LAURENTIDE ICE SHEET

Wisconsinan period

Setting up the place for the LGM

In order to reach its last glacial maximum (LGM) size during the late Wisconsinan, the Laurentide ice-sheet (LIS) needed a base. The periods prior to it, the early and mid Wisconsinan, has been marked by various climatic fluctuations leading to a cycle of glaciations/deglaciations. The extent of the ice mass during the early Wisconsinan (80ka to 65ka) is thought to have approximately covered the late Wisconsinan maximal area (fig) (Occhietti 1987). In counterpart, the thickness of the ice sheet never could have reached the equivalent of the late Wisconsinan. The first part of the mid Wisconsinan (65ka to 44ka) benefit net gains in the earth radiation budget based on the theory model of the astronomic component (Ochietti, 1987). Summers at a latitude north of the 60° parallel had higher rate of incoming radiation than the actual period (fig). A vast retreat of the ice fronts affected the Laurentide ice-sheet without nevertheless leading to a complete ablation. Studies confirm persistent imposing mass of ice on the continent. The second part of the mid Wisconsinan (44ka to 23ka) was marked by a significant drawdown in the incoming radiation. The relative retreat is interrupted by localize advances and readjustment in the balance of the ice-sheet mass (Occhietti et al., 1987). The deficit and diminution in the radiation budget continued till 18-17ka and the LGM.

Formation of the ice sheet and the extent

Accumulation period – building of the ice-sheet

The laurentide ice-sheet is believed to have reach is maximum extent during the late Wisconsinan in a period of low global sea level and during time of relative climate stability approximately around 18ka±4 (Dyke et al, 2002). The extension of the ice-sheet was managed by a multidome dispersion model (figure). A generally accepted model proposes that the laurentide ice-sheet was a system of three interacting sectors: Keewatin, Baffin and Labrador (fig). Each of these sectors had a distinct glacial dynamic and was composed of multiple domes, satellite ice caps and ice divides.

At its maximum extent, the laurentide ice-sheet was a system. The independent dynamism of each domes and satellite ice formations were controlling the margins of the glacier and thus the position of accumulation center and ice divides (Occhietti et al., 1987). This model explains the non-linear evolution and the non-repetitive responses of the laurentide ice-sheet throughout the time to astronomic and climatic changes. Reaching a critical ice mass each of the main sectors gained their own dynamic modifying and responding to regional climatic changes.

The asynchronicity of the advances and retreat shows a wide variety of responses by the laurentide ice-sheet to climatic changes. The margins of the different sectors reached their maximum extent at various time before and after the LGM. The northwest, southwest and south margins behaved synchronously but out of step with the southeast and northeast margins (Dyke et Prest, 1987). In the western most part of Canada, the Cordilleran ice-sheet have reached its maximum extent towards 14ka, presenting a delay of 4-6ka after the glacial paroxysm (Occhietti et al., 1987).

