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# Hudson Strait ice dam collapse: An explanation for the onset of the Younger Dryas cold climate in Europe in only one year

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**Abstract:**

The Younger Dryas cold climate event in Europe began abruptly at about 12,679 years BP. The abruptness of the onset was caused by the rapid collapse of a dynamic ice dam that had existed because of ice stream flow across the east end of Hudson Strait in northern Canada. The resulting flood of icebergs into the southern half of the Northern Gyre adjacent to the Gulf Stream converted western Europe's mild climate to an arctic climate. The collapse event was caused by the last large accumulation of glacial ice in the thick ice dome of Hudson Bay. The accumulation created a pressure gradient that forced an ice stream flow eastward in Hudson Strait. A highly saline sub-glacial lake had formed earlier in the western part of the strait. The ice stream flow entrained saline lake water in a network of channels at the seabed between the lake and the ice dam, melting and extending the network eventually to and beneath the ice dam. This detached much of the ice dam from its frozen bed and caused its catastrophic collapse and the onset of the Younger Dryas in only one year.

**Keywords:** Younger Dryas, Ice dam collapse, Sudden climate change, Laurentide ice dome.

## 1: Method.

The rapid collapse of an ice dam at the eastern end of Hudson Strait is proposed in this paper to explain the abruptness of the onset of the Younger Dryas climate change in Europe. An analysis of the factors causing the collapse is developed using land elevations and water depths from Google Earth. A study of these data and the probable changes in snowfall over northeastern Canada resulted in the hypothesis of a highly saline subglacial lake in western Hudson Strait. The role of the lake in the analysis yields a physically realistic model of the abruptness of the collapse. The context of the collapse is consistent with the quasi cyclic nature of Heinrich events that shut down the Atlantic Meridional Overturning Current (the AMOC), and caused the repeated deglaciation of much of the Laurentide Ice sheet.

## 2: Introduction.

The Younger Dryas is named for an abundant Arctic flower that marks the severity of the climate in the European records between ~12,700 and ~11,400 C yrs BP, (calendar years before 1950). This cold climate interval coincides with H0, the last of a series of Heinrich events[1] in which large quantities of glacial debris were carried into the North Atlantic on melting icebergs at the time of the Younger Dryas. The cause of the Younger Dryas event is widely debated. MacAyeal proposed a fundamental instability in the Laurentide ice sheet[2]. Leydet et al. noted that the start of the cold event occurred about the time that the St. Lawrence Valley became ice-free and allowed melt water from the great Lake Agassiz to drain into the Gulf Stream[3]. This possibly reduced the Atlantic Meridional Overturning Circulation (the AMOC) causing zonal atmospheric circulation and a cold European climate. Alvarez-Solas et al. suggested that Heinrich event H1 (and others) may have been an example of dynamical ice sheet reaction to oceanic changes[4]. However, none of these mechanisms can explain the abrupt change of European climate in only one year, as implied by change in wind patterns reported by Brauer et al.[5] from analysis of annual varves in lake sediments from western Germany. The abruptness of the climate change suggests an equally abrupt event as its cause. Such an event would have been the collapse of the ice dam at the eastern end of Hudson Strait, as proposed by Johnson and Lauritzen[6]. This paper revisits their proposal and offers a detailed analysis of the ice dam collapse, which was followed by the draining of ice from the Laurentide ice dome through Hudson Strait during the Younger Dryas.

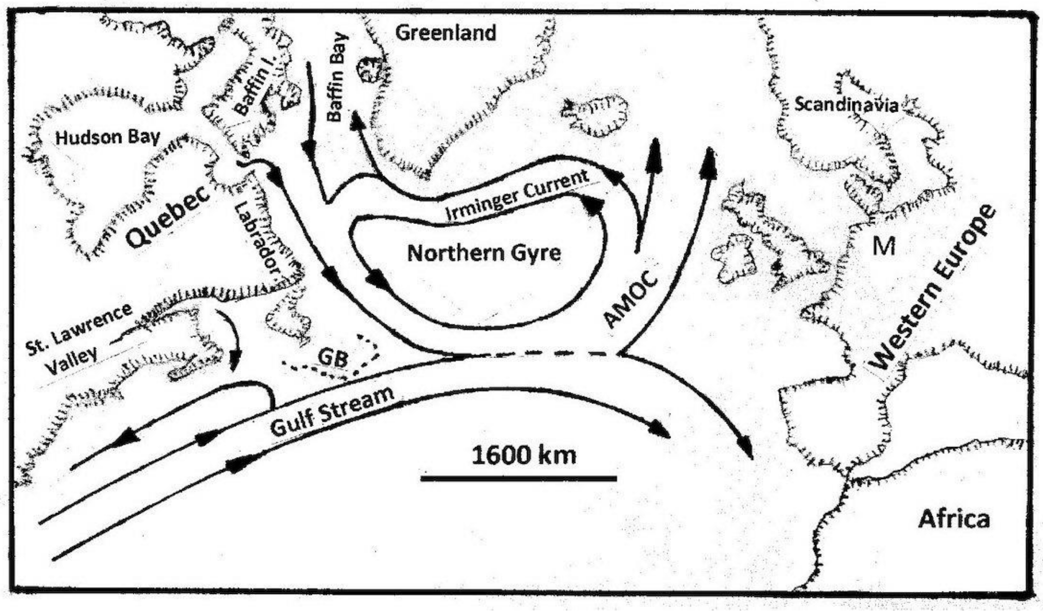


**Figure 1: Northern Gyre and Gulf Stream currents in the high-latitude North Atlantic, mapped on Lamberts Azimuthal Equal Area projection. AMOC: Atlantic Meridional Overturning Current. GB: Grand Banks southeast of Newfoundland. M: Lake Meerfelder Maar. Mid Atlantic dashed line indicates mixing of cold Canadian current with warm Gulf Stream.**

