HEINRICH EVENTS: CAUSES & EFFECTS

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INTRODUCTION

In 1988, Hartmut Heinrich, a German scientist, discovered six layers in the North Atlantic sedimentation record that displayed peculiar traits. Since this time, these have been termed Heinrich layers, or the process of their deposition, a Heinrich event. The events are designated H-1 to H-6 counting back in time, and they have approximate ages of 14,500, 21,000, 27,000, 40,000, 54,000, and 65,000 years before present. H-1 to H-3 age approximations are from ^{14}C dating of foraminifera, and H-4 to H-6 are based upon extrapolation of sedimentation rates in sediment cores (Bradley). The oldest layer is located near the start of the last glaciation period, and the youngest layer lies near the most recent deglaciation.

It is now known that the Heinrich layers were deposited by the melting of huge armadas of icebergs carrying glacial debris. The analysis of sedimentary cores containing the Heinrich layers produced many anomalies compared with overlying and underlying ambient glacial sediment. The Heinrich layers contain a lack of foraminifera, rapid accumulation of sediment, sediments high in calcium carbonates ($CaCO_3$), and reduced $\delta^{18}O$ values. Research since their discovery has published many explanations and theories for a variety of events that could have produced the above described anomalies, some of which have been accepted and others rejected. The paper will give a brief introduction into what was found in the Heinrich layers, the causes of these unique sedimentation processes, and the regional and global climatic implications associated with these events.

LACK OF FORAMS

At the time of their discovery, the Heinrich layers exhibited properties very different than overlying and underlying sedimentary layers. First, the Heinrich layers have very low foraminifera concentrations; drops from thousands per gram to hundreds per gram (Hartmann). The uppermost layers were first noted by Ruddiman and McIntyre in 1981 and referred to as foraminifera barren zones. The small amount of foraminifera fossils present are mostly *Neogloboquadrina pachyderma* (left coiling), which are characteristic of very cold waters. These were discovered down to around 45º N, thus arctic waters extended much farther south than current temperatures. Concentrations are so low that it is possible that the fossils were bioturbated into place from above or below the Heinrich layer, and no foraminifera were actually present during these times (Broecker et al. 1992). Oxygen isotope ratios for these foraminifera are 1 – 2 $^{0}/_{00}$ more negative than for the exact same species above and below the Heinrich layers. These two discoveries hint that the upper ocean was relatively cool at the time, hence the presence of polar foraminifera, and that the upper ocean layer had a reduced salinity concentration due to melting of the drifting icebergs.

A few theories exist to explain the reduced foraminifera concentrations. One possible explanation is that the fossils were dissolved during their deposition. However, adjacent sedimentary layers display no partial dissolution in their foraminifera records, thus this theory is not widely accepted. A second theory proposes that foraminifera production was greatly reduced in the surface waters during Heinrich events. The reduced productivity could be attributed to a large scale cover of icebergs in the North Atlantic which temporarily reduced sunlight and affected plant productivity. A third explanation is that the armada of icebergs rapidly melted, and foraminifera concentrations were diluted by the rapidly accumulating sediment (Broecker et al. 1992). Low productivity and high sedimentation rates probably were the major factors for reduced foraminifera concentrations in the Atlantic, but an definite cause has not been determined. Simply put, rapid deposition of ice rafted debris (from an armada of icebergs) diluted an ocean with reduced foraminifera (due to cooling sea surface temperatures) resulting in foraminifera depleted Heinrich layers. Now we have a theory for a reduction in foraminifera concentrations for the Heinrich events, but where did these armadas of icebergs originate?

DETRITAL CARBONATES

The presence of detrital limestone and dolomite in four of the six Heinrich layers is quite different from adjacent sedimentary layers where none is found. As much as 20% of the lithic fragments (>150 µm) are limestone or dolomite debris, as compared to ambient glacial sediment which contains mostly quartz, feldspar, black volcanic glass, and only a few percent detrital carbonate (Bond et al. 1992). This suggests that the sedimentary debris accumulated during Heinrich events originated from a source different than normal glacial debris.

In addition, the thickness of the detrital carbonate layer decreases from west to east for the four layers where deposition is high. Decreases range from several meters in the Labrador Sea to a few centimeters 3000 kilometers away in the eastern Atlantic, as shown in Fig. 1 for H-1 and H-2 events (Rahmstorf). For H-3 and H-6 events, the two anomalies in terms of detrital carbonate, higher detrital carbonate percentages are found in the Labrador Sea but none in the trans-Atlantic.

Lastly, the ^{40}Ar – ^{40}K ratios of the fine grained material found in the detrital carbonate layers dates the material at approximately 900 Ma, as compared to adjacent layers with glacial sediment around 440 Ma. The older ages are evidence of pre-Cambrian shield rocks, which are present in both Greenland and northeastern Canada. Smectite was not found in Heinrich layers, as it normally is in ambient glacial sediment, thus it is concluded that no debris originated in Iceland. Further dating of sediments, coupled with the increased thickness of the detrital layers around the Labrador Sea, and that the bedrock around the Hudson Strait is primarily limestone and dolomite, lead to the determination that the sedimentary layers originated from the Churchill province of the Canadian Shield. This pre-Cambrian shield formed 2.7 Ga and was metamorphosed about 1.8 Ga, which caused the radiogenic decay clock for the Ar and K isotopes to be reset (Broecker 2002b).