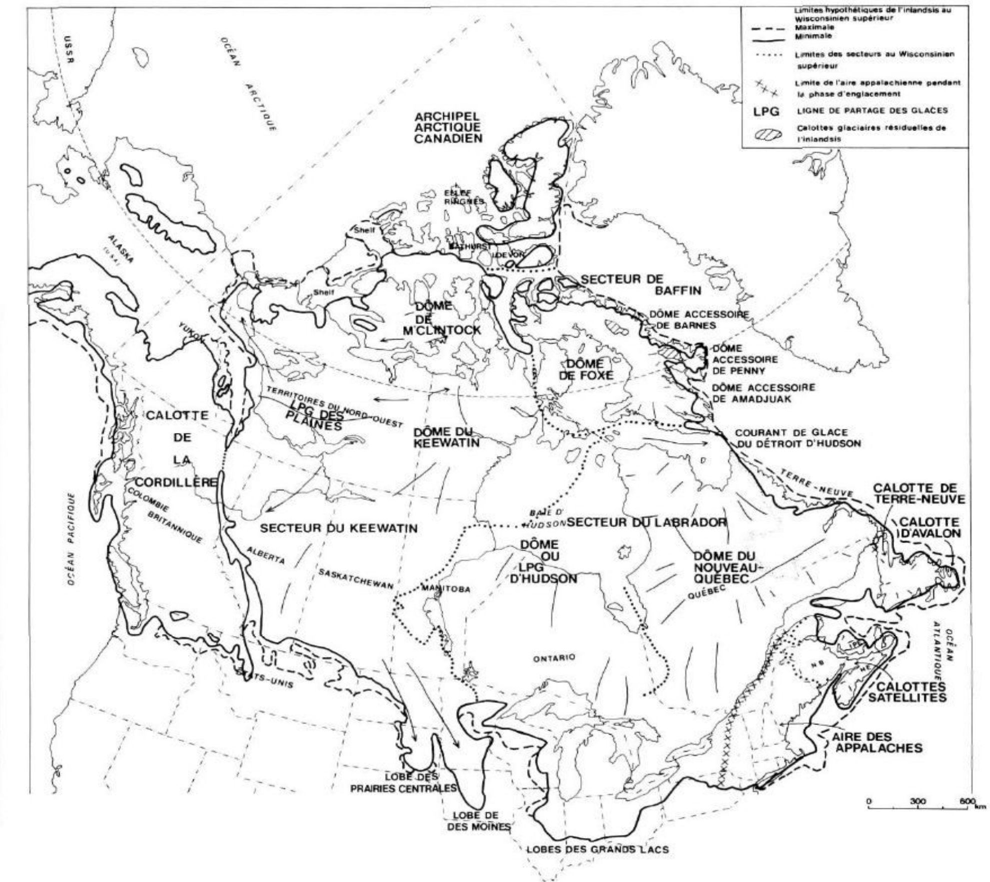

Figure: Domes, ice divides and maximum extent of Laurentide ice-sheet (LIS) at the last glacial maximum (LGM). (Occhietti et al., 1987)

The maximum volume of the laurentide ice-sheet is estimated to $18*10^6$ km³ (Occhietti et al., 1987). It extended on 4200 km east to west and 3700km north to south reaching its maximum area at $12.5*10^6$ km². At the LGM, towards 18±4ka, the thickness of the ice varied between 3200m and 400m. Starting from the main dispersion sectors situated on the Canadian Shield, the LIS covered the sedimentary platform of the Canadian plains to reach the foothills of the Rockies on the west margin. A possible coalescence of the LIS and the Cordilleran ice-sheet in the uppermost latitude (west-central Alberta to 60°north) and southernmost latitude (southern Alberta to Montana) of that margin is believed to have occurred near 18ka (Dyke et Prest, 1987). An ice free discontinuous corridor is believed to have existed between those coalescent margins. Numerous discontinuous deposits are locally overridden each showing a pattern of advance/retreat or overlapping of the ice flow (Occhietti et al., 1987). The east and southeast margin were characterised by satellites ice caps on the Atlantic Provinces which were added to the global mass or stayed coalescent with the LIS. The LIS is believed to have reached the continental shelves limit during its maximum extent (Shaw, 2006). The extent at the northern and northeastern margin is not as defined as the other one. Most of it was glaciomarine and extremely dynamic. In 2002, Dyke et al. inferred that the specific LGM margin cannot be define on the Labrador shelf. The southern margin is most prolific in datable material characterizing the advances. The ice advanced trough partly forest covered area which left numerous sub-till organics remains (Dyke et al., 2002). Each recessional or interstadial interval could be associated with vegetative growth permitting to precisely date further advances. The main lobes influencing this margin were: Lake Michigan lobe, Lake Ontario lobe and Lake Érié lobe. Together they formed the main advances of the Great Lakes lobes and contributed to build up one of the most known moraines complex. The Lake Michigan lobe reached its Late Wisconsinan limit around 26ka (Dyke et al., 2002). Further advances (22.5ka, 18.5ka, 17.5ka, 15.5ka) had consolidated that limit. The Lake Érié and Ontario lobes had attained their maximum limit at 23ka. Ice margins in the Great Lakes area can be correlated to stadials and interstadials period found in the Greenland ice core. This suggests that the southern margin was sensitive to climate changes in the North Atlantic region.

