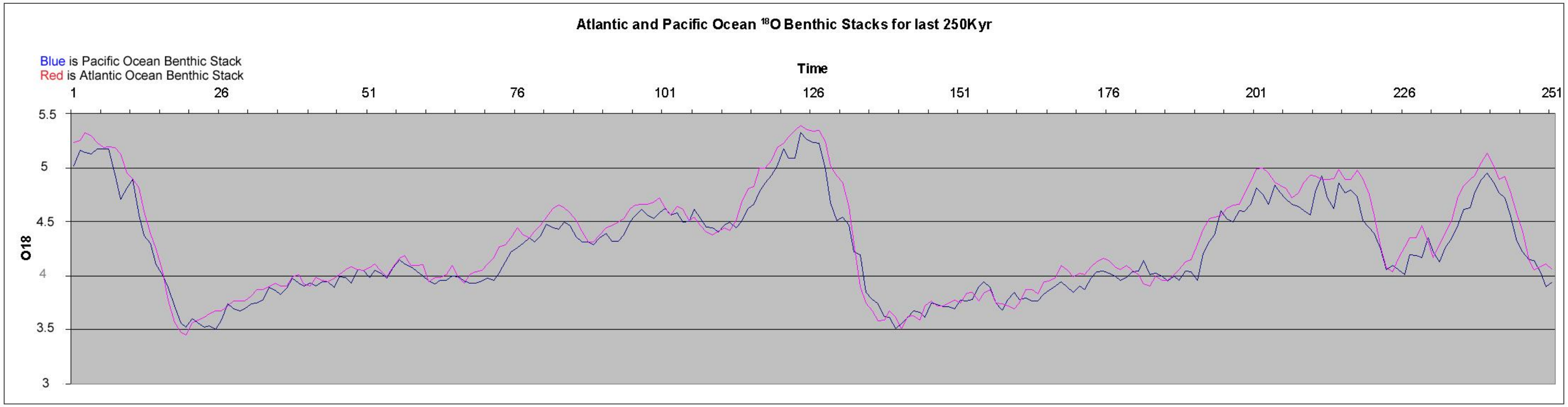
The IAFI Puget Lobe Chapter monthly newsreel:

Introduction to the Milankovitch Theory, Ch 4, p. 1

Last time we talked about how marine sediment cores helped develop the stratigraphy we now use for the Pleistocene timeline and Continental Ice Sheet timelines. This stratigraphy is applied worldwide. See the lists in the lower left-hand corner (below) of the applicable marine sediment cores for the Atlantic and Pacific Oceans:

The below chart reflects 20 combined Atlantic (red) and 14 combined Pacific Records (blue). Note how similar they are.



Atlantic records are from ODP sites 980, 982, 983, 984, 552, 607, 664, 502 658, 659, 925, 926, 927, 928, 929, and 1090, and 1089, and sites RC13-229, GeoB1041, and GeoB1214.
Pacific records are from ODP sites 677, 846, 849, 1012, 1020, 806, 1123, 1143, and 1146, and sites V19-28, V21-146, PC72, and PC18

Original reference:
Lisiecki, L.E. and Yaymo, M.E. 2009
Diachronous benthic $\delta^{18}O$ responses during late Pleistocene terminations
Paleoceanography, 24, PA 3110, doi:10.1029/2009PA001732

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However, we want a better understanding of the time prior to the Pleistocene:

During the Mesozoic (248-65mya)/Tertiary era (65-1.8mya) the Mean Global Temperature is described as warm

The breakup of Pangaea (100 mya) resulted in continental land masses migrating towards the northern latitudes.

Temperature curve shows overall cooling of the earth atmosphere

Sea level during the breakup is rising (transgressing) (rising due to warm mid-ocean ridges; also, spreading and sinking "cooling" continental cratons)

From 125-30mya the main ocean current was equatorial (circum-equatorial)
Water still flowed east / west through the opening between North and South America (Isthmus of Panama) until 4-3mya.

Put in drawing of closure and temperature

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However, we want a better understanding of the time prior to the Pleistocene: (cont)

During the Cenozoic era (65mya – today) ice sheets start around 3mya

The Mid/Late Mesozoic era (248-65 mya) / Tertiary period (65 – 2.8 mya) was one of climatic warmth (Winter, p. 260-292)

During the Mid/Late Mesozoic Period the following major Continental Flood Basalts occurred

Early Jurassic (199-175 mya), Karroo, South Africa (associated with Tristan hot spot)
Early Cretaceous (145-96 mya), Parana, Brazil (associated with Tristan hot spot)
Cretaceous-Eocene (145-33.9 mya), Deccan, India (associated with Reunion hot spot)
Miocene (17.5 – 6mya), Columbia River Flood Basalts, NW US (associated with the Yellowstone hot spot

Show global map of CFBs

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However, we want a better understanding of the time prior to the Pleistocene: (cont)