DIFFERENCES IN H-3 & H-6

There exist a few differences between H-3 and H-6 and the four remaining Heinrich events. As discussed previously, H-3 and H-6 events do not contain large amounts of detrital carbonate in the trans-Atlantic regions, although an appreciable amount is found around the Hudson Strait area. An additional indicator of differences in these two layers is from uranium isotope measurements. Heinrich events H-3 and H-6 contain excess of ^{230}Th, whereas the remaining four events contain no excess of ^{230}Th. The excesses found in H-3 and H-6 are very similar to those found in ambient glacial sediment. One explanation is that these events occurred when the Laurentide ice sheet was smaller, thus the icebergs for these events were smaller and melted quicker (Gwiazda et al.). Fig. 2 supports this idea, as H-3 and H-6 mark the onset of major ice growth, thus during these two Heinrich events the ice sheets must have been relatively small. But, this theory only addresses the fact that sedimentation during these two events was not nearly as widespread as other Heinrich events, but why such a difference in sedimentation contents?

H-3 and H-6 events have also been correlated to major Antarctic dust events (Fig. 3), and the dust associated with these events could have mixed with the debris from the melting icebergs. Explanations for these differences are speculation or correlations with alternate climatic events around the globe, and further research is needed to accurately define the factors contributing to these two anomalies.

WHY DID THE ICEBERGS BREAK OFF?

The question remains as to what was the external event or forcing function that caused huge amounts of calving, approximately 10% of the total ice sheet size (Rahmstorf), to occur at the edges of the Laurentide ice sheet. Calving is simply the process in which huge chunks of ice break off from an ice sheet at its margins. One theory suggests that Heinrich events were triggered by seismic events. The estimated size of the Laurentide ice sheet could have caused a 400 meter depression of the crust. The increased shear strain from this vertical force resulted in "at least six major episodes of deformation that included complete failure of the brittle crust in M = 7-8 earthquakes" (Hunt and Malin). Arguments against this theory result from the fact that no faults have been correlated to these events, and that the underlying sediments for each Heinrich layer are not seismically disturbed or slumped.

The most widely accepted theory for the calving of the Laurentide ice sheet is geothermal heating at the base of the continental glacier. Ice sheets grow due to external climatic changes, until their size begins to form internal instabilities. The kinetic energy between the glacier and underlying crust causes enough warmth that basal ice melting occurs and ice streams form. The basal ice melting provides a surface for sliding to occur, similar to hydroplaning in a car, and the ice sheet surges forward at an increased rate. Massive icebergs formed as the Laurentide ice sheet reached a marine environment and calving occurred (Bradley). Icebergs would continue to form as long as the ice sheet surged into the Hudson Strait oceanic water.

Opponents of this theory ask why dropping temperatures that induced surging in the Laurentide ice sheet did not produce similar scenarios around the Atlantic. Cores taken from various locations in the North Atlantic around the Fennoscandia, Svalbard-Barent Sea, and Greenland ice sheets show little correlation with the Heinrich events. Data obtained along the continental shelf located off the coast of Norway identify ten distinct ice rafted debris events from approximately 54,000 to 13,000 years ago, but only two of these events are remotely similar to Heinrich events (Dowdeswell et al. 1999). These discrepancies are commonly attributed to differences in ice sheet dynamics from location to location. Now we have addressed the kinematic process that produced massive icebergs into the Atlantic, but we have not determined the climatic source that led to increased mass of the Laurentide ice sheet.

The idea that an internal mechanism in the Laurentide ice sheet led to surging is not very plausible. Ice sheet surging around the globe has been correlated with the Laurentide ice sheet surgings, thus it is believed that the same external mechanism drove all the ice sheet surgings. Lowell et al. (1995) used ^{14}C dating to correlate Southern

Hemisphere glacial surging and retreating with Northern Hemisphere temperature fluxuations.

In addition, it is believed that atmospheric temperatures, not North Atlantic thermohaline circulation, provided the cooling to drive ice sheet growth, since Heinrich events have been better correlated with the air temperature around Greenland than sea surface temperatures in the North Atlantic (Bradley). The best evidence for this process is the fact that 5 of the 6 Heinrich events occurred at the end of progressive cooling episodes, and were followed by rapid warming periods lasting just a few decades (Bond 1995). As seen in Fig. 4, Heinrich events are followed by a much more negative $\delta^{18}O$ values, thus warmer temperature led to a decrease in $\delta^{18}O$ values. This see-saw cooling and heating process incorporates the Heinrich events in Dansgaard-Oeschger cycles. Dansgaard-Oeschger cycles are defined by progressively cooling temperatures that are sometimes concluded with a Heinrich event. Each Heinrich event is then followed by a rapid warming Dansgaard-Oeschger event, which in time gets gradually cooler until another Heinrich event occurs. This process is sometimes referred to as a Bond cycle (Rahmstorf). The abrupt warming that followed Heinrich events caused a retreating of the Laurentide ice sheet and reduced, or completely discontinued, the formation of icebergs until the conclusion of another Bond cycle.