**3: Why the Younger Dryas wind circulation change occurred in only one year.**

In a study of varved sediments from Lake Meerfelder Maar in western Germany, Brauer et al.[5] found evidence for a change in wind strength in a one-year interval at 12,679 C yr BP. The change was from prevailing mild westerlies to the dominant storminess of the Younger Dryas. They suggested that this was the result of a switch to a stronger and more zonal atmospheric jet stream. As proposed here and illustrated in Figure 1, a switch to a more zonal jet would be expected if a large discharge of ice and meltwater from Hudson Strait into the North Atlantic began suddenly. This could have lowered the temperature of the gyre adjacent to the warm Gulf Stream, which steered storm systems to a zonal path. If the velocity of the rim of the gyre were equal to the 0.05 $msec^{-1}$ of the Irminger Current as found by Greatbatch and Xu[7] over a modern five-year interval, the first part of a continuing discharge of icebergs and cold meltwater could have occupied the southern rim of the gyre and mixed into the Atlantic Meridional Overturning Current (the AMOC) as in Figure 1 in 2.6 years or less after the abrupt collapse of the ice dam began. Therefore, in about one year the strong temperature contrast at the north edge of the Gulf Stream and the associated more zonal jet stream would have become established, with stormy conditions in Europe. The lower sea surface salinity in the high latitudes would have nearly stopped the AMOC flow immediately, as Heinrich event H0 began. To understand the failure and restoration of the cross-flowing ice stream dam, it is useful to describe changes in atmospheric circulation that accompanied Heinrich events.

**4: Heinrich events and the cross-flowing ice dam at the mouth of Hudson Strait**

Quasi-periodic events in which melting icebergs distributed glacial debris across the high-latitude North Atlantic were described by Heinrich in 1988[1]. In the JohnsonLauritzen model, the event begins with the abrupt failure of the cross-flowing ice dam due to increasing pressure of ice flowing eastward in Hudson Strait as illustrated in the sequence of ice sheet profiles of Figure 2. The event continued for more than a thousand years with the

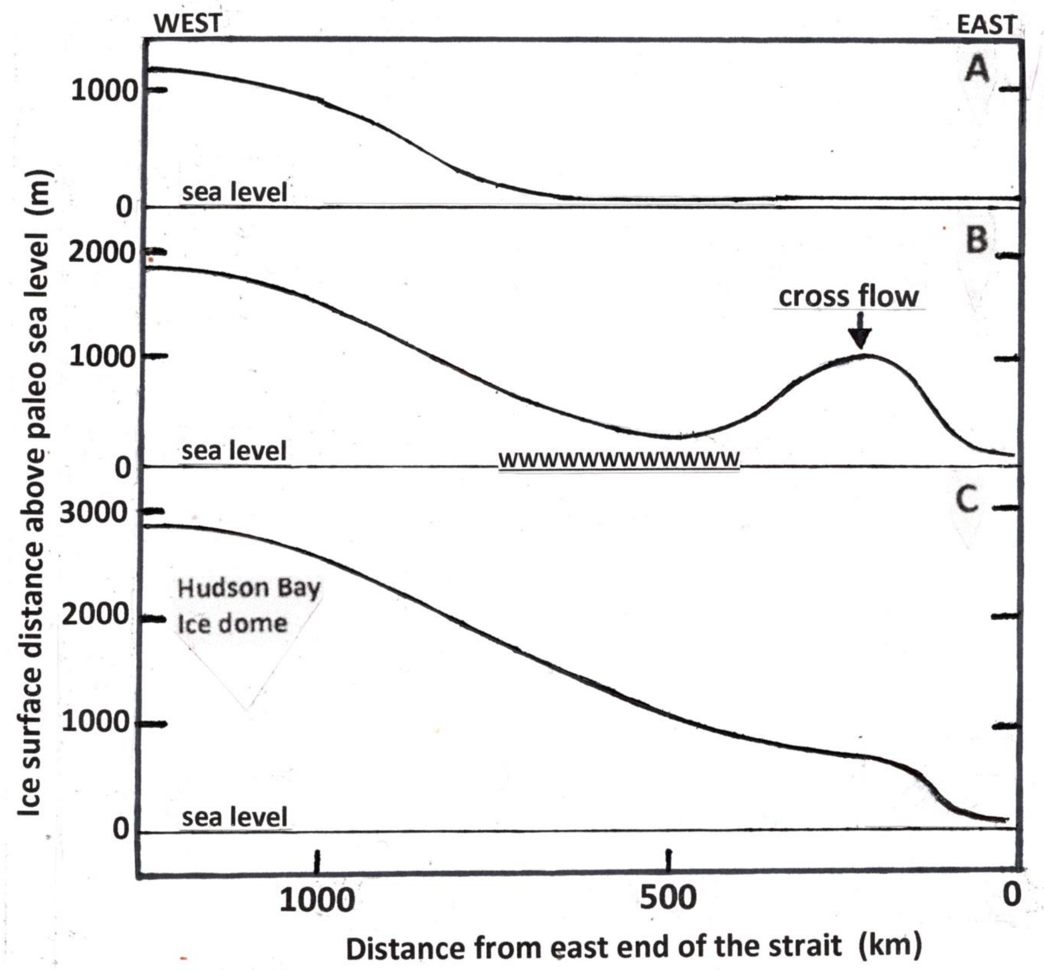


**Figure 2: Schematic profile of ice flow surface between a northern high point of the ice dome over Hudson Bay and the mouth of Hudson Strait at three points in the Heinrich event cycle. A: After the interval that drained away much of the ice dome through Hudson Strait. B: After the crossflow had restored the ice dam. C: Just before the maximum height of the dome was reached and before the outflow destroyed the crossflow of the ice dam. Hatched area is the location of a subglacial lake of highly saline water.**

