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no information about this crucial mechanism of excitation can be gleaned from its structure. With NaChBac—a primordial member of the ion channel gene family—in hand, we can look forward to resolving questions about ion selectivity, voltage-dependent activation, and inactivation at the structural level.

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PERSPECTIVES: PALEOCLIMATE

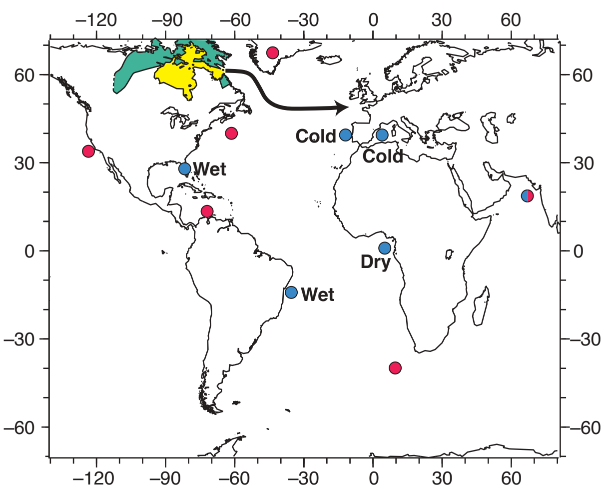
Climate Swings Come into Focus

Wally S. Broecker and Sidney Hemming

Over the past million years, Earth climate has experienced large-scale oscillations between glacial and interglacial conditions. Increasing evidence from ice cores and marine and terrestrial sediment cores shows that during glacials, climate was extremely variable on a millennial time scale. But not all the data fit into one neat pattern, as the study of the so-called Heinrich events illustrates.

In 1988, Heinrich observed six discreet layers of sediment rich in ice-rafted debris in a deep-sea core from the eastern North Atlantic. The oldest layer was located near the beginning of the last glacial period and the youngest close to the onset of the last deglaciation. Heinrich postulated that these layers had been deposited from melting icebergs (*1*). Four years later, confirmation of the existence of these layers created interest in their mode of origin (*2*). The layers are several meters thick in the Labrador Sea but get progressively thinner to the east, reaching a thickness of just 1 to 2 cm by 10°W (*3*, *4*). Measurements of lead isotopes in feldspar grains (*5*) and of argon isotope ratios in amphiboles (*6*) pinpointed the source of the rock fragments to be the Canadian shield's Churchill Province (see the first figure). Further support for this source region is provided by the presence of 20 to 30% detrital calcium carbonate, which originates in the limestone that underlies Hudson Bay and Hudson Strait (*2*, *4*, *7*).

MacAyeal (*8*) was quick to suggest a binge-purge hypothesis. As the Laurentide Ice Sheet, which covered much of north America during glacials, thickened in the region of Hudson Bay, geothermal heat gradually warmed its base until melting occurred. Guided by the soft sediment underlying Hudson Bay and Hudson Strait, the ice whooshed out into the Labrador Sea. From there, it was transported by the prevailing currents and winds eastward across the Atlantic (see the first figure). The great armadas of icebergs melted along the way, dropping debris to the sea floor. Once the deluge exhausted itself, the ice sheet once again began to thicken, initiating another cycle. This hypothesis is consistent with the 10^4-year spacing of these events because 2 to 3 km of ice could accumulate in this time.



Spatial patterns of climate change events. Sites where the climatic impacts of Heinrich events dominate are indicated with blue dots; sites where those of DO events dominate are indicated with red dots. The black arrow shows the pathway followed by the ice armadas, the green patch is the area where Churchill Province crystalline rocks outcrop, and yellow indicates the limestone underlying Hudson Bay and Strait.

Heinrich events are not the only prominent climate cycles. The millennial duration Dansgaard-Oeschger (DO) events are recorded in Greenland ice and in a number of detailed paleoclimate records from the Northern Hemisphere. In these records and in the ice cores, Heinrich events generally show up only as a second-order modulation of the timing and amplitude of the DO events (*7*), although a few published records do show Heinrich impacts that are more prominent than DO impacts. For example, the pollen record in Florida's Lake Tulane reveals alternating pine and oak episodes geared to the Heinrich-event timing (*9*). A sediment core from Brazil's continental margin shows a large pulse of continental debris for each Heinrich event (*10*). And a Chinese loess record shows intensified winter monsoons that correlate with Heinrich events (*11*). A sediment record from the Arabian Sea off Pakistan shows both DO and Heinrich impacts (see the second figure) (*12*).

DO events are widely believed to be triggered by reorganizations of the thermohaline circulation related to the Atlantic's salt balance. Why do the massive inputs of fresh water generated by the melting of the ice armadas during Heinrich events not produce more noticeable climatic impacts?

