Quaternary Research (2021), **101**, 1–3
doi:10.1017/qua.2021.2

Preface

Heinrich Events

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In 1988, Hartmut Heinrich published his paper, "*Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130,000 years*," in *Quaternary Research*. This paper was to have a significant impact on Quaternary science, leading to the concept of Heinrich events. His paper detailed three deep-sea drilling cores from the "Dreizack" seamounts (19°40'W; 47° 23'N), situated in the eastern part of the North Atlantic Ocean. He noted that the upper part of the cores, representing approximately the last 140 ka, consisted of a succession of marine glaciogenic overlaying calcareous sediments. Heinrich identified 11 thin layers enriched in quartz sands within this sequence. The upper six layers in the marine glaciogenic deposits contained more quartz grains than the lower five layers in the calcareous sediment that included polar Foraminifera species. These observations, confirmed by subsequent analyses, resulted in differentiating six distinct layers composed of coarse-grained terrestrial material originating from ice-rafted debris (IRD). Unable to date the cores at that time, Heinrich concluded that the 11 layers formed after the end of the penultimate glacial, and he linked their formation to precessional orbital forcing that help drive catastrophic iceberg discharges from the ice shields of the Northern Hemisphere ice sheets that bordered the North Atlantic Ocean during the last glacial. Later dating of the IRD layers showed a temporal spacing of ca. 10 ka within the calcareous deposits (MIS 5e–5a) and 7–8 ka in the marine glacial deposits (MIS 4–1).

Heinrich's paper did not immediately receive much attention when it was first published. But four years later, when Broecker et al. (1992) tried to explain the recurring process that produces IRD-sediments for the upper six IRD-layers and introduced the term 'Heinrich events' (HEs), named after their discoverer, the impact of Heinrich paper became more apparent. In the years that followed, HEs and other climatostratigraphic cycles, such as Dansgaard-Oeschger cycles, became a framework for classifying and contextualizing new findings from other last glacial deep-sea marine and terrestrial sediment sequences.

The imprint of Heinrich events is evident in many last glacial terrestrial archives. As such, this thematic set of papers in this volume of *Quaternary Research* highlights recent work and advances on HEs in terrestrial archives.

The majority of studies fall into one of two different approaches:

Cite this article: Faust D, Antoine P, Heinrich H (2021). Heinrich Events. *Quaternary Research* **101**, 1–3. https://doi.org/10.1017/qua.2021.2

The first approach to studying HEs is a correlation approach that objectively adopts the chronological classification of the HEs and has an independent, dated geochronological framework (Porter and An, 1995). However, dating HEs is challenging, as discussed by Hemming (2004) and Andrews and Völker (2018). Even for HE 1, which is considered to be well defined by radiocarbon dating, there are different studies reporting ages ranging between ca. 14 ka (Vidal et al., 1999; Andrews et al., 2001) and ca. 17 ka (Bond et al., 1993; Alvarez-Solas et al., 2011a, b).

The second approach to studying HEs is a correlation approach using recurring characteristics (peaks or horizons) in terms of chemically or physically distinctive features in terrestrial records and correlates them to comparable frameworks described by Heinrich (1988) and others in the marine sedimentary record. If successions of terrestrial sediments show a similar cyclic pattern, then they are associated with the HEs.

Marine archives generally have few erosional horizons and hiatuses compared to terrestrial archives, especially fluvial and aeolian successions that are systematically characterized by hiatuses and erosion phenomena. When correlating fluvial and/or aeolian archives with marine cores, it must be borne in mind that sedimentation rates in terrestrial systems vary in response to complex deterministic and random factors. The magnitude of sedimentological variations depends mainly on the nature of the geomorphic system and the sedimentary environment (Sinnesael et al., 2019). Another critical point is that many factors are involved in the formation of terrestrial archives and that these archives are not necessarily controlled by climate, which limits the comparability of each archive.

Interpreting terrestrial archives is complex, as is well illustrated in aeolian sequences. For example, high-resolution loess profiles for the last glacial are considered good archives for correlation with HEs. But even loess profiles are often subject to a very different genesis, as in the Central European loess deposits where soil formation occurred during phases when loess accumulation almost stopped. In western Europe, soil formation happened during the longest interstadials in loess layers that had been deposited during stadials (Rousseau et al., 2017). Although strongly reduced, dust deposition is however still active during the shortest DO interstadials (≤1 ka) of the last glacial period (Antoine et al., 2009; Moine et al., 2017). This is not the case in loess deposited along the desert margin or in the Mediterranean region, where loess accumulation persists during soil formation ("accretionary soil formation" of Faust et al., 2020), however, under different conditions. This implies that phases of soil formation in subtropical regions can hardly be related chronologically or in terms of conditions to those reported from Eurasian loess profiles. Loess in central Europe comes from nearby sources and is mainly transported over short distances. This relationship allows conclusions to be drawn about local climate conditions during loess accumulation. On the other hand, there are loess archives that were built up by dust transported over long distances. Loess deposits in the Canary Islands are very good examples (Roettig et al., 2019; Heinrich et al., this issue). However, in these cases, it is not possible to infer the local climate from the on-site loess accumulation because the dust originated in the distant Sahel and Savanna regions of Africa (Scheuvens et al., 2013).