What geological/climatic features made the Quaternary unique: (slide 11)

- The Indian Subcontinent collided with the Asian continent creating the Himalayan Mountains about 35 mya creating a high massif (contributing to Rosby waves)

- By 3mya the opening between North and South America had finished closing which created the Isthmus of Panama

- Prior to closure, northward flow of warm water into the North Atlantic was insufficient to create conditions for ice sheet development
  - Insufficient warm water reached into the polar regions to provide sufficient moisture for snow fall/accumulation. Warm water could flow out the opening of the pre-isthmus gap in Panama North Atlantic Deep Water was non-existent up to that point

- Closure of the isthmus caused greater amounts of warm water to flow northward
  - Closure shut off the equatorial flow of water that had been in existence since opening of the Atlantic Ocean between landmass of N. America and Europe between 40-20 mya
  - Allowed development of the North Atlantic Deep Water (NADW) which is the driving force for the surface/deep water currents world-wide (thermohaline circulation)
  - Provided sufficient moisture to the northern latitudes for snow accumulation

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The Cordilleran mountain ranges rose on the western North American continent Canadian Cascades/batholiths, Washington/Oregon Cascades, and California's Sierra Nevada

- Clague (1989) indicates that the coastal belt has uplifted and eroded between 5 to 25 km during the last 65my and consists primarily of metamorphic and plutonic rocks.
- In the area of the ice dome (50°N) uplift in the last 10ma was roughly 2 km (>0.2 m/ka)

- The Washington Cascades have uplifted xx during the last xx ma
  - The High Cascades of xx years ago (shield volcanoes)
  - The modern Cascades of today (composite volcanoes)

Also, the creation of the mountain chains across central Asia (other than the Himalayan)

Thus, Rosby waves are created which pull down colder arctic air into the lower latitudes

- In the Antarctic the circulation is circum-polar (circulation is unimpeded by land masses)
- This same effect has been noted during glacial periods when the ice sheets gain sufficient altitude to split the jet stream towards the south which effectively starves the ice sheets of moisture.

Now let's step back and look at Marine Sediment Cores which are the basis for worldwide geological stratigraphy

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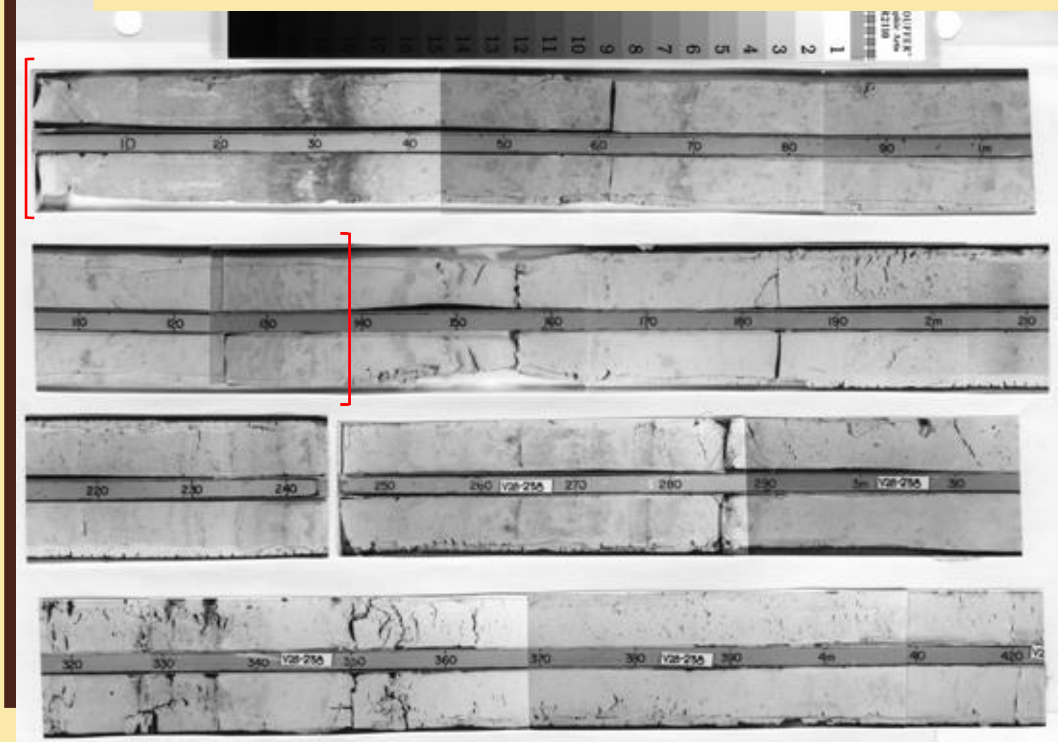
Marine Core V28-238 – A view of the first four meters w/descriptions of the first 140 cm (see brackets). The $\delta^{18}O$ was measured and resulted in the values shown on next chart.



