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The role of the formation and destruction of the Hudson Strait glacial ice dam in changes of climate and sea level during the Last Interglacial-Glacial transition

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Abstract

During the Last interglacial period of constant sea level, large coral reefs formed on the tectonically rising island of Barbados, and a broad lagoon with a small barrier reef formed at the Cane Vale site. The constant sea level was ended by a rapid glaciation, causing a fall of world sea level of 2.4 m, as measured by surveys of features associated with breaking waves on Barbados. The fall began about 120 ka BP, and lasted roughly 400 years, according to a lake pollen record from western Europe. That rapid fall was terminated at a wave-cut step on Barbados and with a quite small reversal in falling sea level. The small rise was caused by rapid melting of the marine-based Barents Sea ice dome and other ice masses, due to a restored strong Atlantic Meridional Overturning Circulation (AMOC) flow. The sea level fall then resumed until it was halted at a wave-cut step at a world sea level 12.3 m below the last interglacial level, as recorded at the University of the West Indies site on Barbados. Following the erosion of that second step, a zonal northern North Atlantic circulation prevailed, causing a glacial ice-volume decrease and rise in sea level of 3.8 m. These two sea level fall reversals were caused respectively by the formation and destruction of a Hudson Strait ice dam and the resulting increase and much later decrease in the rate of AMOC flow.

Keywords: Glacial sea levels, Barbados reefs, Glacial climate change, Heinrich events.

1. Method

The paleo sea level changes found in the fossil record of tectonically uplifted Barbados and reported here were measured in surveys made during six expeditions to Barbados from 1991 to 1998. The changes in the elevation of world sea level were stratigraphically referenced to the constant world sea level at the time of the last interglacial, 125 ka BP to 120 ka BP. These sea level changes during the following interglacial-glacial climate transition are of interest because they reflect the effects of oceanic circulation changes that resulted from oceanic interactions with glacial events in the high latitude northern North Atlantic, not all of which were recognized at the time of the surveys. A correlation between oceanic circulation variations and sea level changes during the Last Interglacial-Glacial transition is proposed with supporting evidence from the island of Barbados.

2. Introduction

2.1 Background

Earlier workers have described the series of coral reef terraces that record past interglacial sea stands on the now tectonically uplifted Island of Barbados[1-4]. The Barbados surveys that are described here were done during a series of six expeditions from 1991 to 1998 in an effort to achieve a relatively independent age measurement of the large anomalous deglaciation that ended about 136.5 ka BP[5]. The significance of the survey data for climate variations that accompanied the subsequent Last Interglacial-Glacial transition was not fully realized until later years. The widespread ongoing interest in the cause of the Heinrich event, H0, that started the Younger Dryas interval of arctic climate in northwestern Europe was brought to a sharp focus by the report in 2008 that the cold event in Europe began in only one year[6]. This prompted the question: Could the cold Younger Dryas event have been caused by collapse of the Hudson Strait ice dam in only one year? The answer, thirteen years later is "yes"[7]. This prompted another question: Did the early Heinrich event that probably ended the last mild interglacial climate in Europe also start in only one year? The answer, as found on the island of Barbados, is "no," and this paper discusses the reasons why.

2.2 The Barbados paleo sea level context.

Tectonically uplifted Barbados in the West Indies has minor paleo sea level features at many different locations above present sea level that suggest temporarily stable world sea levels. Each sea level feature was not found at every coastal location because buildup rates of coral debris were different, depending on water depths and on seabed gradients. Because of these complexities, six research expeditions were needed to obtain the results of the paleo sea level surveys reported in this paper. The urban expansion is destroying many of the exposures of interest, and road construction both exposes and destroys others. In 1991, recently completed highway construction had exposed a large deposit of coral cobbles on the University of West Indies hill that provided impressive evidence of a reversal in sea level fall. In 1998 growth of tropical vegetation had completely hidden that cobble exposure.