Loess systems in different climatic zones are all dominantly controlled by dust availability. This may sound trivial, but subtropical loess systems (e.g., desert margin loess) responds immediately to climate change because dust is always available in nearby arid areas. In the periglacial regions of Europe, the silt from which the loess is formed must first be generated by glacial processes and reworking, which creates a long lag time to climate change. Although loess is always correlated with very cold spells, aridity is the leading cause of loess activity regardless of temperature. This control begs the question as to where we are able to translate temperature changes to aridity degrees.

Each terrestrial system responds differently to climate or other forcing factors, resulting in different response times, and making developing chronologies challenging. Therefore, selecting suitable terrestrial archives for correlation with HEs, such as climate-sensitive archives (e.g., lake sediments or sinter deposits), is advantageous. In principle, a sedimentary archive should always be carefully checked for its suitability for a reasonable correlation.

Contemplating these challenges and the value of considering HEs in terrestrial systems inspired us to offer a session of talks entitled "*Heinrich Events in terrestrial archives*" at the INQUA Congress in Dublin 2019. We were particularly focused on discussing the difficulty of establishing causal links between marine and terrestrial archives, as has been increasingly practiced in recent years. Some of those exciting contributions have been included in this thematic set of papers.

In the first contribution, Fuhrmann et al. (2021) present a continuous terrestrial sediment record from the Auel Maar (Eifel Mountains, Germany) that includes almost all Greenland stadials and HEs between 60 and 13 ka. They report about a general transport system change at the beginning of HE 3, and that during the LGM the mineralogy of aeolian sediments in the Maar points to a change in the prevailing wind direction from westerly dominance to more easterly dominance. This finding significantly extends previous knowledge of past regional air masses.

Next, the contribution by Velay-Vitow et al. (2021) is an important discussion of why sedimentological features of HE 3 are markedly different from other HEs. They point to an instability of the ice streams during HE3 that enables a contribution from several eastern Atlantic sectors. By excluding several source areas, they point to the Irish ice stream as an important controlling system and comment upon the probability of contributing to HE3 from this source.

The next contribution by Pérez et al. (2021) impressively demonstrate in their contribution impressively demonstrate by using the example of Lake Petén Itzá in Guatemala that ostracodes combined with pollen analyses provide valuable insight into past climatic conditions, water temperatures, evaporation dynamics and rapid environmental changes. From their analyses it seems evident that HS5-1 was obviously colder and dryer, which is reflected in reduced diversity. HS6 and HS5a, on the other hand, indicate warmer conditions with similar aridity. Surprisingly, the diversity was noticeable higher in the warmer, albeit comparatively dry environment. The strongest shift in the composition of ostracodes occurred in the Pleistocene between 62 ka and 51 ka, possibly triggered by HS6. The study indicates that in the northern hemisphere the effects of the Heinrich-Events are still clearly noticeable far into the lower latitudes.

Domínguez-Villar et al. (2021) follow by suggesting a modeling approach on speleothem records. They show that with increasing cave depth, the HE surface temperature anomaly is attenuated, and the lag time to build up a corresponding signal increases. They stress that it is not appropriate to assume comparable conditions between the surface and the cave interior in terms of temperature and synchronous thermal variability in most cases. The model scenarios of this contribution also show that the thermal impact of Heinrich stadials on speleothem $\delta^{18}O$ records play a decisive role in isotope variability in most cave sites outside the tropics.

The next paper, by Heinrich et al. (2021), presents new IRSL ages on eolianites from Lanzarote in the Canary Islands and describes different depositional types within dune sequences on the island. One type of sediment is characterized by a substantial contribution of dust originating from the African continent. They assume that the deposition of African dust happens during HEs under stadial conditions. Recurring dust deposited could probably be associated with HEs. This connection would imply that the sub-Saharan and Savanna region, from which the red dust was delivered, was drier during the HEs because dust availability requires aridity and a thinned-out vegetation cover (Roettig et al., 2019). Skonieczny et al. (2015) and Sánchez-Goñi (2018) also pointed to increasing aridity in the sub-Saharan region during periods of stadial conditions in the Northern Hemisphere.

The paper by Pérez-Mejías et al. (2021) follows, and they present a precisely dated and highly resolved speleothem record showing that $\delta^{18}O$ anomalies can be attributed to freshwater events that result from instability of the Atlantic Meridional Overturning Circulation. The $\delta^{18}O$ record of the studied stalagmite suggests that in southeastern Spain, the early Older Dryas (18.17–16.20 ka) was characterized by wet conditions and the late Older Dryas (15.92–14.81 ka) by relative dryness. Both phases were separated by a $\delta^{18}O$ anomaly that could be associated with a freshwater event. The paper also highlights some of the dating problems, even for the younger HEs, that challenge a direct correlation between meltwater and HEs.

The last paper, by Wolf et al. (2021), presents a study from the inner part of the Iberian Peninsula. Their research examines the influence of marine cold spells on terrestrial environments by using a multi-proxy approach. They consider the entire last glacial focusing on loess deposits and their paleoenvironmental significance. They argue that the geomorphic system is highly sensitive to North Atlantic SST fluctuations and that there is a strong relation between loess deposition and HEs during MIS 2. The implications for this are that North Atlantic SST fluctuations with respect to HEs had a much stronger effect on landscape evolution on the Iberian Peninsula than expected, not just in coastal areas but even in the much drier interior.

All contributions for this volume show the importance of studying HEs in terrestrial sedimentary systems and have shown that there is still an immense need for more detailed research to understand the land-sea interactions, specifically the marine influence on terrestrial ecosystem dynamics. However, matching signals or features in the corresponding archives does not always have to have a causal relationship; coincidence should be considered—sometimes.

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