Core V28-238 - First Four Meters

Lamont Geological Observatory
of
Columbia University
Preliminary Description
NOT FOR PUBLICATION

VEMA 28-238

Megascopic Description of a Split Core

Latitude:	01°01'N	Longitude:	160°29'E
Corr. depth:	3120 m	PDR depth:	1670 fm
Date taken:	8 May 1971	Date opened:	7 December 1971
Date described:	8 December 1971	Date photographed:	7 December 1971
Described by:	J. Lovegreen	Flow-in:	323 cm
Core length:	1602 cm		

GENERAL: Foraminiferal chalk (white, very light gray, yellowish gray and light gray) interbedded with foraminiferal chalk ooze (white, very pale orange and pale blue to blue gray), chalk, (white, light gray and yellowish gray) and foraminiferal ooze (white). High carbonate content. Coarse fractions contain primarily planktonic foraminifera with minor sponge spicules and pteropods.

0-2 cm: Foraminiferal chalk ooze, white (N9), moist and firm. Carbonate content high. Coarse fraction 40%, consisting of planktonic foraminifera. Basal contact a sharp color change.

2-25 cm: Foraminiferal chalk ooze, very pale orange (10 YR 8/2), moist and firm. Carbonate content high. Coarse fraction 50%, consisting of planktonic foraminifera. Basal contact a gradational color change.

25-35 cm: Foraminiferal chalk ooze, pale yellowish brown (10 YR 6/2), moist, firm and mottled. Carbonate content high. Coarse fraction 35%, consisting of planktonic foraminifera. Basal contact a sharp change in color and composition.

35-50 cm: Chalk, yellowish gray (5 Y 8/1), moist and firm. Carbonate content high. Coarse fraction 5%, consisting of planktonic foraminifera. Basal contact a burrowed change in color and composition.

50-140 cm: Foraminiferal chalk, yellowish gray (5 Y 8/1), moist, firm and burrowed. Carbonate content high. Coarse fraction 15%, consisting primarily of planktonic foraminifera.

140 cm = 55.11 in

The Macroscopic Description (right) gives a physical description; however, N. J. Shackleton spent ten years developing a spectrometer that would measure the $\delta^{18}O$ in the foraminifera shells samples.

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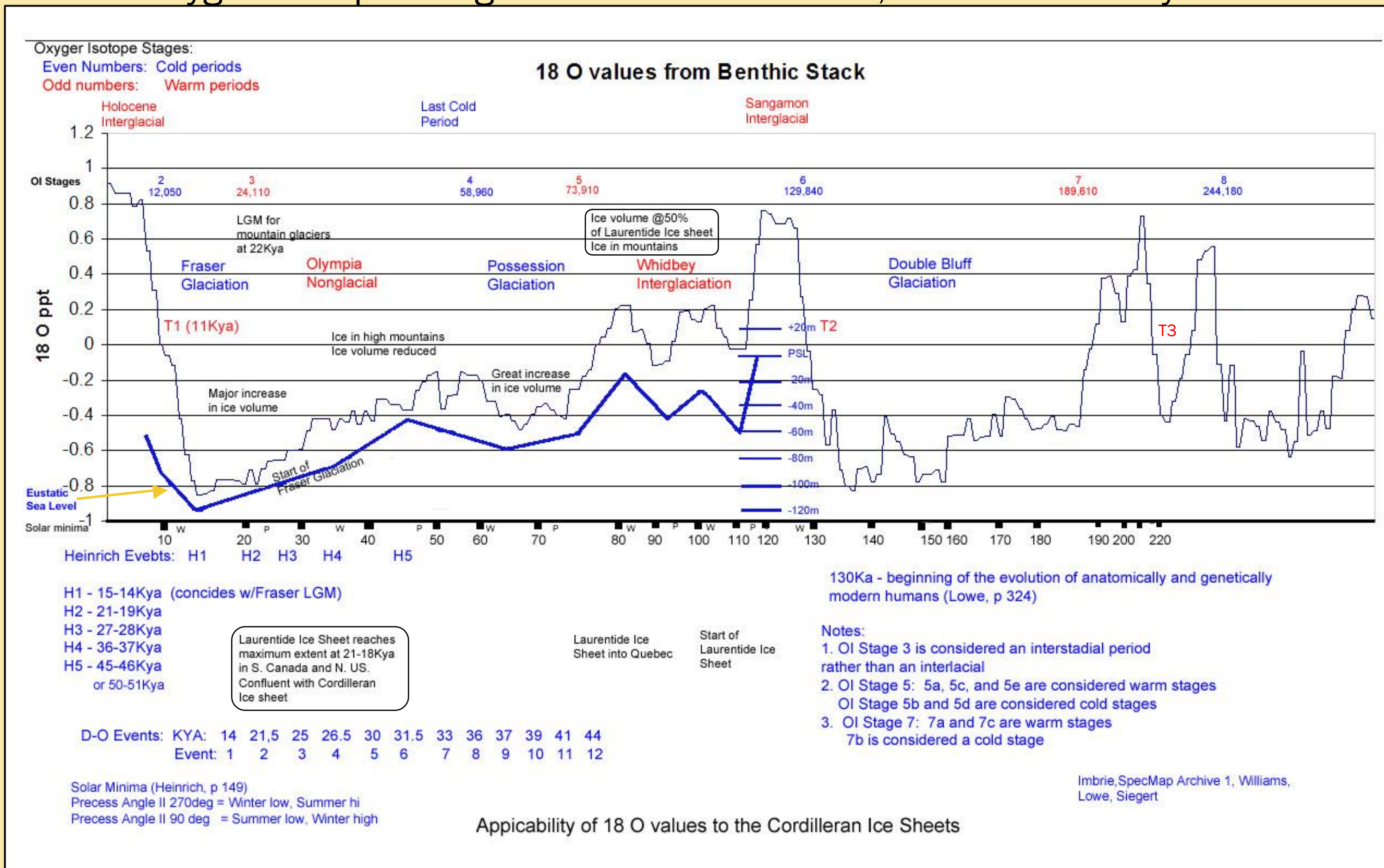
Consequently, a non-normalized time chart* could be developed upon which the marine oxygen isotopes stages could be shown. Yes, this chart is busy.