BASAL SLIDING

Movement of ice sheets is comprised of three main processes: plastic deformation of the ice itself, deformation of the underlying bed, or sliding of the ice sheet over the underlying bed. Deformation of the underlying bed can occur if it consists of saturated sediment at a pressure similar to the overlying ice sheet. Sliding of the ice sheet occurs when the basal ice begins to melt, thus these two processes are often coupled together. Movement due to basal sliding is on the order of ten times greater than internal deformation. Ice sheets always move in a direction down slope, following gravity, even if it is a retreating or advancing. Retreating ice sheets simply have an ablation rate than accumulation rate, but the ice still moves in the same general direction.

Basal sliding can occur several different ways, but meltwater must be present at the interface between the ice sheet and underlying bed for sliding to occur. Meltwater reduces friction, and allows the ice to move faster. Once the melting point is reached at the base of a ice sheet, meltwater is formed. The formation of meltwater is aided by the fact that high pressure at the base of the ice sheet reduces the temperature at which ice will melt. The thicker the ice, the greater the basal pressure, thus a lower temperature at which it will melt.

Meltwater can be generated from melting of the glacial bed, melting inside the ice mass, or melting at the surface. This melting occurs due to solar radiation at the surface, internal friction due to ice flow, or geothermal energy (Van Der Veen). Surface melting from solar radiation is the major contributor to glacial meltwater, thus the discharge of meltwater from the surface varies daily and seasonally with the current rate of solar radiation. This melted water at the surface flows through the ice sheet to the glacial bed or out at the terminal edge. Since meltwater has a coupled relationship with glacial motion, the variation in the amount of meltwater produced has an effect on ice sheet movement, but at a lagged time. This lag time is mainly from the time needed for the water to get from the surface, through internal pathways, to the bed. Different types of ice sheets and glaciers have varying amounts of meltwater. Temperate glaciers have high amounts of surface meltwater, thus movement for these glacier types can often be quite rapid.

Geothermal heating can also create meltwater at the base of a glacier. Due to the thickness and weight of an overlying glacier, the lithosphere can be compressed and displaced vertically. As the lithosphere is displaced vertically, there is an increased flux of geothermal energy from the Earth's interior to the glacier.

Polar glaciers do not have a great amount of surface derived meltwater, but since they are extremely thick, there is an increase amount of meltwater due to geothermal heating. Amazingly, there is a large lake present beneath the Antarctic ice sheet supposedly from the large amount of vertical deformation of the lithosphere, but more research is needed in this area to determine the exact cause of the lake's origin.

One of the original theories to account for basal sliding was proposed by Weertman (1957). The theory attempted to explain how a glacier, assumed to be at the melting point along the base, moved past irregularities in the underlying bed. Weertman modeled the underlying bed with a perfectly smooth inclined sliding surface (shear stress equals zero) with cubical obstacles spaced at equal distances from each other. The basal resistance to movement of the glacier down slope comes from the normal force acting upon the vertical upstream sides of the cubical obstacles. The stresses are compressive along the upstream side and tensile on the downstream side. The pressure differential between each side causes the melting point of the ice to be lower on the upstream side of the obstacle. Since the ice is at a lower melting point along the upstream side, it melts and flows around the obstacle where the melted water encounters an increased melting temperature and refreezes along the downstream side. The latent heat during refreezing is transferred through the obstacle to the upstream side to fuel this process called regelation (Fig. 5).

Weertman (1957) approximated the velocity of a moving glacier due to regelation with the following steps. Let τ_b be the average shear stress mobilized between the glacier and the underlying sediment. The area along the underside of the glacier affected by the resistance of one obstacle is λ^2, and the area upon which the normal force is exerted is a^2. The average shear stress per obstacle is '$\tau_b * \lambda^2$' , and the resistance against this force is from both the compressive and tensile strength of the obstacle. Assuming that each side of the obstacle accounts for exactly half of the stress mobilized against it, the stresses along the upstream and downstream sides are $\pm \frac{\tau_b * \lambda^2}{a^2}$. The temperature differential between the upstream and downstream melting points can be calculated as follows:

$$\Delta T = C \frac{\tau_b * \lambda^2}{a^2}$$

Where, C = 7.42 x 10^{-5} K $(kPa)^{-1}$ for hydrostatic pressure

As refreezing occurs and latent heat is released, the heat flux toward the upstream side of the obstacle is,

$$Q_u = K * a * \Delta T$$

Where, Qu = Heat flux

K = thermal conductivity of the obstacle

The volume of ice melted per unit time on the upstream side of an obstacle and refroze on the downstream side is,

$$VOL = U_R * a^2$$

Where, U_R = Velocity of the glacier due to regelation

The refreezing process releases latent heat on the order of;

$$H = U_R * a^2 * \rho * L_f$$

Where, H = Heat released during refreezing

ρ = density of ice

L_f = latent heat of fusion

Thus the heat released during refreezing must equal the flux of heat back toward the upstream side. A simple modification produces,

$$U_R = \left(\frac{K * C}{a * \rho * L_f} \right) * \left(\frac{\tau_b * \lambda^2}{a^2} \right) = \frac{C_1 * \tau_b}{a * R^2}$$

Where, R = a / λ or the roughness coefficient for the underlying bed

Weertman's second mechanism for movement is plastic flow. Near an obstacle along the underlying bed, there is an increase in horizontal compressional stresses in the ice, thus an increase in the strain rate. Velocity of the ice is proportional to the strain rate times distance, thus an increased velocity is expected around obstacles.

