b28 Greenland ice cores, North Atlantic deepsea cores, and Lake Agassiz < stadial, interstadial; Heinrich events >

From 1989 to 1994, European and U.S. glaciologists separately drilled holes through the Greenland ice sheet:[1]

European Greenland Ice Core Project (GRIP) located at 72º 35' N, 37º 38' W.
U.S. Greenland Ice Sheet Project Two (GISP2) located at 72º 36' N, 38º 30' W.

Measured were 1) present-day meteorological conditions and 2) environmental and physical parameters in each ice core such as *ec* (electrical conductivity), ions, and isotopes. The European ice core was drilled at the summit of Greenland's ice sheet, while the U.S. ice core was drilled 30 kilometers away on the flank. The upper 90 percent of these 3,000-meter-long (10 cm diameter) ice cores match. But oxygen isotopes and electrical conductivities measurements do not match between the lower tenths of the cores. The deepest section in the U.S. ice core record is complicated by folds turned as the glacier base flowed over hills in the bedrock. Both core records show the last 8000 calendar years to have been a time of remarkable stability when compared to rapid climate shifts before. The great surprise from GISP2 is the information that climate systems can change in just a few years from long-term snow accumulating to snow ablating conditions and vise versa.[2]

Ice sheets at present and during historical time have been small compared to the extensive ice sheets in existence during several "ice age" glacials of the Pleistocene Epoch. In world climate variation, the Quaternary Period overall is an "icehouse" (icesheets exist). During a *glacial*, a *stade* (syn. *stadial*) is a time when ice sheets have temporally advanced and an *interstade* (syn. *interstadial*) is a time when ice sheets have temporally retreated. (Note: when Earth is in a "greenhouse" state, no ice sheets exist). The Greenland ice-core oxygen isotope data show interstadials to be of uneven durations. The abrupt 10ºC climb onset of an interstadial is called a D-O event—named for Willi Dansgaard (1922-) and Hans Oeschger (1927-1998). These between 15,000 and 110,000 years BP and numbered 1, 2, 3, ... , 23 going back are partly shown in ***Figure b28.1***. Climate instability evident in the Greenland ice cores is also well recorded in deepsea North Atlantic sediment cores.[3]

Antarctic ice cores from the WAIS (West Antarctic Ice Sheet) Divide (where ice flow directions diverge) so far record to 740,000 years ago at 3,100 m down. Below, geothermal heat has brought Antarctic ice close to melting and so difficult to collect. The potential is to 900,000 years ago.[4]

Torben Fronval reports that when air temperature over Greenland decreases, the deposition of glacial debris in the Norwegian Sea increases. Ice-rafted sediments reached a maximum rate of accumulation when the ice sheets expanded to cover large areas of the continental shelf. At such times, marine "drawdown," which is a eustatic (***Footnote b28.1***) drop in mean sealevel, could explain the high rate of iceberg discharge.[5] These coldest stadials associated with sea ice expansion and iceberg discharges into the North Atlantic ocean (as recorded by large amounts of ice-rafted drift (IRD) in the core samples which palaeoceanographers document) are *Heinrich events* named for expositor (in 1988) Hartmut Heinrich[6] (***Footnote b28.2***).

The change to the warmer climate of the current interstadial 1, the Holocene, was interrupted by a 400 year long chill that began about 8500 years ago. That was also when (according to Peter U. Clark) eighty-five percent of the volume (9,500 cu km of freshwater) of then Lake Agassiz (a proglacial lake southern to the vanishing Laurentide ice sheet) drained via the St. Lawrence River into the North Atlantic (raising the ocean over a foot). Holocene warming had previously resumed 11,100 (calendar) years ago after a 250 year long cold snap called the Preboreal Oscillation that began 11,350 years ago. Just before, water levels had dropped about fifty percent in 3 years in Lake Agassiz. The meltwater (Timothy G. Fisher finds from carbon dating of sediments of Big Stone Lake and Traverse Lake in Minnesota) spilled episodically into the Mackenzie River, northwestern Canada, and so to the Arctic Ocean. From there it flowed to the North Atlantic to interrupt thermohaline circulation.[7] This time of melting had been preceded by 10 ºC warming over 10 years

in a 60 year long event 11,800 years ago that began the Holocene Epoch by ending the millennia of end-Pleistocene Epoch sustained cold called the Younger Dryas that began abruptly 12,900 years ago. Lake Agassiz, at its greatest, covered more than 134,000 sq km. Where Winnipeg now is, its icy waters then had a depth of 200 m. Lake Agassiz first formed when the Laurentide ice sheet started to diminish during the Bølling-Allerød warm climate about 12,900-14,700 years ago.[8] While ice blocked northwestern and eastern routes to the sea, meltwater overflow spilled down the Mississippi River, as perforce it had during the Wisconsin glacial (the last major glacial of the Pleistocene).❑