*The time is not normalized – meaning the time tick marks at the bottom of graph are not equally spaced according to time. Also, each data point in the δ^{18}O Oxygen Isotope line is repeated which causes the jagged appearance.

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Location of Ice Domes and ice flow lines over North America

This chart does not appear to show eustatic sea level, which would be 120 m/390 ft lower than the current shoreline that is shown.

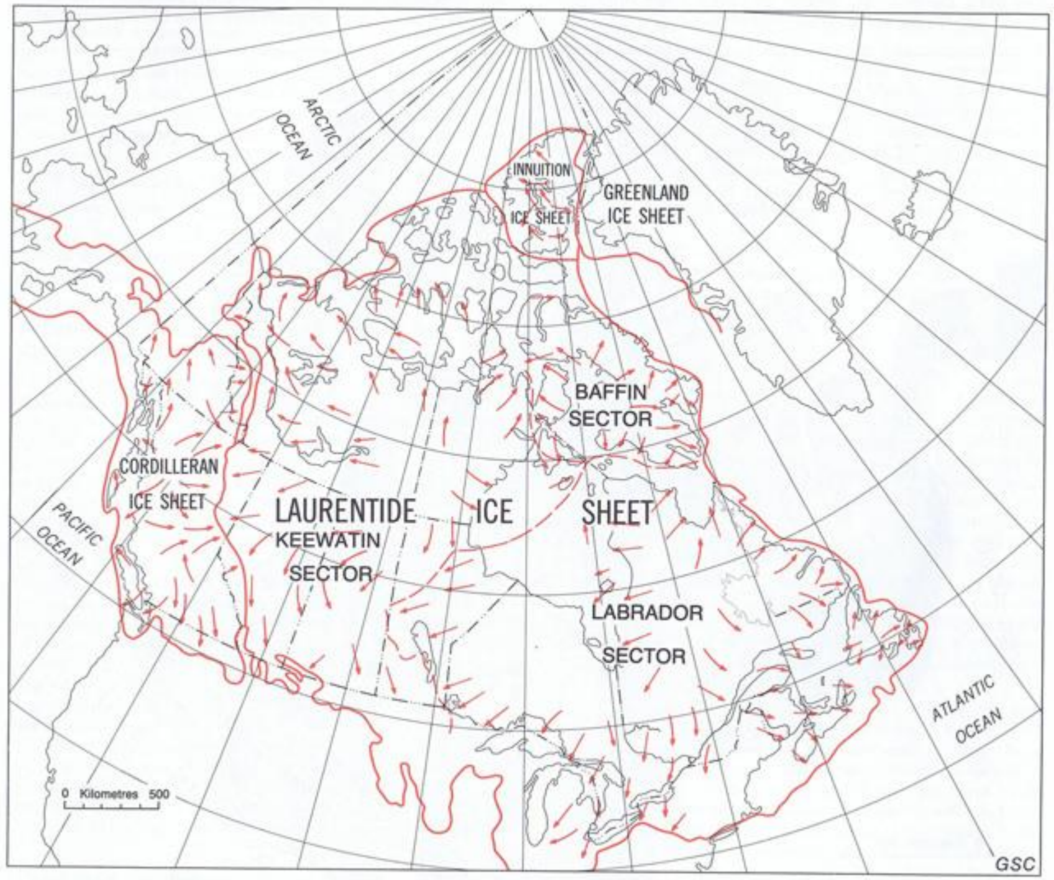

Figure 4. Approximate extent of main ice sheets during the last (Wisconsin) glaciation; arrows indicate probable directions of ice flow at the glacial maximum. Taken largely from Prest et al. (1968) and Prest (1984) but with some modifications.