2.3 Barbados surveys measured wave-cut elevation differences.

World sea level elevation differences measured by wave-cut elevations of steps caused by breaking waves usually require uplift rate corrections. Uplift rates vary along the west and south coast up to a maximum of 0.40 m per thousand years at the University of the West Indies site. See the map in Figure 1. Barbados is largely covered with a thick cap of coral debris, although the coral surface of the east side of the island has been strongly eroded by trade wind rainfall. The lea side on the west and southwest receives much less rain, and the coral reef record there is still largely intact. Previous investigators have documented the fossil coral reefs on the western side that rise in prominent steps to the island top at an elevation of 340 m [1-4]. The large coral reefs provide a record of past cyclic sea level maxima. However, the fine details of sea level change are often found only at locations with surface slope and orientation that favored erosion of the coral debris of the terrain by

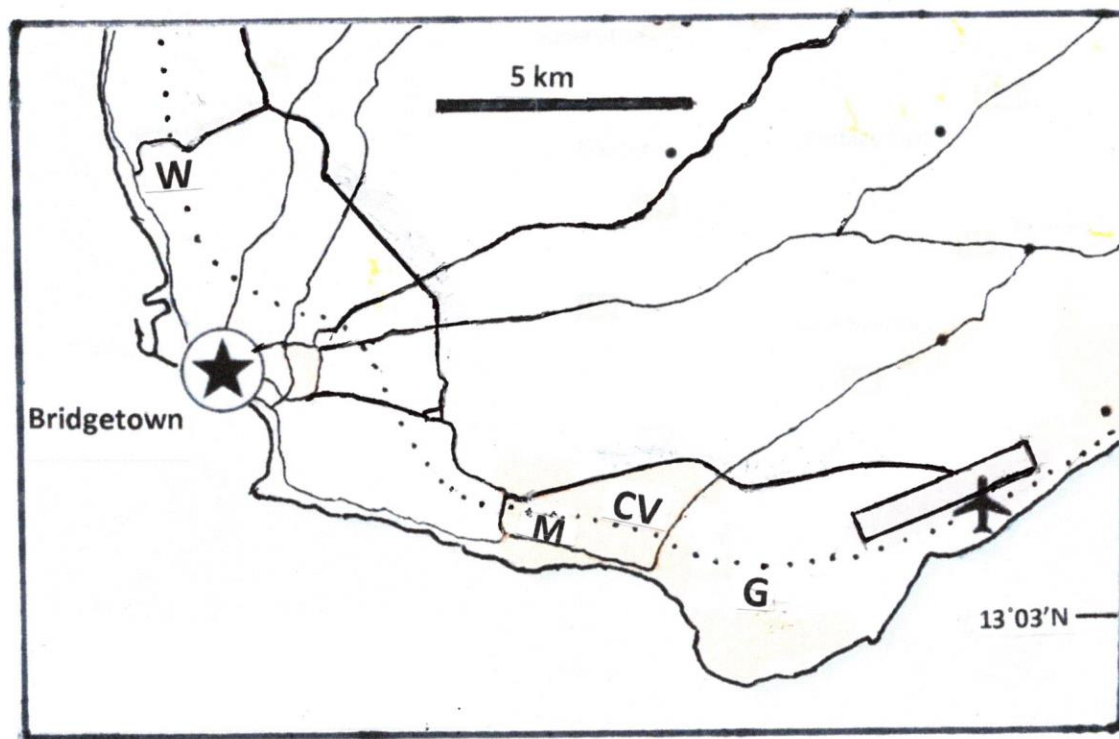


Figure 1: Southwestern part of Barbados showing highways and four of the sites where paleo sea level features were surveyed. Dotted line is the coral debris formation known locally as "the First High Cliff." W: University of the West Indies hill. M: Maxwell hill. CV: Cane Vale paleo lagoon. G: Gibbons hill.

wave action. Such sea level changes described here were the results of surveys conducted on Barbados on six expeditions beginning in the year 1991. This was soon after highway construction had exposed evidence of a major reversal of sea level fall, and before urban development destroyed much other paleo sea level evidence. Sea level changes observed in the Barbados record have now been correlated with past changes in the Atlantic Meridional Oceanic Current (AMOC) that now flows strongly northward in the northeastern North Atlantic and

gives western Europe its mild climate. The AMOC northward flow is dependent on its sea surface water of higher salinity that is winter-cooled and sinks to intermediate levels in the high latitude North Atlantic.