Figure b28.1 [9] **Correlation of Greenland Summit ice core and North Atlantic ODP (Ocean Drilling Program) site 644 records** The ratio of abundances of two isotopes of an element can change during a chemical reaction or a physical process. This isotope fractionation factor can be measured and is found itself to be a function of temperature. Snow that falls in polar regions is oxygen-18 depleted in comparison to equatorial seawater by as much as 5 %.

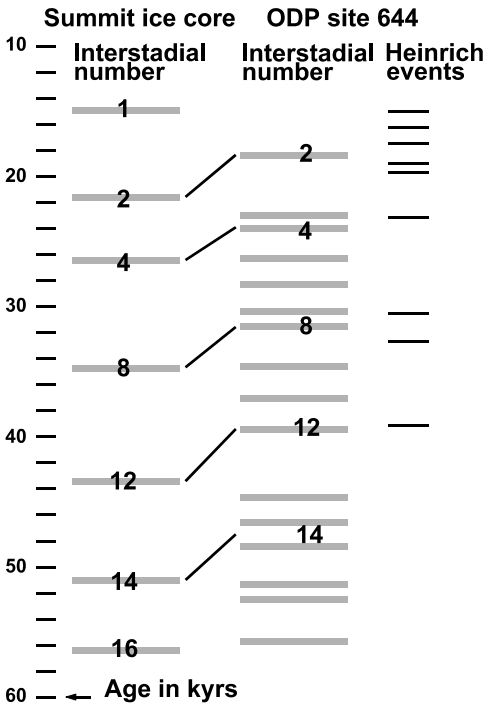
The physical processes that result in low and also variable amounts of oxygen-18 in the summit ice core record are:

Condensation preferentially leaves oxygen-18 in the air.

Evaporation leaves oxygen-18 preferentially in water. (The precise permillage (‰) depends upon the air temperature.)

Oxygen-18 is sequestered in calcium carbonate precipitated from seawater by some 2.5 % over that in the water. (The precise measure of fractionation of the light and heavy isotopes in equilibrium in the water and in the salt, depends upon the temperature of the water).

The Greenland ice sheet climate record is for 123,000 years. Recorded is that the first rapid climate change into the last major glacial (Würm, Wisconsin) began about 114,000 years ago. Before, temperatures had been declining gradually from the prior interglacial (Eemian, Sangamon) warmth.



Footnote b28.1 Eduard Suess, coined the adjective "eustatic" in *Das Antlitz der Erde,* 1888, in a defining passage that, in the 1906 William Johnson Sollas translation (with his italics) is: "We must commence by separating from the various other changes which affect the level of the strand, those which take place at an approximately equal height, whether in a positive or negative direction, over the whole globe; this group we will distinguish as *eustatic movements. The formation of the sea basins produces spasmodic negative eustatic movements ... The formation of sediments causes a continuous eustatic positive movement of the strand-line*." [10]

To quote Robert H. Dott, Jr. (*GSA Memoir* 180, 1992, p. 3): "The prefix 'eu' means good, well, true, or most typical. The familiar suffix 'static' means stationary or at rest, but can also mean 'balanced.' Suess apparently meant 'truly balanced or level,' which Arthur Bloom suggests should be taken as 'global level' (written communication, 1991)."[11] The noun "eustasy" was coined by Clarence Dutton in 1889. His original spelling "eustacy," which has sometimes been used since, was changed when it was pointed out that there is no *c* in the Greek alphabet.[12]

Footnote b28.2 Presently, about 300 of the world's 100,000 large glaciers surge occasionally in their flow. *Different* from the Heinrich stadial scenario, this happens when sediment under the ice blocks meltwater drainage and hydroplaning starts when the glacier loses contact with bedrock. Malaspina glacier, Alaska's largest, flows west from St. Elias Mountains 140 miles to the coast at about a foot a day normally, but in 1994 it moved sometimes 300 feet a day to advance 6 miles until on July 26 it released a flood of meltwater from its base. "The force of the water blew house-size blocks of ice off the glacier's face," was glacial geologist Bruce F. Molnia's description of this event to Boris Weintraub.[13]