From: Fulton, 1989, p.8

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The driving condition for starting a Continental Ice Sheet

Insolation – The amount of sun received on the earths surface w / m^2 * which varies between 1 - 2% based on eccentricity.

Aphelion: the furthest point from the sun in earths orbit around the sun

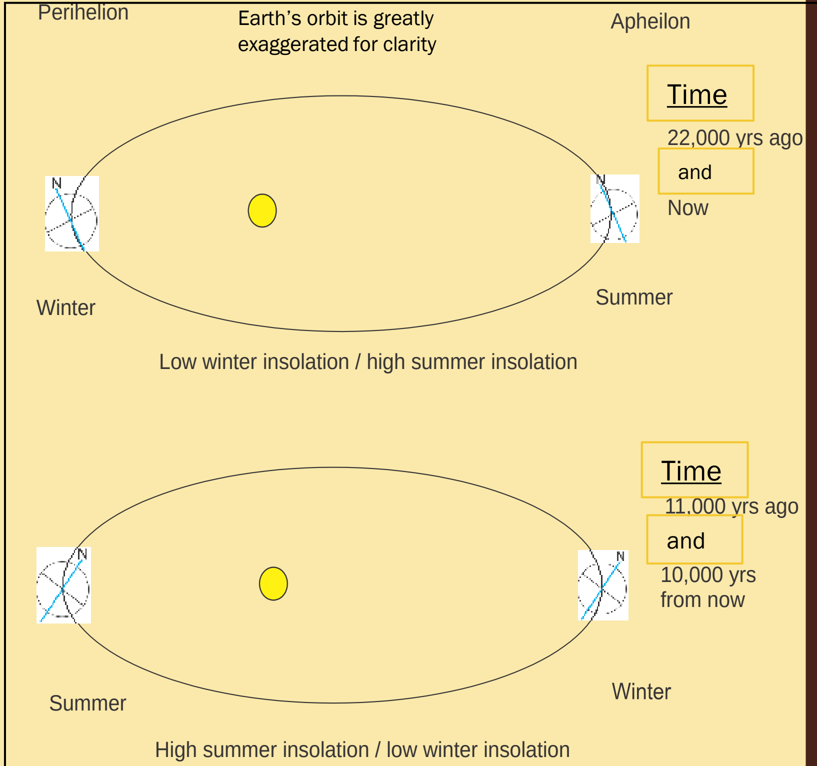
Perihelion: the nearest point to the sun in the earths orbit around the sun

Which hemisphere (North/South) is pointed towards the sun during its orbit determines insolation amount received:

The northern hemisphere has the majority of land mass

Glaciation is more severe in the northern hemisphere when it is pointed away from the sun

- During obliquity
- During precession



Insolation in Northern Hemisphere

see Imbre,p.73, Lowe, p.14

* (watts per square meter)

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Associated feedback processes:

As the conditions for continental ice sheet generation increase, feedback mechanisms increase. $\delta^{\underline{16}}O$* is the main oxygen isotope constituent in the evaporation of sea water.

A drop in sea level enriches the ocean with $\delta^{\underline{18}}O$*, as $\delta^{\underline{16}}O$ is the main oxygen constituent of sea water(i.e., and a lighter isotope- $H_2{}^{16}O$) and evaporates first.

> $\delta^{18}O$ in ice is also a function of snow elevation and distance from moisture source as sea water becomes depleted of $\delta^{\underline{16}}O$; consequently, the heavier $H_2\delta^{\underline{18}}O$* will start evaporating more due to the lowered incidence of $H_2{}^{16}O$.
>
> Because of the enrichment of $\delta^{18}O$ in the oceans during glacial periods, foram shells will be enriched/contain more $\delta^{18}O$ as evidenced by deep sea cores and is measured.
>
> The "increased concentration" of $\delta^{18}O$ in seawater is an "indicator" of the size of the ice sheets.

In addition, sea level drop was due to ice accumulation of the Fennoscandian, Siberian, Tibetan, and Antarctica ice sheets (a relatively stable ice sheet).

* Underline added to differentiate isotopes of Oxygen

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Conversely, ice melting/iceberg generation (Heinrich/D-O events) will cause sea level rise (transgression) during glacial periods; which

> floats the grounded ice on the exposed Continental Shelf which caused the glacier to calve and generates icebergs
>
> which will allow ice behind it to become unrestrained and subsequently cause a surge.
> Sea level can vary '3.5' meters due to Heinrich/D-O events

A Dansgard-Eschner Event (D-O event) is a decades /century long warming event that culminates or is followed with a rapid decrease in temperature.