eastward flow of massive amounts of ice and meltwater through the strait into the high-latitude North Atlantic from the central Canadian ice dome over Hudson Bay. Glacial debris carried by melting icebergs is found almost as far east as the coast of Ireland[1]. The Heinrich event ends when the supply of ice for the outflow from the ice dome diminishes and the outflow of ice becomes weak, which enables the restoration of the cross-flow. The close proximity to a somewhat warmer Labrador Sea source of moisture then enables a rapid increase in dam thickness until the local rate of outflow to the sea equilibrates with the precipitation and cross-flow rates. The ice surface profile on the approximate center line of Hudson Strait for three points in the Heinrich event cycle are depicted in Figure 2. When a Heinrich event begins, the sea surface is freshened by large volumes of ice bergs and meltwater that effectively shut down the AMOC flow making Europe much colder. The increased zonality of circulation during the event steers storm paths to the south, following the temperature contrast line between cold meltwater and the warm Gulf Stream. The increasing zonality is also felt to the west, which diminishes precipitation on the North American continental ice sheet, causing a northward retreat of the southern front. The zonality also somewhat diminishes the precipitation that would supply ice to restore the crossflow, which favors a longer Heinrich event. When the crossflowing dam is restored, icebergs no longer pass through Hudson Strait into the Northern Gyre, and it rapidly warms. Consequently, in about a hundred years storm paths return more often to the northeast and frequently supply precipitation that ensures a strong cross-flowing ice dam. But over the next 6,000 - 10,000-yrs before the next ice-dam failure, the thickness of the central Canadian ice dome slowly increases and the front of the Canadian ice sheet again extends southward. These two effects tend to diminish the moisture in storms reaching the ice dam area. Therefore, the strength of the cross flow somewhat diminishes as the central ice dome height increases. A Greenland ice core record[8] supports this sequence of changes. The progressive loss of moisture in storms that continue onward to Greenland results in a slow change of oxygen isotope ratios toward the more negative values found in a Greenland ice core in the last few thousand years

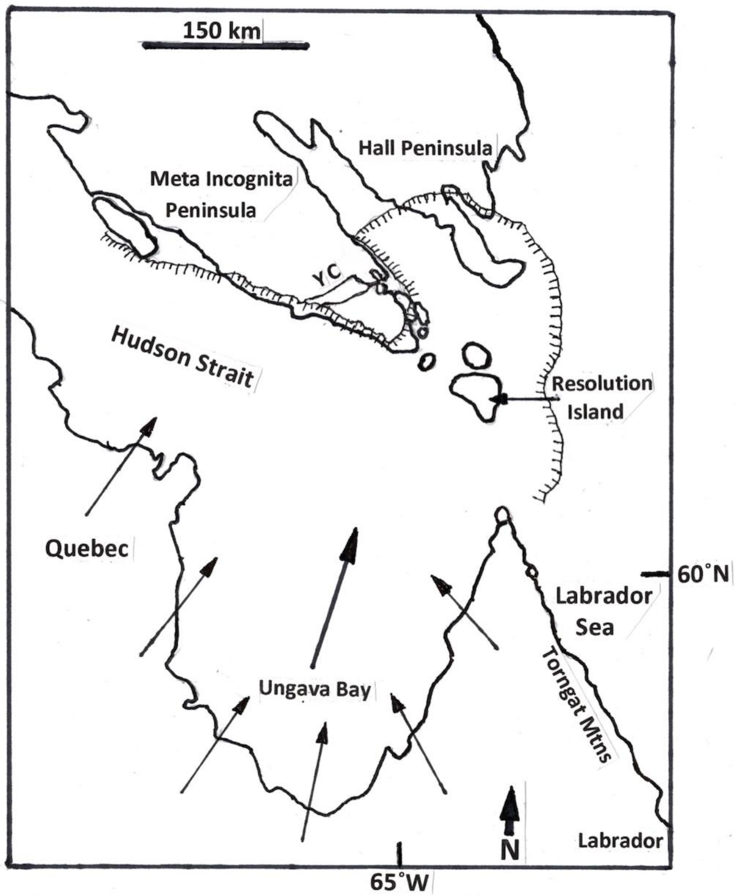


**Figure 3: A glacial ice stream cross flow at the mouth of Hudson Strait at 10,900 C yrs BP[9]. The northward extent of the cross flow is indicated by limestone erratics that were plucked out of the sea bed of Hudson Strait by glacial freezing action. YC: York Canyons.**

between each Heinrich event. The weakening of the crossflow would hasten the ice dam collapse that starts each Heinrich event. However, failure of a small ice dam might not supply enough ice to explain the abruptness of the European climate change, and a thick ice dam associated with a longer interval of accumulation may be required. It is therefore desirable to identify the range of ice dam thickness.

## 5: Two extremes of ice dam thickness

### 5.1: A small ice dam when the precipitation rate was low during the last deglaciation

Stravers, Miller, and Kaufman[9] reported evidence for ice stream flow northward through Ungava Bay, across the mouth of Hudson Strait, and as far north as the Hall Peninsula (Fig. 3). The northward flow, indicated by bedrock striations and glacial erratics of limestone plucked from the frozen bottom of Hudson Strait, was dated to10,900 C years BP, 500 years after the end of the Younger Dryas, and at a time when precipitation rates were smaller. The thickness of the ice dam at that time is suggested by the limited advance of the ice to an elevation of only approximately 100 m on the eastern end of the Meta Incognita Peninsula (Fig. 3). The crossflow surface at the center line of the strait would have been only slightly higher above present sea level. Together with the present maximum depth of 400 m at one location between Labrador and Resolution Island, this indicates an ice thickness of 300-500 m.