For plastic flow around obstacles during basal sliding we look at the stress increases at each individual obstacle. It was shown earlier that the compressional stress increase along the upstream side is $-\frac{\tau_b * \lambda^2}{a^2}$. This stress increase produces a strain rate,

$$\dot{\varepsilon} = -\left[\frac{\tau_b}{2R^2} \right]^n$$

Assuming that the strain rate and the horizontal compressive stress act over the disctance "a" of the obstacle, the velocity due to plastic flow can be calculated as,

$$U_f = C_2 * a * \left(\frac{\tau_b}{R^2} \right)^n$$

Where, n ~ 3

C_2 = Constant

Thus the total velocity of the glacier due to basal sliding can be calculated as,

$$U = U_R + U_f$$

The above expression can account for the velocity of a glacier due to basal sliding over large and small obstacles. In the case of larger obstacles, the heat transport through the obstacle becomes negligible and the velocity due to plastic flow dominates. In the case of smaller obstacles, velocity due to regelation dominates.

REGIONAL CLIMATIC EVENTS

On a regional scale, the Heinrich events affected thermohaline circulation in the North Atlantic. The release of fresh water from the melting armadas of icebergs lead to a decrease in the salinity of the surface waters in the ocean, and thus reduced the formation of North Atlantic deep water (NADW). The reduction in NADW formation could have led to an increase in Southern Ocean deep water formation, thus affecting ocean circulation on a global scale. In response to decreases in NADW, there would have been a reduced transport of warm, tropical surface water to the North Atlantic. Fig. 6 displays a global climate model (GCM) in which NADW is shut down. As one can see, the atmospheric temperature in the North Atlantic would become cooler, while areas in the tropics would warm. It is possible that North Atlantic water decreased in temperature, thus increasing in density, as the NADW formation was reduced. Once the water became dense enough to sink, the circulation system would slowly start again.

Alternately, this lower salinity cap over the deep ocean could have warmed up quickly, leading to higher atmospheric temperature and increased $\delta^{18}O$ values from increased evaporation. This idea is supported by $\delta^{18}O$ values in the Greenland ice sheet project (GRIP) cores. Either of these events would have existed only temporarily, because as temperatures warmed the ice sheet would have retreated inland and calving rates would have decreased. Slowly sea surfaces would have increased in salinity, and thermohaline circulation would likewise increase. The increase in thermohaline circulation would have slowly brought the North Atlantic back to equilibrium (Bradley).

Second, melting of the icebergs in the Atlantic would have temporarily increased sea surface levels until the released water was once again stored on the continents in glaciers. The rise in ocean levels could have reduced the geochemical cycle thus leading to increased in CO_2 levels that potentially assisted in the temporary warming period following each Heinrich event.

PROPOSED GLOBAL EVENTS

Heinrich events have been correlated to various anomalies around the globe. First, ice cores taken from Greenland exhibit abrupt $\delta^{18}O$ shifts associated with changes in atmospheric methane. Since methane, CH_4, is usually formed in anaerobic conditions associated with tropical wetlands, this implies that the climatic events that affected Heinrich events were also felt around the globe (Bradley). Warm temperatures, along with rises in sea level, could have created inland seas in tropical regions where anaerobic conditions were present. In addition, pollen records from a core at Florida’s Lake Tulane showed drastic increases in pollen during Heinrich events as compared to ambient glacial events (Grimm et al.). This led researchers to conclude that wetter conditions must have occurred in this particular sub-tropical region in relation to Heinrich events.

Sediment cores taken from the continental margins surrounding Brazil show an increase in continental debris during Heinrich events. This region is normally characterized as a dry savannah, and ambient glacial sediment is high in $CaCO_3$. Fe/Ca isotope records show sharp increases during six Heinrich events, as seen in Fig 7. Reduced thermohaline circulation in the North Atlantic in relation to Heinrich events could have led to warmer equatorial regions of the Atlantic (Arz et al.). This warming of the equatorial regions could increase surface evaporation and precipitation, thus increasing surface runoff. In addition, Arz analyzed sediment cores off the western coast of Africa, and found that six anomalous dry events correlated with Heinrich events (Broecker 2002b).

Organic carbon records from the Arabian Sea show drastic decreases during Heinrich events. Biological production in the Arabian Sea is affected by monsoonal circulation. During summer, monsoonal winds blow away from the sea and towards the Himalayan region leading to monsoonal upwelling. High biological activity occurs after the upwelling, thus during much of the winter season. The decreases in organic carbon, Fig 8, that closely follow each Heinrich event suggest that monsoonal upwelling was not active for these times (Porter and An). Warming of the Arabian Sea and Indian Ocean is a possible explanation for reduced monsoonal weather patterns.