2.4 Wave-cut steps as markers for reversals of falling or rising sea level.

Most of the survey points were on steps made by erosion due to waves breaking at the paleo shore line during a reversal in sea level fall (or rise) when the level remained almost constant. The ability of breaking waves to cut into the surface of coral debris and make a step is strongly dependent on the degree to which the surface has become cemented by the action of slightly acidic rainwater during previous times of lower sea levels. Rain water flowing down the slope becomes super-saturated with carbonate, which tends to be redeposited as a cement within the surface debris. At some quarries on the island where the unconsolidated coral debris below



Figure 2: Paleo lagoon and R. Higashi at Cane Vale B in 1993, a rare flat area on Barbados. The far end of the street descends slightly to join the Maxwell Top road, and a step formed by the first reversal of sea level fall is just beyond the edge of the road, and on the crest of the first High Cliff hill.

the surface is mined for fill or road construction, large boulders of the well cemented surface are unusable and are discarded at the quarry site. Therefore, during times of falling or rising sea level the breaking waves do not have the time or the cobble tools to break into the cemented layer that can armor the surface. Erosion therefore can be minimal when sea level is changing, unless the terrain surface is new and not yet cemented. It is only when sea level fall or rise is being reversed and sea level is temporarily almost constant that steps are formed in the island's cemented surface by the breaking waves.

3. The Barbados record.

3.1 The last interglacial sea level at the Cane Vale site.

The Cane Vale site (map of Fig. 1) is the only known location on Barbados where seabed slope and water depths enabled the complete buildup of coral debris to form a shallow paleo lagoon during the Last Interglacial interval.

The shallow paleo lagoon, now occupied by houses and streets (Fig. 2), became nearly filled with coral debris and mud. Sea level near the end of the interglacial at 120 ka BP (calendar years before present). was marked by a small barrier reef at mean sea level at the outer edge of the lagoon. The base of the barrier reef was at the low tide level. A government survey marker is located at the outer edge of the lagoon, and its elevation gives an uplift rate of 0.14 m per thousand years for the Cane Vale site when an allowance is made for a 5.5 m higher world sea level during the Last Interglacial. Unless otherwise stated, all sea level differences are corrected for uplift.

3.2 The first world sea level fall and reversal after the Last Interglacial.

The first decrease in world sea level due to the earliest ice sheet growth after the last interglacial consisted of a rapid fall of 2.4 m, measured from the low tide sea level at the edge of the paleo lagoon at the Cane Vale site (see section 4). The fall was ended by a small deglaciation that caused a halt and brief small reversal of the sea level fall. At the time of this reversal, local sea level was nearly constant, probably for many decades. Such times enable the growth of large colonies of *Acropora palmata* coral pieces that thrive in the turbulence at or



Figure 3 Flat step of the first reversal at the top of Gibbons hill. Street construction had begun on the flat of the step. E.G. Johnson assisted.

just below the low-tide level. The colonies are broken up by breaking waves when sea level eventually falls, leaving large coral pieces embedded in the surface debris just below the flat step, as in the first reversal. Examples were found in the *palmata* pieces exposed on the crest of Holders Hill, and on the footpath on the hilltop crest adjacent to the first flat reversal step at the Cane Vale B site. Because the coral debris that had accumulated during the ~5,000 years of the last interglacial had never been exposed to rain water, it was not cemented. Therefore, considerable erosion by breaking waves occurred as sea level initially fell 2.4 m. This eroded strip was later flattened to form the modern short Maxwell Top road. When the first reversal of sea level fall occurred, breaking waves eroded a flat step about 1.5 m wide located between the outer edge of the Maxwell Top road and the adjacent crest of the First High Cliff at the Cane Vale site. At the Gibbons site with a smaller slope of the terrain, the breaking waves created a flat step about 8 m wide, and a short street had been partially constructed (Fig. 3) to take advantage of the broad step. At the University of the West Indies (UWI) site the First High Cliff terrain is very steep and the flat step is less than a meter wide. The rate of the first sea level fall was probably about 6 m per thousand years (see section 4) and the first reversal was quite brief.