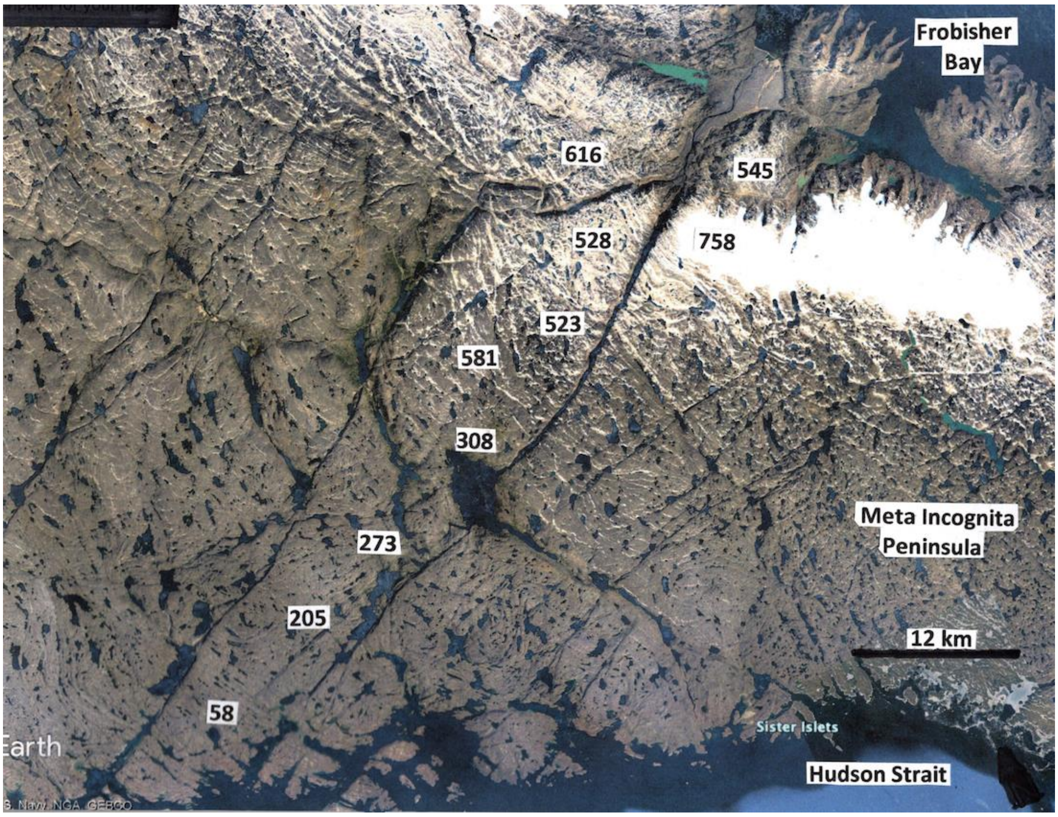


**Figure 4: The York Canyons on Baffin Island. These channels that were eroded into old fault lines carried summer melt water from the Hudson Strait ice dam. The channels were eroded in hard crystalline rock, and carried meltwater from present sea level up over the Meta Incognita Peninsula and discharged into Frobisher Bay. Elevations are in meters. Image and elevations from Google Earth.**

### 5.2 : The York Canyons indicate a maximum crossflow thickness.

The York Canyons on Meta Incognita Peninsula (Fig. 4) are located about 150 km west of Resolution Island and in the zone of the crossflow. They were eroded sub glacially on old fault lines in the hard, crystalline rock[10]. The

canyon depths increase in the northeastward direction. They extend from sea level northeastward over 60 km before merging together and discharging into Frobisher Bay. This implies water flow up the slope of the peninsula, which implies a substantial hydrostatic pressure difference due to a higher elevation of the ice surface of the crossflow at the center line of the strait. Before merging, they cross terrain that is almost 600 m above present sea level. The depth at the center line of the strait south of the merging point is about 400 m below present sea level (Fig. 5), which implies a maximum cross-flowing ice dam thickness of somewhat more than 1000 m. As argued previously, the elevation of the cross-flowing ice surface when the Younger Dryas began was probably somewhat less than this maximum, although still several hundred meters above sea level. A possible schematic elevation was about 500 m above today's sea level at the time saline subglacial lake water caused the collapse.