Heinrich events have also been correlated to very cold oceanic temperature in the Atlantic Ocean off the Portugal coast, the French coast, and also in the western Mediterranean Sea. These temperature are significantly cooler than glacial ambient temperatures in these regions. Data also confirms that at many Antarctic locations, increased warming occurred in correlation with Heinrich events (Broecker 2002b).

CONCLUSION

All these global events support the idea that whatever climatic event caused the Heinrich events, also affected other areas around the world. In addition, the changes in NADW formation and sea surface temperatures from the trans-Atlantic armada of icebergs affected not only regional weather patterns, but weather patterns on a global scale. These six geologically short events demonstrate how fragile our oceanic circulation system is to fluctuations in climate. Such a globally small event such as increased iceberg production in one bay of North America lead to years of climatic change all over the Earth. Further research into Heinrich events could focus on a better understanding of the climate over the Laurentide ice sheet that caused to it surge and retreat as it did, oceanic temperature patterns that caused different rates of melting in the icebergs and changes in their deposition patters, or additional correlation to climatic events around the globe during the Heinrich years.

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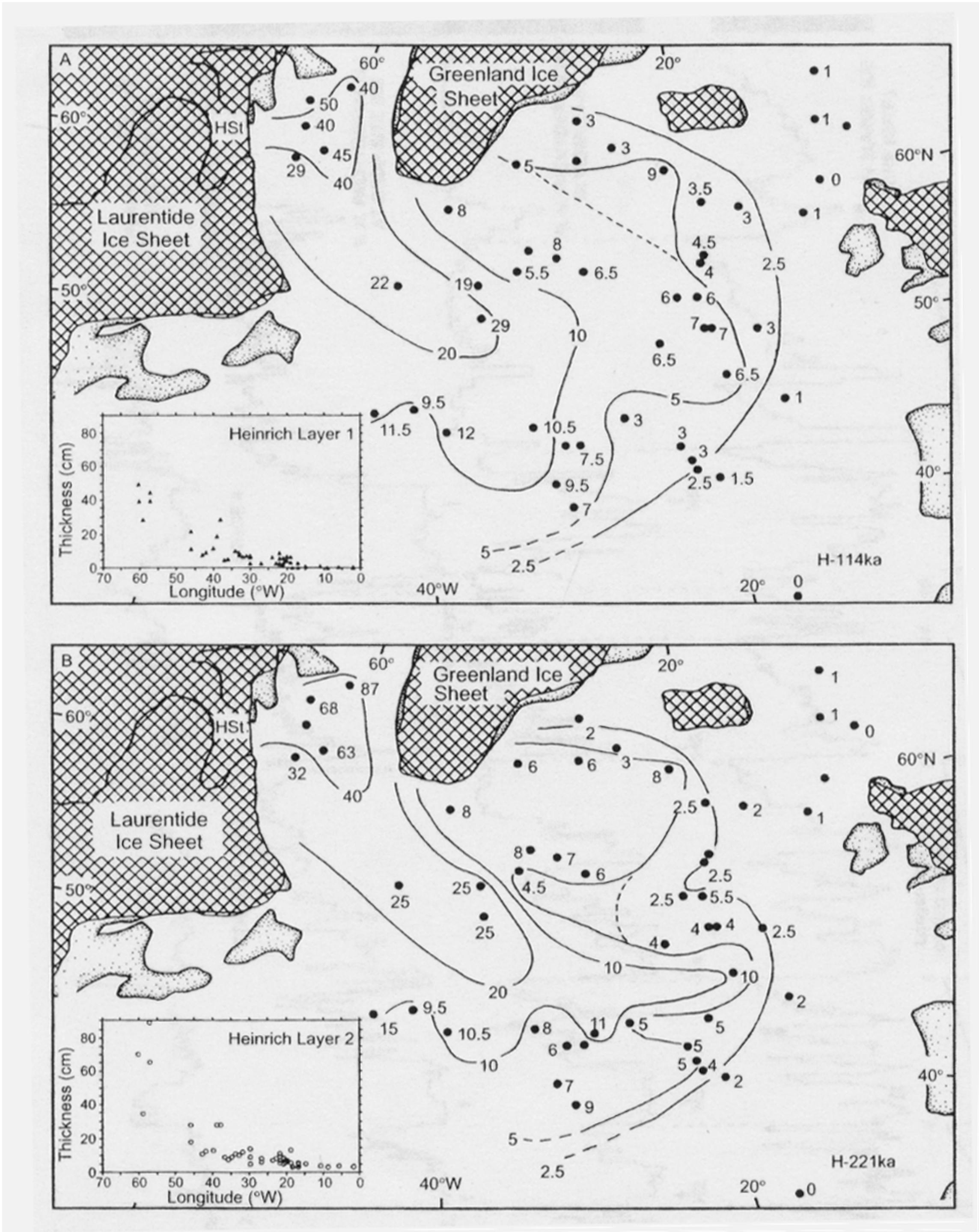

Fig. 1 Thickness of Heinrich layers (cm) in North Atlantic sediments. Upper Figure: Heinrich Event 1. Lower Figure: Heinrich Event 2. (Dowdeswell et al. 1995).