At this point we will digress and explain Heinrich and D-O events. Heinrich Events are mostly associated with iceberg generation in the North Atlantic. While D-O Events are "sudden" warming periods followed by return to cold periods.

The last Heinrich Event (H1) is associated with Fraser LGM and termination of the Fraser Glaciation. A D-O Event also occurred at Termination 1 or Fraser Ice Sheet termination.

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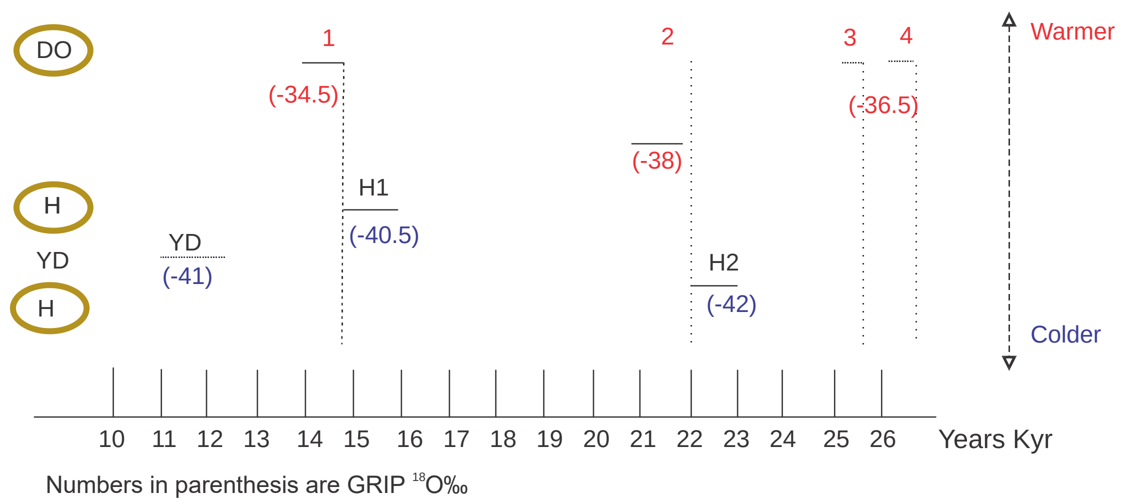

Figure xx: Correlation between Heinrich (H) Events and Dansgaard-Oeschger (DO) Events also showing Younger Dryas (After Siegert, 2001, page 68; and Lowe et al, 1997, page 341)

Ratio of $\delta^{16}O$ to $\delta^{18}O$:

500:1

Ice sheets retain the $\delta^{16}O$ that would normally be returned to the oceans as runoff,

Consequently, more $\delta^{18}O$ is found in shells as the ocean is enriched with $\delta^{18}O$ during glacial periods.

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Associated feedback processes (cont):

Ice Sheet Elevation – Snow accumulates over greater distance and depth

- Too great an elevation can also starve the growth of the ice sheet because moisture is blocked by the high elevation.
  - Greater snow accumulation occurs on the windward side of the ice sheet and at lower elevations
  - Consequently, the Laurentide ice sheet's northeast section was starved for snow
- Snow accumulation over a greater distance and depth caused a separation of the jet stream into two streams in the North American hemisphere (ACM A / ACM B) as a result of ice height.
  - Jet stream bifurcated into a northerly and southerly stream around the Laurentide ice sheet
  - Once the ice sheet lowered, the jet stream returned to its normal stream (only one stream)

See Laurentide Ice Sheet Heinrich Event for a graphic representation on next chart