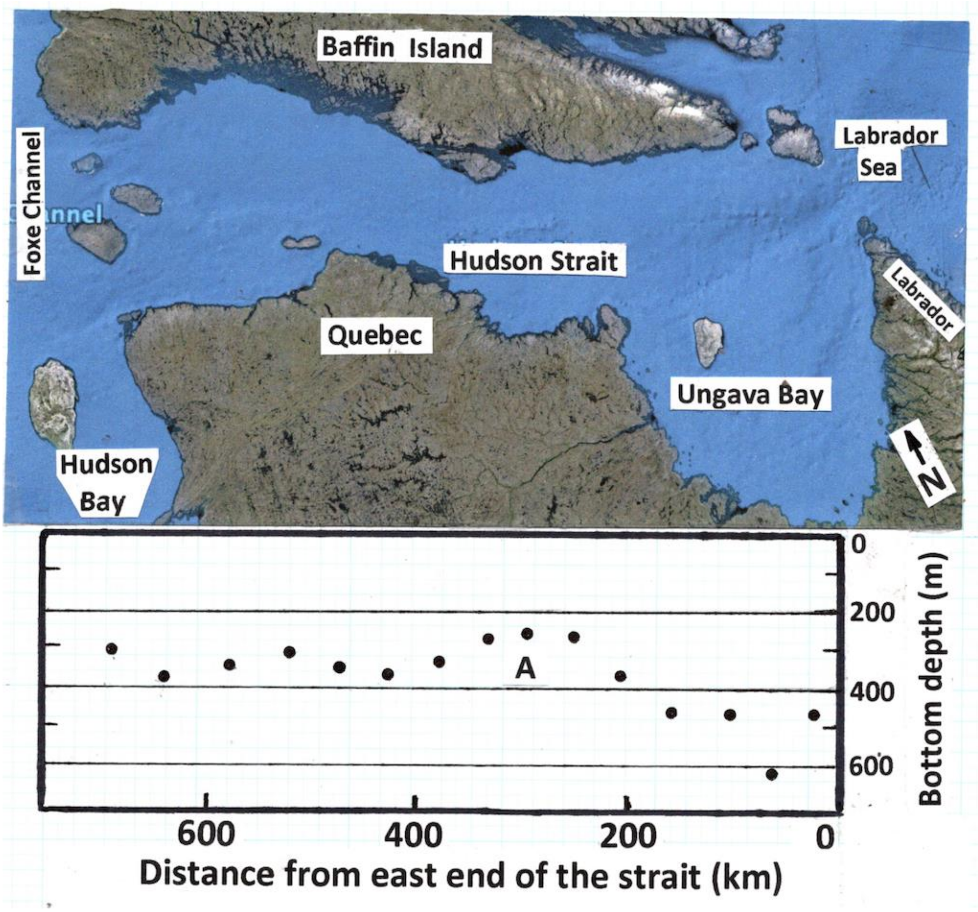


**Figure 5: View of Hudson Strait and its longitudinal depth profile on the approximate center line of the strait. Data and image from Google Earth.**

### 6: The abrupt collapse of the Hudson Strait ice dam

#### 6.1: A chain of causes

For thousands of years after the previous Heinrich event the dynamic ice dam remained in place, frozen to the seabed and sustained by flow of ice from the Labrador-Quebec area through Ungava Bay, with the ice discharged into the Labrador Sea and the Northern Gyre. The low rate of discharge was not of climatic significance. The abrupt collapse that caused the interval of arctic climate in Europe was preceded by a series of events and factors that were unique to Hudson Strait. As proposed in the following sections, they include the ice accumulation in the Hudson Bay ice dome, the formation of a highly saline subglacial lake in the western part of the strait, and the formation of channels at the seabed that carried saline lake water to the ice dam and effectively detached it from the frozen seabed.

#### 6.2: Formation of the highly saline subglacial lake.

Referring to profile **A** of Figure 2, at the end of each Heinrich event, grounded ice still blocked the west end of Hudson Strait. The adjacent part of the strait to the east contained ocean water that had become isolated when the grounded cross flow at the east end was restored. At points between the thick ice of the cross flow and the thick ice west of the strait, **B** in Figure 2, the ice surface would initially have been close to sea level. Consequently, freezing occurred repeatedly, and the salt rejected in the freezing process would always have been added to the remaining isolated sea water, thus increasing its salinity and lowering its freezing point. The freezing point for sea water falls about 1.5˚C for each 10 ppm (parts per thousand) salinity increase. A salinity of 90 ppm might have been attained, with a freezing point of about -10˚C. Eventually, the insulation provided by the thickening ice sheet, the low freezing temperature provided by the increasing water salinity, and geothermal heat flow would have stopped the freezing process. The lake may have existed unchanged for thousands of years until increasing ice accumulation in the Hudson Bay area developed the pressure gradient that removed the low zone, and raised the ice surface profile to that of **C** in Figure 2.

### 6.3 : Melting flat cracks and channels beneath the ice stream.

As the low zone of the ice surface in the strait was being removed, the increasing hydrostatic pressure gradient of the ice sheet over central Canada forced highly saline lake water eastward under the ice at the seabed interface in the direction of the ice stream flow. The probable mechanism that enabled the lake water to penetrate under the ice can be described with the aid of Figure 6. This cartoon shows a slice in a vertical plane in the ice stream that contains the lake-ice-seabed intersection. The ice is frozen to the seabed east of the edge of the lake. The ice and lake temperature is well below 0˚ C. However, the temperature is too low to allow the salt in the lake to react with and significantly melt the ice above. The key to the penetration of the lake water beneath the ice stream is the frictional warming caused by the shearing action in the ice at the interface with the frozen seabed. The warming enables salt to melt the ice at the water-ice-seabed intersection. Salt for the melting is supplied by an entrainment current at the ice- water interface. Melting enlarges the crack and propagates it eastward, as shown between **B** and **C** in Figure 6. The warming enables salt to melt the ice at the water-ice-seabed intersection. Melting enlarges the crack and extends it eastward, as shown between **B** and **C** in Figure 6. But as ice melts and the apex extends, the concentration of salt at the apex diminishes there and must be restored if a steady rate of growth is to be maintained. For short channel lengths, an adequate amount of salt is brought to the apex by the entrainment current at the ice-water interface, despite the diffusive loss from inflow to the reverse outflow. But for long thin channels, losses would accumulate and stop the channel extension if hydrostatic pressure did not force the roof of the channel away from the seabed.