Participants at a recent miniconference on Heinrich events at Lamont-Doherty

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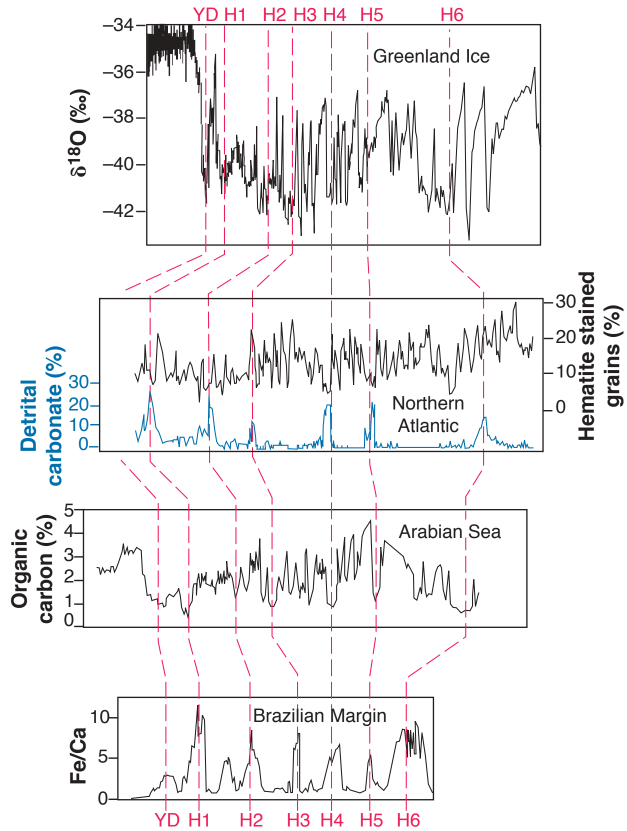

Heinrich events versus DO events. In the Summit Greenland ^{18}O record (**top**), DO events dominate. In records of ice rafting in the northern Atlantic Ocean (*13*) and of organic matter in the Arabian Sea (*12*) (**center**), the impacts of both Heinrich and DO events are apparent. In the record of lithic input off Brazil (**bottom**), only Heinrich events are seen (*10*). Time and depth scales were removed deliberately. The Heinrich events H1 to H6 occurred about 16,000, 22,000, 30,000, 38,000, 45,000, and 65,000 years ago. On the basis of ^{230}Th dating and ^{18}O to ^{16}O measurements on a Missouri speleothem, Jeff Dorale (University of Missouri at Columbia) presented what may prove to be the most precise ages for Heinrich events 4 and 5. YD, Younger Dryas.

Earth Observatory (LDEO) (*13*) went some way toward answering this question. They reported exciting new developments in defining the spatial pattern of climatic change associated with Heinrich events. Edouard Bard (Université d'Aix-Marseille III) presented alkenone records from Atlantic cores off France and Portugal that document pronounced temperature minima for each of the six Heinrich events. Isabel Cacho Lascorz (University of Cambridge) provided convincing evidence that during Heinrich events, marine and terrestrial temperatures in the western Mediterranean were considerably colder than the glacial ambient. Helge Arz (Universität Bremen) reinforced his earlier conclusion that wet events in eastern Brazil were associated with each Heinrich event. He also presented new results from an equatorial Atlantic core from beneath Africa's bulge showing that Heinrich events were associated with dry episodes. Finally, Eric Grimm (Illinois State Museum) used the entire suite of pollen in the Lake Tulane record to reconstruct the climate associated with Florida's pine events. His tentative conclusion was that the events represent wet and perhaps warm climate.

Several participants confirmed that the debris contained in the armada layers originated in Canada's Churchill Province. Also confirmed was the observation by Bond (*14*) that each Heinrich event is associated with a precursor event. Using Nd isotope data, Francis Grousset (Université Bordeaux I) demonstrated that the source of the ice-rafted debris associated with these precursors was quite different from that delivered by the ice armadas. Claude Hillaire-Marcel (Université du Quebec à Montreal) and Harunur Rashid (McGill University) also reported precursors to Heinrich events in the Labrador Sea—thick, fine-grained, carbonate-rich intervals that are laminated and appear to represent melt-water pulses from the Hudson Strait before the iceberg armadas.

Using a three-dimensional ice model, Reinhard Calov (Potsdam Institute for Climate Impact Research) showed that the portion of the ice sheet overlying Hudson Bay was susceptible to a binge-purge cycle, with each ice collapse being guided by slippage over the soft sediment underlying the Hudson Strait that connects it to the Atlantic. Gerard Bond (LDEO) pointed out that the observed temperature pattern in the northern Atlantic during Heinrich events (when it was much colder in the east) is in accord with the pattern obtained by global circulation models when deep-water formation in the northern Atlantic is shut down (*15*). Mary Elliot (LDEO) presented carbon isotope results from northern Atlantic cores consistent with conveyor shutdowns during each Heinrich event.

It is tempting to conclude that the fresh water released by the melting of the ice armadas reduced the salinity of surface waters so much that they could no longer sink to the abyss. Although different in detail from the Heinrich events, two other conveyor shutdowns have been suggested, one during the Younger Dryas, a short cold period during the last deglaciation (*16*), and the other 8200 years ago (*17*). In both cases, sudden diversions of melt water stored in proglacial lakes, which formed in the downwarped forelands of retreating ice sheets, into the northern Atlantic appear to have provided the impetus.

If this explanation is correct, then these two events and the Heinrich events clearly tie the operation of the Atlantic's conveyor circulation to stochastic freshwater releases from the Laurentide Ice Sheet. Furthermore, Heinrich events mark the onset of the sharp terminations of each of the last several 100,000-year cycles, sawtoothed cycles characterized by long declines in temperature followed by a sharp termination restoring full interglacial (warm) conditions. This suggests that freshwater inputs can trigger major reorganizations of the climate system (*18*).

If the climatic impacts of Heinrich events are indeed linked to conveyor shutdowns, then what is the cause of DO millennial cycles? As shown in the first figure, the impacts of Heinrich events and DO events have quite different spatial patterns. Perhaps, as simulated by a number of ocean models, the ocean's circulation has three distinct states, each of which gives rise to a quite different pattern of atmospheric operation (*15*).

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