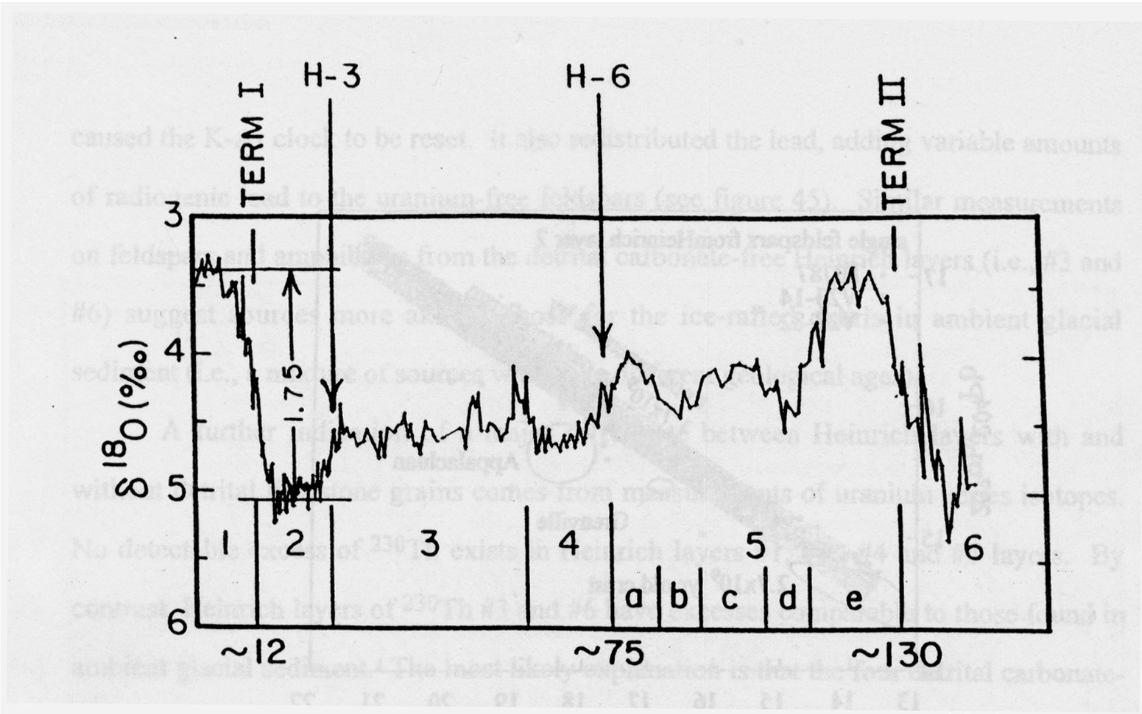

Fig. 2 Placement of H-3 and H-6 in oxygen isotope record for benthic foraminifera from the eastern equatorial Pacific. The two events mark the onset of periods of rapid ice sheet growth. (Shackleton)