### 6.4: Transporting salt through long channels.

As the ice stream profile in Figure 2**C** suggests, and analogous to the pressure driving meltwater up through the York Canyons, there would have been a strong pressure gradient that tended to force saline lake water into the channel created by the melting at its apex. The pressure would have been equivalent to a water column height of 100 m, or much greater at some locations. This pressure slowly forced the surface of the ice stream above the broad channel away from the seabed, increasing the channel thickness by many tens of centimeters or eventually even meters. The greater thickness would have made turbulent flow by entrainment possible, and high concentrations of salt would always have occurred at the beginning of the short and thin parts of the channels., making greater amounts of salt available to be carried to the apex. In effect, the edge of the saline lake would have been extended eastward and would have followed the short lengths of thin channels as they penetrated eastward under the ice at the seabed.

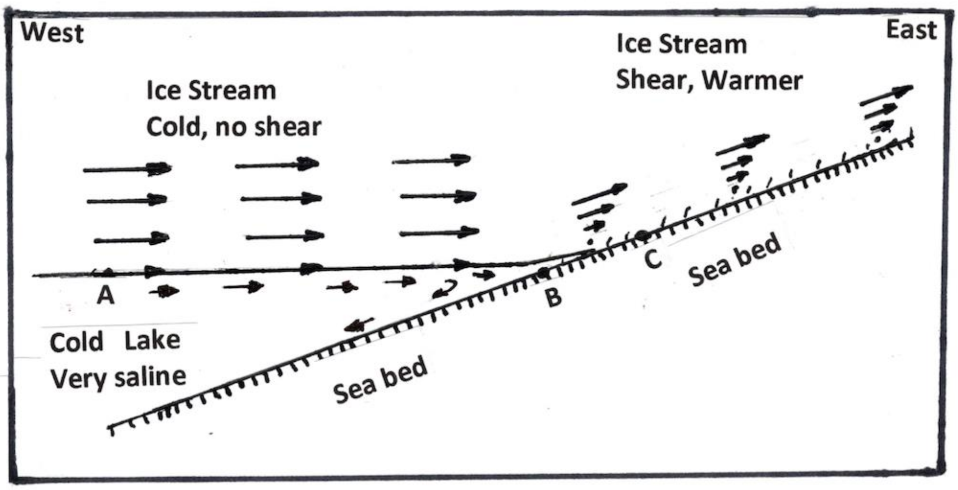


**Figure 6: Hypothesis of short channel generation between the ice stream and its seabed. A: Interface between ice stream and lake water. B-C: Area of crack enlargement and propagation. This cartoon shows the Intersection of the bottom surfaces of the ice stream, the saline subglacial lake, and the sea bed. The**

**shearing friction at the frozen ice-seabed interface warms the intersection enough to quickly melt the ice there, and propagate the channel eastward between ice and seabed.**

**6.5: Lateral spreading: The channel network.**

Roughness of the seabed would have prevented a smooth and laterally continuous crack. For example, a sharp local rise in the seabed would divert the ice around the rise. The extensions of the channel would follow the flow of the ice around the obstacle, and bring the salt to each apex of two wide cracks at the seabed interface. Therefore, the lateral diversions would split the channel in two and widen the effective coverage. Such diversions of flow would have created a channel network and widened the network. The north-south width of the channel network would depend on the width of the lowest part of the bowl-shaped profile of the seabed across the strait, and could be many kilometers as suggested in Figure 7. Such a network would greatly reduce the total resistance of the ice stream to flow, and the flow velocity of ice above the network of channels would tend to increase. The ice stream flow velocity that feeds entrained salt to the crack may be a critical factor. This factor would greatly increase when the crack network reached the ice dam where ice stream surface gradients are large (Figs. 2**B** and 2**C**).

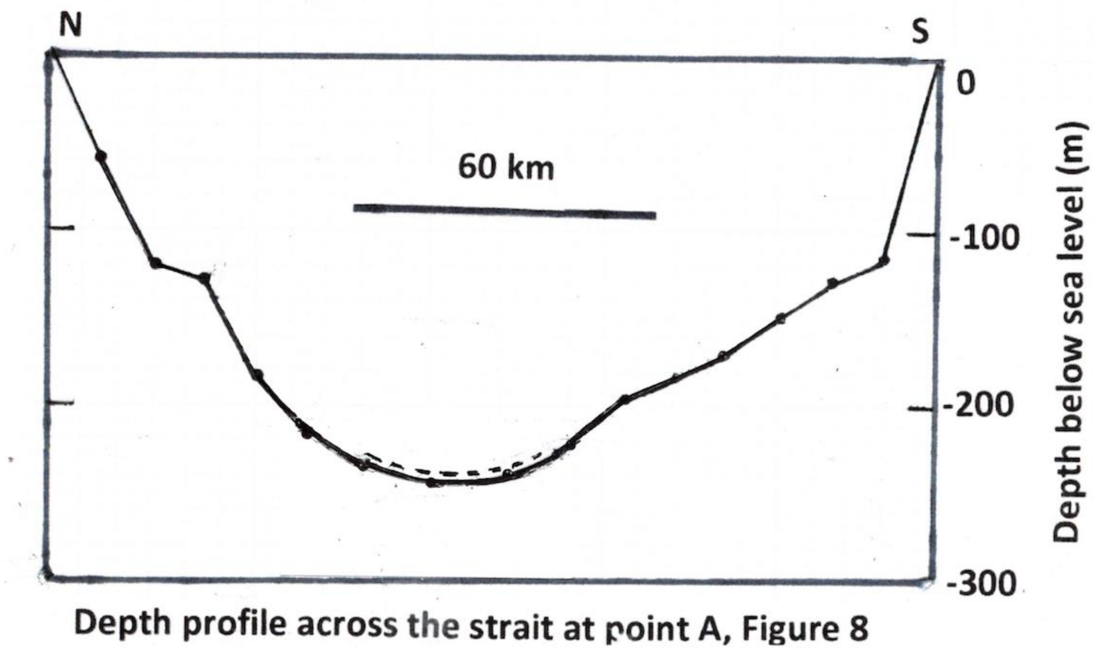


**Figure 7: Present bottom depth profile across the strait at the shallowest point in the longitudinal depth profile, 300 km west of the east end. Dashed line indicates area of eastward channel propagation. Channel propagation at this point might have been confined to a 40 km-wide strip in the lowest part of the profile across the strait.**