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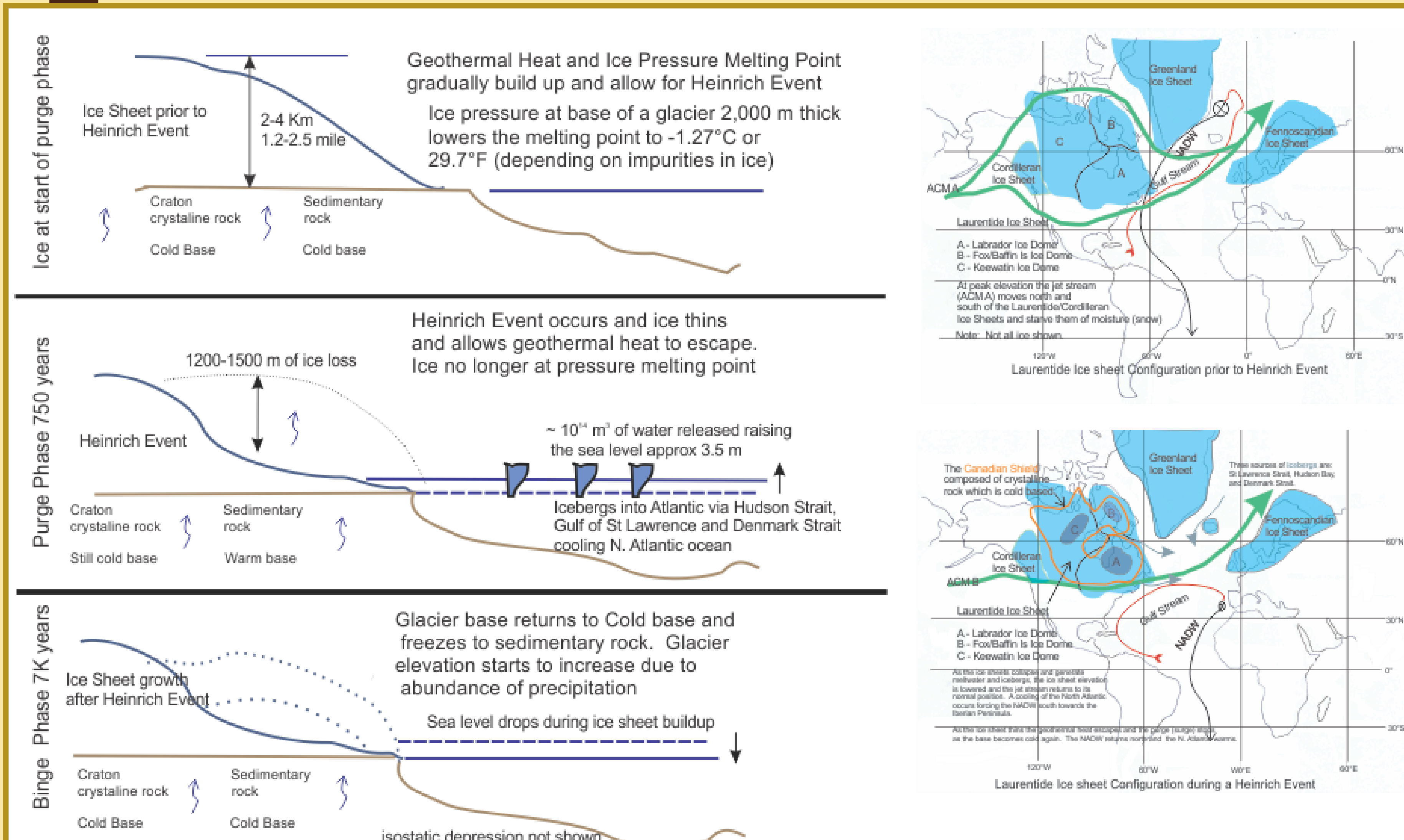
A graphic representation of a Heinrich Event



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Now we'll go back to the Associated feedback processes: (cont)

Carbon dioxide –

Oceans contain 60 times as much CO^2 as the atmosphere and it is from this reservoir that CO^2 is taken in or released to the atmosphere.

Increase of atmospheric CO^2 warms the atmosphere causing precipitation. CO^2 taken out of the atmosphere help induce a colder climate.

With the lowering of sea level (120 meters) and the additional area uncovered by ocean recession, the vegetation growth could have caused additional CO^2 to be sequestered.

Colder seawater absorbs CO^2 more readily than warm water; however, during glacial periods the reduction in water volume and increase in salinity may compensate for most of the additional CO^2

CO^2 has an atmospheric lifetime of between 50 – 200 years, the longest of any the gases

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Associated feedback processes: (cont)

- Upwelling provide the larges source of natural CO^2 to the atmosphere
  - During colder periods more biological activity may draw more CO^2 from the atmosphere
  - Productivity at Last Glacial Maximum (LGM) was twice that of today (Williams, p67)
- An increase in rock weathering during glacial period reduces atmospheric CO^2
- An increase in forams which use calcium carbonate in their shells. Upon death some of the calcium carbonate is sequestered in sediment

Skinner, B.J., et.al., Dynamic Earth…,, p. 199

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Associated feedback processes: (cont)

Ocean circulation – North Atlantic Deep Water (NADW) can be shut off, reduced, or modified

- Sea ice enhances the albedo effect especially if the sea ice lingers during the summer
- Heinrich Events (iceberg formation) in the North Atlantic and cools sea water which reduces evaporation which starve ice sheets by reducing the amount of snow to build ice sheets
- Subsequently, the NADW and Fennoscandian DW can be shut off or reduced
- The NADW does not completely turn off; however, it moves to a position off Portugal
  - See Slide 14, lower righthand corner – "Laurentide Ice Sheet Configuration during a Heinrich Event"
  - The lack of water overturn in the N Atlantic is supplemented by a "tongue" of water from the Antarctic at a subsurface level.
  - This tongue will disappear when NADW "turns on" again

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Associated feedback processes: (cont)

Sea surface temperature (SST) – will be reduced during glaciation (See next slide - the Williams footnote)