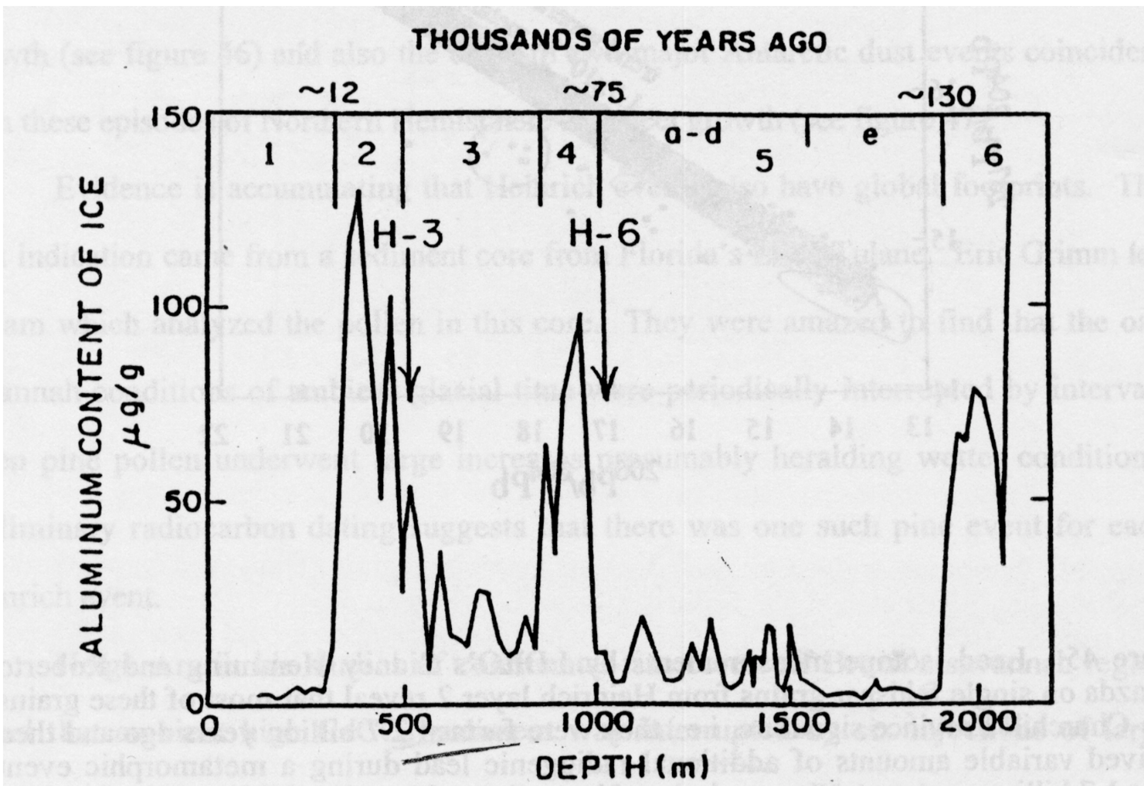

Fig. 3 Placement of H-3 and H-6 in the aluminum record for the Vostok Antarctic ice core. Both episodes mark the onset of major dust episodes. (de Angeles et al.)

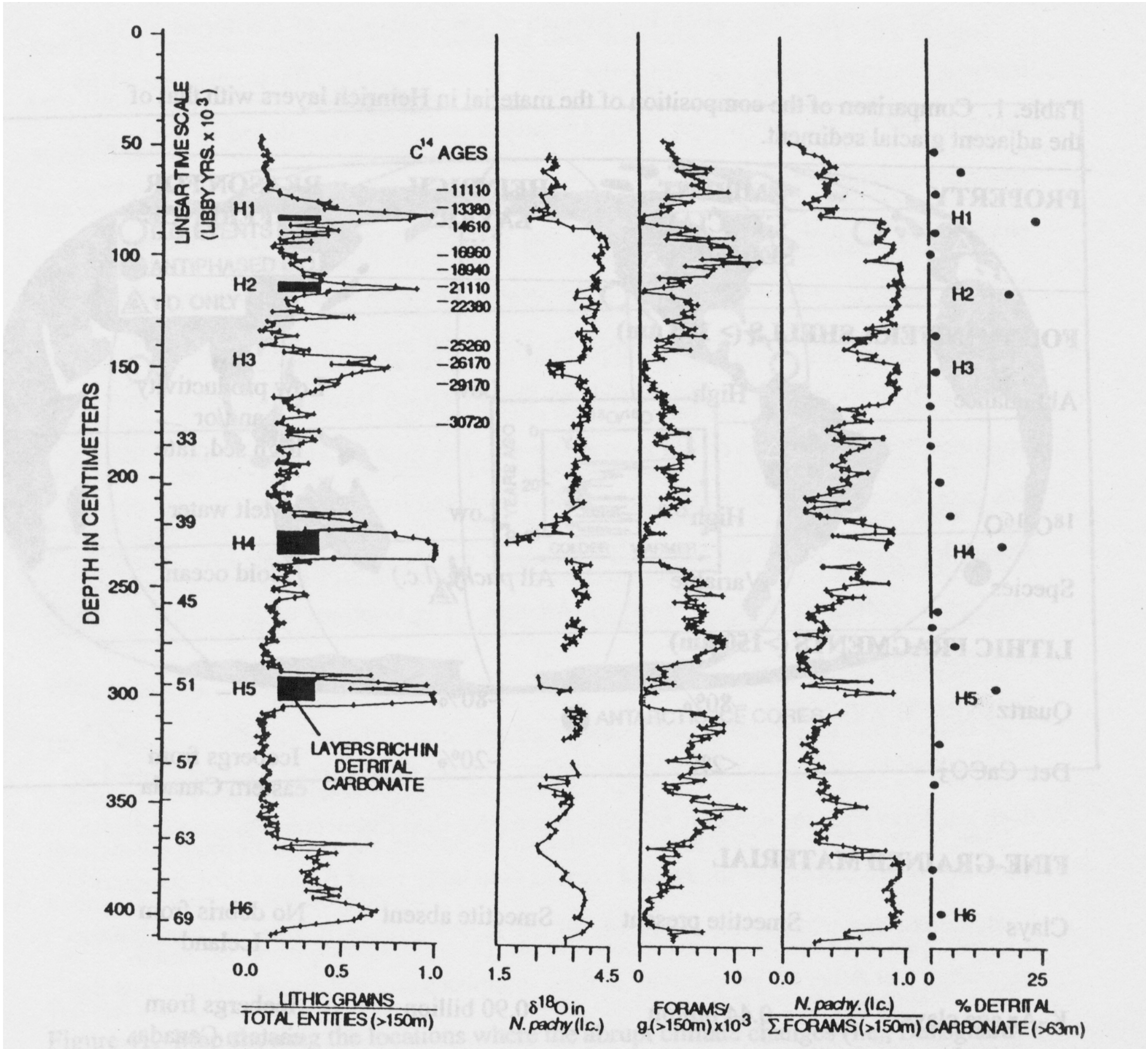

Fig. 4 Records covering the last glacial period in ODP core 609. Shown in black bars are the layers bearing detrital limestone. Also shown are the $\delta^{18}O$ record for *N. pachyderma* (left coiling), the number of foraminifera shells per gram of sediment, the ratio of *N. pachyderma* (left coiling) to total foraminifera shells, and the percent detrital limestone fragments in the lithic fraction. (Broecker 2002b).