**6.6: Ice dam flow before the lake water reached point A in Figure 8.**

Before water of the sub glacial lake reached the ice dam, small amounts of melt water entered the ice of the dam in summer as implied by the flow in the York Canyons. But the minor effect on the ice flow would have been only temporary, and seasonal refreezing would have occurred. The ice surface profile, **S0** in Figures 8 and 9, would have been governed by the mostly frozen ice bed with only small amounts of water seasonally at the base. However, even before the channel network advanced beyond point **A** and the collapse began, the ice dam would have contained ice flowing from the west in addition to that flowing originally northward from Labrador.

**6.7: Ice stream flow in the dam after the saline lake water reached point A (Figs. 8 and 9).**

After the lake water reached the dam and the collapse began, a large part of the seabed in the area of the collapse would have been occupied by the channel network containing saline lake water. The ice dam collapse likely consisted of two parts. In the first part, the network of channels containing saline lake water would have been melting its way eastward to the sea at the eastern edge of the dam, but there would yet have been no rapid flow of salty water through the channels. The pressure of cross flowing ice from Labrador probably forced the channel propagation to the northeast toward Resolution Island. The rate of ice stream flow through the dam would have increased as more of the channel network in the strip undercut the ice at depths where it was still frozen to the bed. In the second part of the collapse, the channels were open to the sea. Rapid flow of saline water through the channels with resulting erosion favored increasing flow velocities of the ice and, and probably resulted in a trough at least 40 km wide in the ice. The ice on both sides would have then tended to flow into the trough as the dam collapsed, consistent with the report that there are no longitudinal striations on the Meta Incognita Peninsula[9]

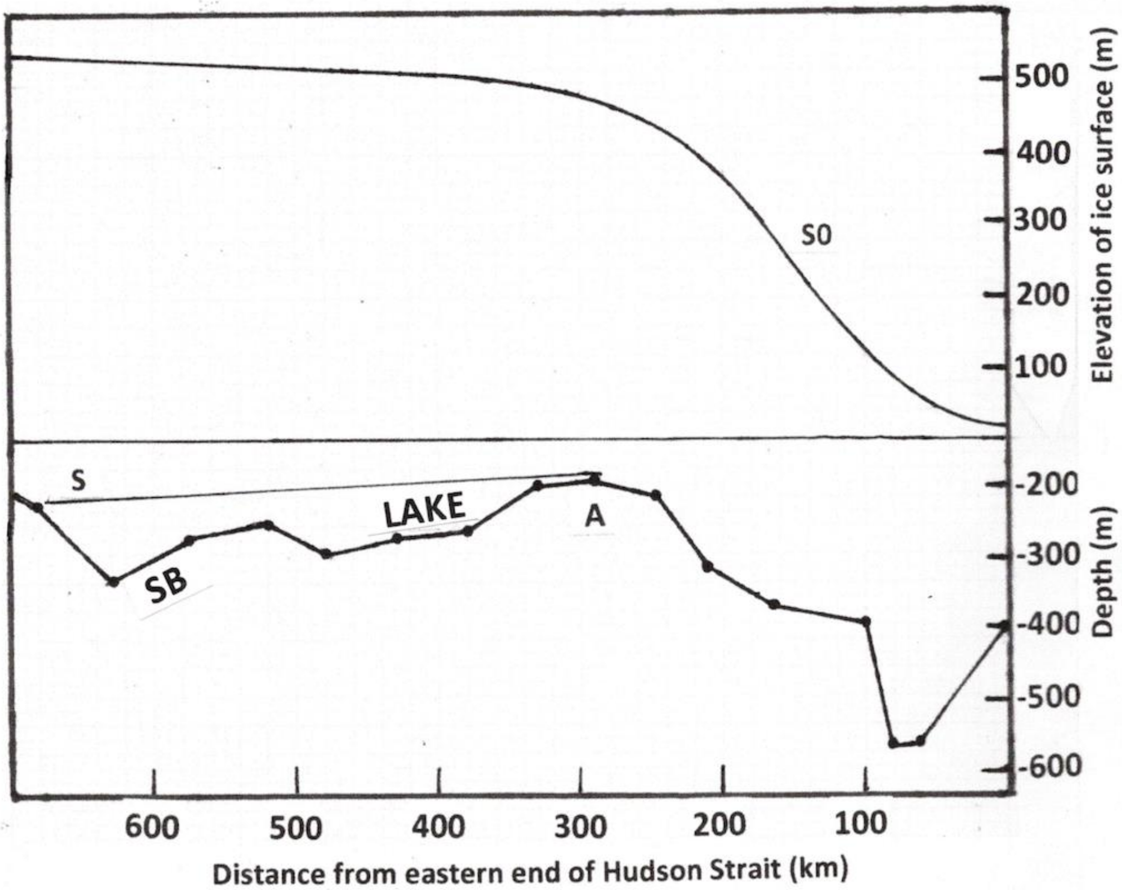


**Figure 8: Hypothetical longitudinal profile of ice stream surface, SO, and profile of sea bottom, SB, in Hudson Strait just before the ice dam collapse began. These profiles are on the approximate center line of the strait. S: the surface of the saline sub glacial lake. SB: seabed paleo depth profile from Google Earth.**