3.3 The second world sea level fall and reversal.

After the first flat wave-cut was formed by reversal of the sea level fall, a world sea level fall of 9.9 m occurred in the Barbados sea level record before being reversed again. Evidence for the second reversal is a large deposit of coral cobbles on a wave-cut step exposed by highway construction half way down on the UWI hill of the First High Cliff (Fig. 4). The width of the step may be as much as 0.5 m because the road construction removed much more coral debris to the left of the surveyor's rod than to the right in the photo. The highway had been constructed shortly before our expedition to Barbados in 1991. The dating of the step was done by measuring the thorium-uranium age of a large *A. palmata* coral head retrieved from the cobble exposure. It was reliably dated to 117 ka BP with a statistical uncertainty of a thousand years (personal communication with C.D. Gallup]. This age agrees well with the age of 116 ka BP for the corresponding climate event from a lake record in Germany[8]. See section 4. This large coral head was retrieved from the larger hole on the step in Figure 4. It, together with the large *palmata* specimen from the other hole, would have grown close to the level of the step. The rate of sea level fall between first and second step was 2.8 m per thousand years. The corresponding rapid growth of glacial ice volume is consistent with northeastward paths of storm systems over eastern Canada that would have resulted from the warmer subpolar North Atlantic reported by Ruddiman and McIntyre[9], and which was enabled by the Hudson Strait ice dam that allowed a warmer sub polar ocean to occur by limiting fresh water input to the AMOC flow.



Figure 4. UWI Hill site where evidence for the second reversal of falling sea level was found. Two large *Acropora palmata* coral heads were retrieved from the large holes to the right of the rod. They were resting on the flat wave-cut step, and probably grew during the interval of quite slowly falling sea level just before the sea level rise began. The surveyors rod is marked in tenths of a foot.



Figure 5: Maxwell Hill site of the second reversal of falling sea level. Wave-cut step where the rise began is just below the surveyor's rod. The limit of the rise, 3.8 m above, is at the step near the rod and black backpack.

3.4 Sea level rise after the second reversal.

The highway construction at the UWI site did not reveal an upper limit for the second sea level rise, but the records at the Maxwell hill and Gibbons hill sites are clear. The location of the flat step that marks the reversal was found on old hillside footpaths. The photo in Figure 5 shows both lower and upper wave-cuts as found at the Maxwell Hill site, separated by 3.8 m. At the Gibbons hill site, the bottom photo in Figure 6 shows a thick deposit of smaller *A. palmata* coral cobbles where the reversal began. The top photo shows the small vertical step cut by waves at the 3.8 m limit of the sea level rise, uncorrected for a minor uplift effect because the duration of the rise is unknown. This sea level rise was mainly caused by a deglaciation of only the early Canadian ice sheet during the first Heinrich event of the last major ice age (see section 5) because significant Eurasian glacial ice had not accumulated at that time. However, a possible contribution to the deglaciation from the Antarctic ice sheet cannot be ruled out. The Barbados record of paleo sea level changes probably reflects Northern Hemisphere glacial ice volume changes that were the result of the formation and destruction of the Hudson Strait ice dam. In the following sections, with the aid of a time scale supplied by a European pollen record, explanations are offered for how these changes occurred.