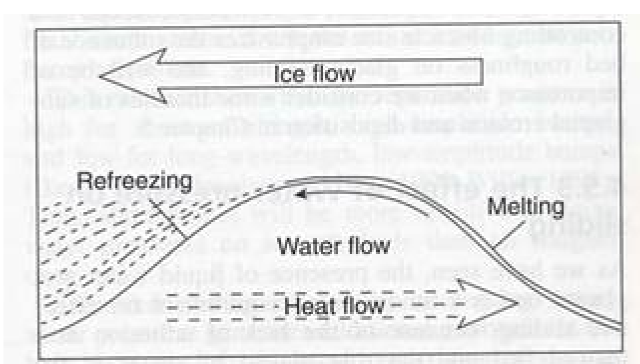

Fig. 5 Regelation Process

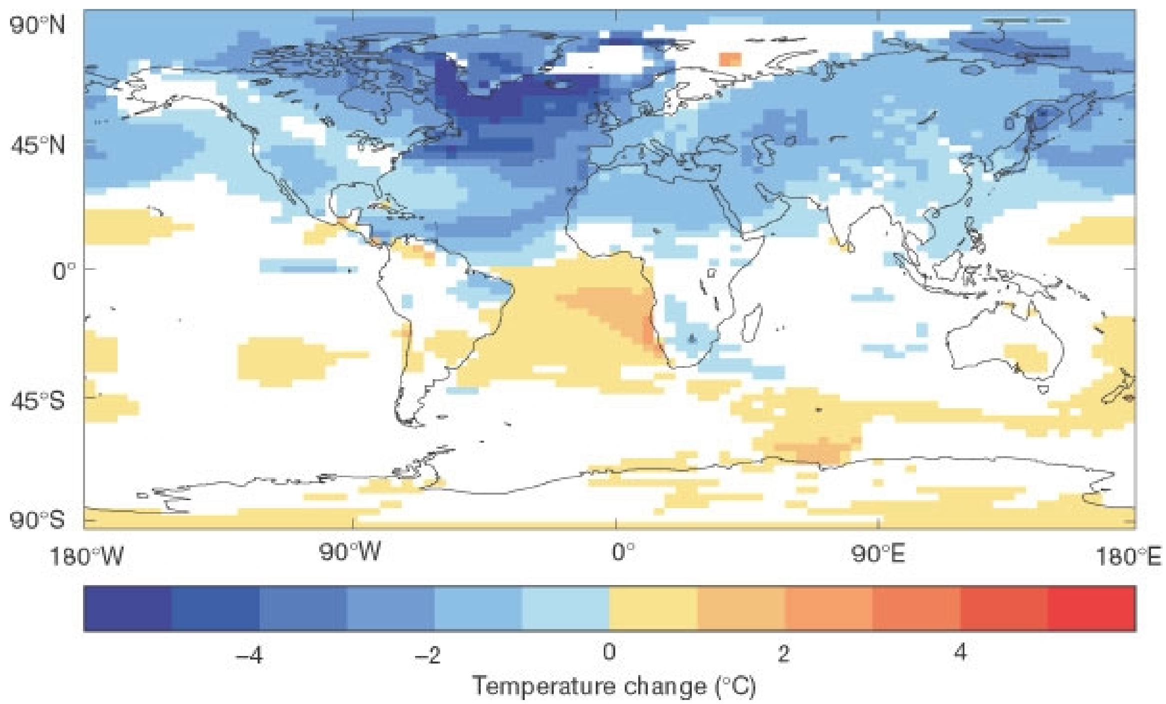

Fig. 6 Changes in surface air temperature caused by a shutdown of NADW formation. Ocean-atmosphere circulation model (HadCM3)[7]. (Rahmstorf)

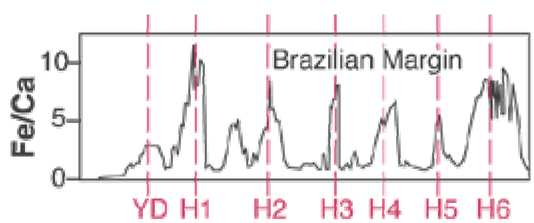

Fig. 7 Heinrich events in relation to lithic input off the coast of Brazil (Broecker 2002a).

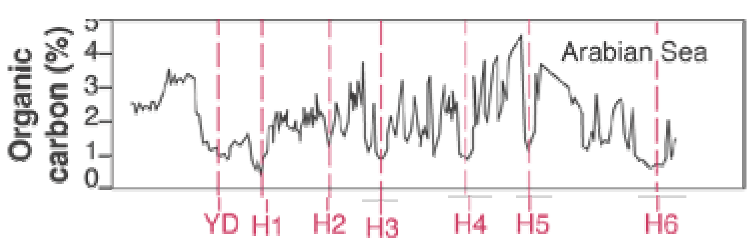

Fig. 8 Heinrich events in relation to organic matter in the Arabian Sea (Broecker 2002a).