**7: Feedback effects.**

Among all the factors that contributed to the collapse of the Hudson Strait ice dam in only one year, the main underlying factor was the presence of the highly saline lake in the western part of the strait. Because quite salty water from the lake under high pressure was able to melt and separate the ice dam from its frozen seabed, the preceding otherwise slow discharge of the ice stream into the sea became catastrophic. Two positive feedback effects that hastened the collapse can be described with the aid of Figure 9. Extending the ice-seabed channel network eastward (dotted line) increased the flow velocity of the ice above by increasing its slope to **S1**, which further increased ice stream velocity and rate of channel propagation, thus enabling the channel network to quickly reach the sea and fully accelerate the collapse. As the collapse began, the greater slope of the ice surface extended back to and beyond **B** in Figure 9. Probably within a few weeks or months, much of the ice in the dam would have been discharged as icebergs into the sea. The resulting zonal atmospheric circulation reduced

Labrador precipitation and eliminated the crossflow, leaving only the flow of ice from the west that drained the central ice accumulation over Hudson Bay through the strait. That flow continued for 1,300 years.

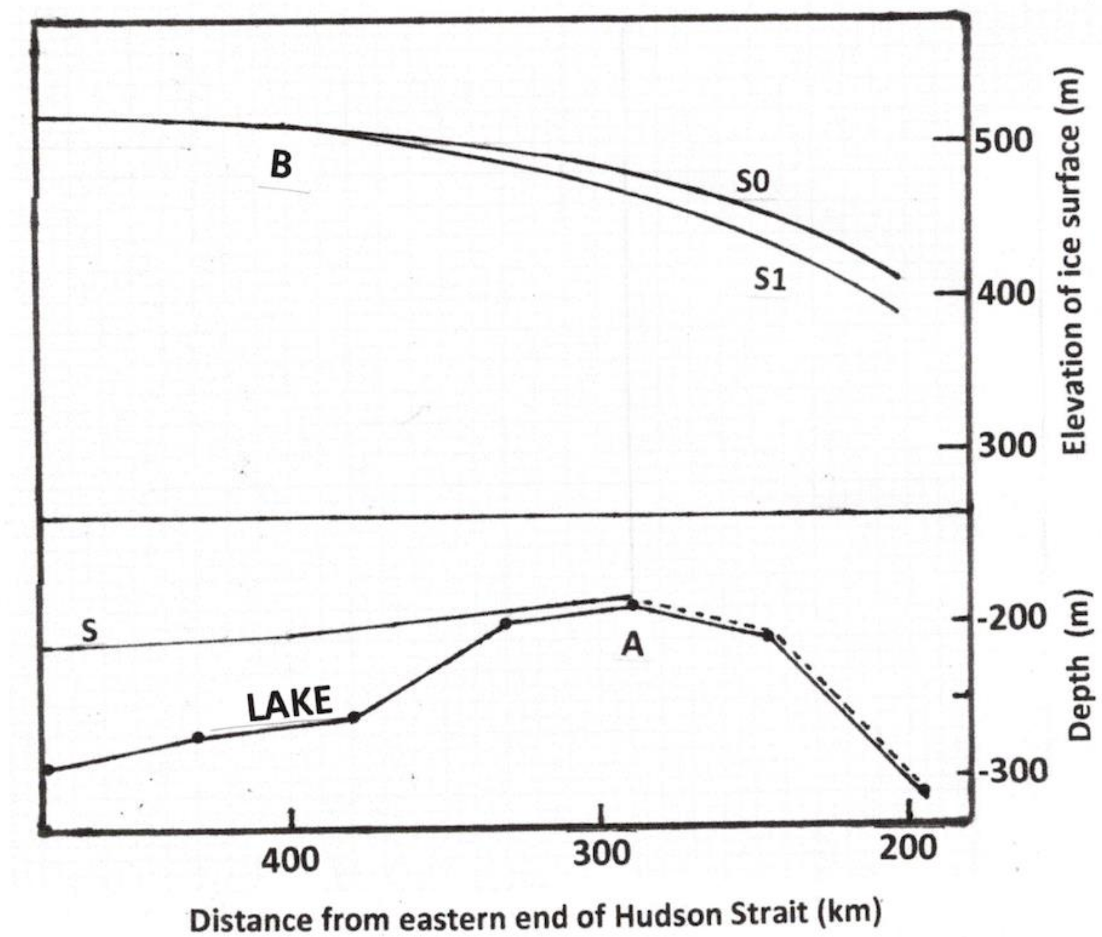


**Figure 9: One of the positive feedback effects in the strip occupied by the saline lake water: Extending the ice-seabed channel eastward (dotted line) increased the flow velocity of the ice above by increasing its slope to S1, which further increased velocity and rate of propagation, thus enabling the channel network to quickly reach the sea and fully accelerate the collapse.**

**8: Concluding remarks.**

The detailed endothermic mechanism for melting the channels in the ice stream at the seabed is based on known physical effects. An analogous melting mechanism is used to clear icy roadways during northern winter climates. If temperatures are not lower than about -5˚C, salt applied to the roadway reacts with the ice at the temperature of the environment. Environmental heat in the ice and salt melts the ice. Consequently, the salty water produced by the reaction becomes colder than the environment, and the saline water runs off into the drains. In the cold paleo climate of Hudson Strait, the environmental temperature of ice and saline water would have been already too low to drive significant melting, and the local heating caused by shearing friction near the crack apex of the channel was required to raise the local temperature and enable the melting to occur.

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