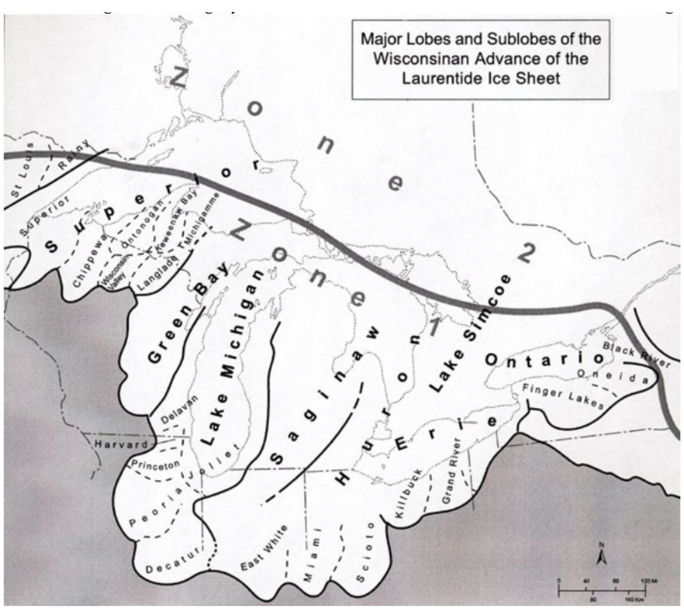

Figure: Division of the Great Lakes lobes from the late Wisconsinan LGM advance. (USGS)

Striations are made on rocks by gradual rubbing and scraping of sedimentary rocks being carried over surfaces by glacial retreats and advances. Moraines are deposits of the carried sedimentary rock that are left behind when a glacier ablates. Movements of the Laurentide ice sheet can be traced by observing these end moraines and striations, and the result of movement on the landscape. For instance, the southernmost extent of the icecap has been recorded in Southern Illinois by using striations to determine the flow direction and the types of rock that were being carried. Moraines left by the glacier are distinguishable, and traveling further south shows a much more different surface topography. Northern Illinois can be categorized by its generally flat surface, whereas Southern Illinois is much hillier.

Other physical markers of the Laurentide Ice sheet are now considered natural landmarks, and are incorporated into state parks, forest preserves, and wildlife conservation areas. One such landmark is The Little Grand Canyon of Shawnee National Forest Preserve, in Southern Illinois. Glacial runoff carved 120 meters deep into the rock to make a valley that channels out to the Mississippi River. Other landforms produced by physical weathering in the preserve include rock arches, and several waterfalls.

Retreat pattern

At 18ka the shoreline in the Atlantic Canada was 115m-120 below present sea level on the outer shelf (Dyke et al., 2002). This level seems to be globally accepted as the global sea level around the LGM. At 14ka the longest marine margin of the LIS was composed of the gulf of Maine, gulf of St-Lawrence, Labrador and North Keewatin. The deglaciation pattern presented here would focus on the eastern part of the LIS and is base on a model proposed by John Shaw. He envisages disintegration on the ice-sheet base on two mechanisms. A gradual rise of the sea level affects the early stage of deglaciation by enhancing the rate of calving at the glaciomarine margin. The second mechanism has been a reduction in the effective rate of ice sheet (Shaw, 2006). This implies a higher ice velocity, a reduction in the basal drag and thus a more efficient transfer of mass from the interior to the margin. These processes induce a positive feedback effect on the LIS and provoked an enhanced calving rate from the ice stream occupied channels draining southeastern Labrador sector.

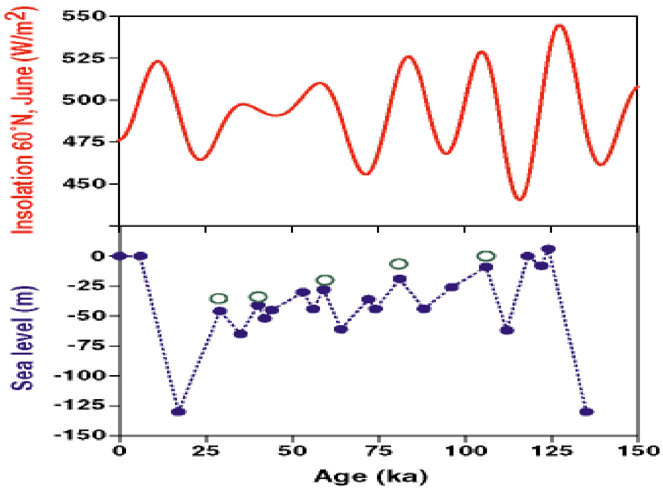

Figure: Wisconsinan variation in incoming insolation and sea level variation. (USGS)

The Laurentian channel calving event effectively separates the southeastern deglaciation in two phases. An early phase of deglaciation took place before 13ka and was characterized by massive ice discharge from marine based ice stream. The late phase extended longer in time and took place on land. The calving phase left an opened corridor reaching far inland. Terrestrial ice melting of the LIS produced numerous concentric moraines network and outwash deposits.

Another thing to look at while we take into account glacial melting is the water table of North America. Glacial melt from the Laurentide Ice Sheet filled aquifers across the continent, the most notable being the Ogallala Aquifer, the largest aquifer in the world. This aquifer spans 8 states, and contains 30% of all fresh water used for irrigation in the United States. Glacial melt has accumulated into this reservoir since the last ice age, and some geologists suggest even earlier given the pore space at depth.