In the northern hemisphere during the last 185 kya the following scenario prevailed for the reduction of SSTs. This is an important concept – as ice builds slowly (Williams, Imbrie, and Heinrich)

> Solar isolation values in the high latitudes of the northern hemisphere fluctuated, followed by
>
> A response in ice volume (greater) that lags about 3ka, followed by
>
> A response in sea surface temperature (SST) (cooler) that lags by a further 6 ka

Hence, SST lags atmospheric temperature by 9,000 years (Williams)

Oceanic cooling precedes and is enhanced by Heinrich Events (iceberg release)

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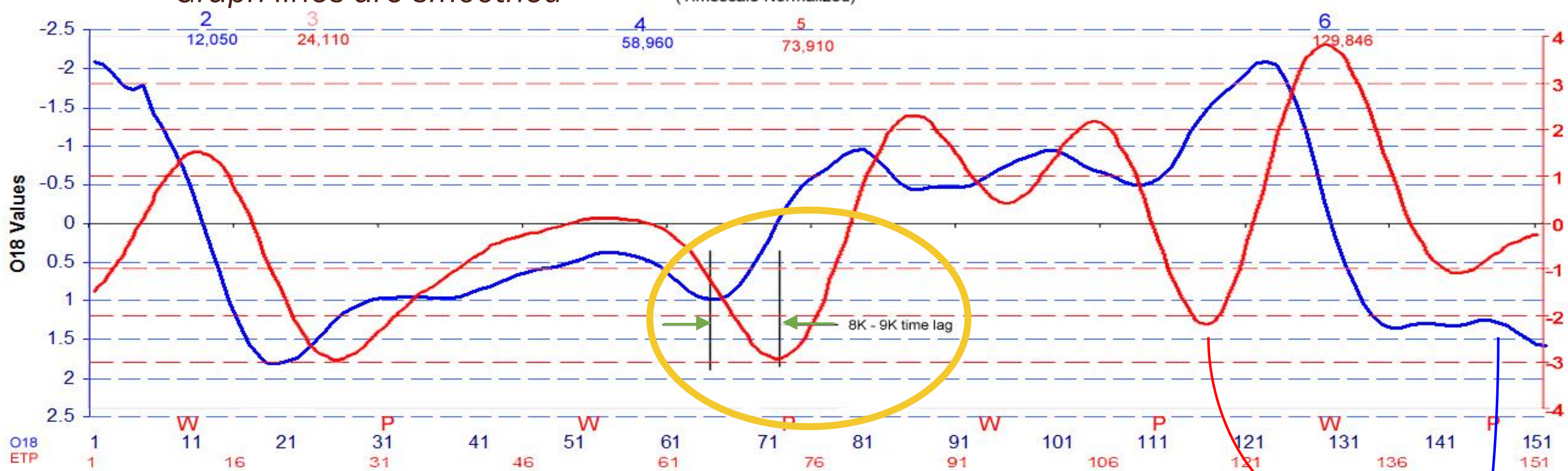
ETP (red) superimposed upon ‰^{18}Oxygen (blue) isotope graph.

- *Time is normalized*
- *Graph lines are smoothed*



Notes:

Heinrich, 1988, Quaternary Research 29: Dropstone record indicates ice rafting not only during stadial intervales by also more or less in the middle of interstades.

Imbrie, 1979, p. 172: The 41K and 23K frequencies precede climatic changes by approximately 8K

Williams, 1997, p. 64: "The northern hemisphere high-latitude summer radiation values flucuate first, followed by a response in ice volumes that lags about 3Ka, and by a response in sea-surface temperature (SST) that lags by a further 6 Ka. This means that SSTs lagged behind insolation changes by an aggregate of 9,000 years.

W = II 270 deg winter minima
P = II 90 deg summer minima

ETP is red
O^{18} is blue

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- Volcano activity – adding dust to the atmosphere
  - Lowers atmospheric temperature
  - Dust can coat ice sheets and initially cause ablation; however, over time the increase in dust will insulate the ice.
    - This, in concert with covering of ice by debris from mountain landsides.
  - Increase in SO_4, CO_2, dust, and ash can block insolation and decrease atmospheric temperature
    - Similar to what happened after Tam Bora and Krakatau
      - After each eruption there were a number of years where atmospheric dust blocked the suns' rays and created cooler summers
- The above are some of the associated feedback mechanisms.
  - And they are considerable in number and impact
  - In many cases, the total impact is unknown or poorly understood

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In Chapter 5, the newsreel will continue:

a. A look at how complex a Continental Ice Sheet is during its life.

b. A short review of: The Mesozoic (248-65mya)/Tertiary era (65 -1.8mya), then a review of timelines for the Cordilleran Ice sheet of the Fraser Glaciation with a nod at what was going on with the alpine glaciers.

A Must Read: John and Katheryn Imbrie's book "Ice Ages: Solving the Mystery", Harvard Univ Press, 1979