRD-1 layer deposits.

Figure 4. Original (left) and treated (right) images of the selected intervals 1 to 5 in the cores studied (see Fig. 3 for location), with differentiation of ichnotaxa. The percentage of bioturbated surface is indicated by both the particular ichnotaxa and the total bioturbated surface.

Figure 5. Tiering models according to the relationship with IRD layer (pre-IRD, IRD and post-IRD) and the general location respect to the Galicia Interior Basin (from west to east), indicating variations in diversity and abundance of trace fossils.

Tables

Table 1. Percentage of bioturbated surface in the selected intervals 1 to 5 for every ichnotaxa (Ich) and total bioturbated surface (BS). Note: *Ch* = *Chondrites*, *Ph* = *Phycosiphon*, *Pl* = *Planolites*, *Th* = *Thalassinoides*, *Th*-l = *Thalassinoides*-like, *Zo* = *Zoophycos*.

	FSG09-10		**FSG09-16**		**FSG09-09**		**FSG09-07**		**FSG09-17**	
	Ich	BS	Ich	BS	Ich	BS	Ich	BS	Ich	BS
5	*Pl* 5.2%	~5%	*Pl* 0.6%	~1%	*Pl* 4.9% *Ch* 0.1%	~5%	*Pl* 2.6% *Th* 3.6% *Th*-l 10.2% *Ch* 1.2% *Zo* 5.9%	~24%	*Th* 12.5% *Ch* 0.7% *Zo* 12.1%	~25%
4		0%	*Ph* 0.8% *Th* 9.4%	~10%	*Pl* 0.4% *Th* 9.9% *Th*-l 6.6% *Ch* 0.3%	~17%	*Pl* 0.9% *Th* 8.1% *Ch* 0.5% *Zo* 5.0%	~15%	*Pl* 2.0% *Th* 1.2% *Zo* 7.8%	~11%
3		0%	*Pl* 2.0% *Th* 1.7% *Ch* 1.7%	~5%	*Pl* 1.6%	~2%	*Pl* 3.3% *Th* 1.1%	~4%	*Pl* 3.7% *Zo* 8.8%	~13%
2		0%		0%		0%		0%		0%
1		0%	*Pl* 4.7% *Th* 4.6%	~9%	*Pl* 4.4% *Th* 2.3% *Ch* 0.8%	~8%		0%		0%