Impact on the Laurentide Ice Sheet on climate and environment

Heinrich event

Heinrich events were first described by the marin geologist Hartmut Heinrich. These events, which occurred during the last glacial age, precisely during the Late-Pleistocene glaciations, are associated with rapid glacial climate variability (not necessarily warming!), where lots of iceberg would break off mainly from the Hudson Strait Ice Stream (HSIS) of the Laurentide Ice Sheet and be discharged to the North Atlantic ocean. As they melted, the eroded substratum they were carrying was deposited on the seabed as «ice rafted debris» (IRD). The study of mud cores of marine sediments revealed six distinct warming events, which are labeled H1 to H6, going back in time; there are some evidences that H3 and H6 somehow differ from the other events.

Heinrich events are global climate fluctuations which coincide with the destruction of northern hemisphere ice shelves, thus relieving an enormous volume of icebergs and sea ice. The events are rapid; they are believed to last about 750 years and their abrupt onset may occur in mere years. Heinrich events, for most of them, occurred during periodic cold spells preceding the rapid warming events known as Daansgard-Oeschger events.

Heinrich's original observations of the ocean sediment cores were of six layers of rocks, containing extremely rich proportions of lithic fragments (rocks of continental origins), from the 180 µm to 3mm scale. The larger-scale fraction cannot be transported by ocean currents and is therefore considered to have been carried by the icebergs that broke off from the Laurentide Ice Sheet then covering North America, and deposited on the sea floor as the icebergs melted. As we move away from the source region, the Labrador Sea, towards the European end of the iceberg route, the belt of IRD (located at 50°N) gets thinner and thinner, showing that the evidence of these events in sediments core decreases considerably with distance.

H3 and H6 (the oldest event) don't fit in the same line of sedimentary evidences than H1, H2, H4 and H5, thus making some scientists believe that they are not true Heinrich events. Here are some unconformities typical to H3 and H6:

- A far smaller proportion of lithic fragments (3000 vs. 6000 grains per gram) is observed during H3 and H6 events. This means that the continental contribution to ocean sediments was relatively lower.
- While H1, H2, H4 and H5 appear to have flowed along Hudson Strait, H3 and H6 seem to have flowed across it.
- IRD doesn't extend as far towards Europe during H3 and H6. In fact some scientists believe that H3 and H6 are events that would originate from Europe. Since the two continents were once together, there are a lot of similarities between the rocks.

Causes

Several models have been provided to explain the Heinrich events. This section is a concise summary of them.

Internal forcing-The «binge-purge» model

This first model suggests that internal forces inside of Laurentide Ice Sheet caused the periodic destruction of major volumes of ice, responsible for Heinrich events. The first phase, the binge phase, is a phase of accumulation that led to a gradual increase of the Laurentide Ice Sheet's mass. The second phase, named the purge phase, is what happened when the Laurentide ice Sheet reached a critical mass. At this point, the soft and unconsolidated sub-glacial sediments formed a lubricant over which the sheet slid. The original model considered that geothermal heat caused sub-glacial sediments to thaw once the ice was thick enough that the heat couldn't escape into the atmosphere. This model works well if we consider events H3 and H6 as parts of Heinrich events because it is based on a 7000 years cycle. Otherwise, it doesn't work, since the main assumptions are based on this periodicity of events. This model may also appear suspect because similar events are not observed in other ice ages, although this may be due to a lack of high-resolution sediments.

External forcings

Several factors external to ice sheet can be accounted for the Heinrich events, but they would have to be very strong to have such an effect on such a big amount of ice. The most discussed and plausible external factor will be the only one described in this section.

Heinrich events have classically been attributed to the Laurentide Ice Sheet instabilities and assumed to lead to important modifications of the Atlantic Meridional Overturning Circulation (AMOC) and the North Atlantic Deep Water (NADW) formation. Recent detailed paleoclimate datas however showed that most of the Heinrich events probably occurred after the AMOC had already slowed down and the NADW collapsed, within a thousand years. This implies that the AMOC reduction could not have been caused by the events themselves.

On the opposite, this model suggests that the change in the LIS dynamics associated with the Heinrich events was caused by changes in the North Atlantic ocean. In fact, the reduced NADW and weakening of AMOC led to a sub-surface warming in the Nordic and Labrador Seas which resulted in the rapid melting of the Hudson Strait and Labrador Ice shelves.

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