4. A pollen record of European climate events in the Last Interglacial-glacial transition.

Figure 8 depicts the percent pollen abundance records for temperate climate trees in western Europe during the Last Interglacial-glacial transition, as reported by Field et al.[8]. The resolution is good in this German lake sediment record, with pollen counts summed over 200-year intervals. But there is only one data point with little or no pollen at 120 ka BP, at the accepted age for the beginning of new glaciation in Canada. This suggests a relatively short cold European interval. However, adjacent preceding and following data points could have contained barren 100-year intervals without pollen and still given a warmer climate count. Therefore, the cold interval is more likely to have been as long as 400 years, or even slightly longer. In the lake sediment record, the subsequent return of large amounts of oak pollen and small amounts of elm pollen indicate a slightly cooler interglacial climate for the next ~3,500 years. The ~400-year cold interval is correlated with the first rapid fall of sea level found on Barbados, the expected rapid growth of an ice sheet in Canada, a weak AMOC flow, and a

similar buildup of thick ice on the frozen marine-based Barents Sea and the Siberian coast to the east. The reappearance of temperate climate tree pollen correlates with the expected return of strong AMOC northward flow. This flow brought back warmth to western Europe, broke up and melted the Barents Sea and other coastal ice accumulations and caused the first quite small reversal of sea level fall on Barbados. The final disappearance of Oak pollen correlates with the second reversal of sea level fall on Barbados. The final disappearance of Oak pollen correlates with the second reversal of sea level fall on Barbados. These sea level changes are summarized in Figure 7. The proposed explanations for these events involve the formation and destruction of the ice dam in Hudson Strait.

5. How the formation of the Hudson Strait ice dam enabled the return of temperate tree pollen during the climate transition.

The key to the first part of the series of events of the interglacial-glacial climate transition is the extremely heavy precipitation west of Greenland in the Baffin Island, northern Quebec and Labrador areas that ended the Last Interglacial climate in Canada[10]. The cause of the precipitation increase was the year-round presence of warmer open water in Baffin Bay and the Labrador Sea, and the resulting persistent low-pressure atmospheric system. The heavy annual precipitation implies a large increase in fresh water from central Canada draining out through Hudson Strait and into the Northern Gyre, with some of it mixing into the AMOC flow. Straneo and Saucier measured the modern outflow through Hudson Strait with a moored array, and reported that the fresh water transport accounts for about 50% of the fresh water in the Labrador Current segment of the Northern Gyre[11]. An estimated precipitation increase of a factor of eight can be obtained from the world sea level fall of 2.4 m and the frozen areas west of Greenland that were affected by the snowfall increase. Therefore, a factor of eight increase of precipitation would imply an increase of an approximate factor of four in the amount of fresh water mixing into the AMOC flow from the Northern Gyre. The resulting lower sea surface salinity east of Greenland and the resulting reduced AMOC flow is the likely explanation for the ~400-year cold interval in Western Europe. At the end of the ~400-year cold interval the heavy snowfall in Labrador and northern Quebec developed a glacial ice stream across Ungava Bay that blocked the drainage through Hudson Strait with a glacial ice dam within the strait at its east end. This interval was similar to the 500-year interval reported by Stravers, Miller, and Kaufman[12] that was needed to re-form the ice dam after the end of the latest Heinrich event that ended at 11.4 ka BP. The blocking of the fresh water component in the Hudson Strait outflow only 400 years after new glaciation began in Canada could have restored a strong AMOC flow, and broken up and melted the marine-based ice dome on the Barents Sea, which briefly halted and reversed the paleo sea level



Figure 6: Gibbons hill site of the second reversal of falling sea level. Top: Upper limit of sea level rise that formed the step below the white cap. Below: *A. palmata* coral cobble layer on the step where the sea level rise of 3.8 m began.

fall as observed on Barbados. Continued blocking of the outflow from Hudson Strait therefore enabled the ~3,500-year continuation of a mild climate in northwestern Europe, while glacial ice accumulated in Canada.

6. A comparison of two Heinrich events: The slow destruction of the Hudson Strait ice dam terminated the Last Interglacial period in Europe.

6.1 Two Heinrich events.

The last Heinrich event at 12.7 ka BP and the first event of the last ice age at 116 ka BP were caused by the destruction of the Hudson Strait ice dam and each event had the same effect on high-latitude North Atlantic

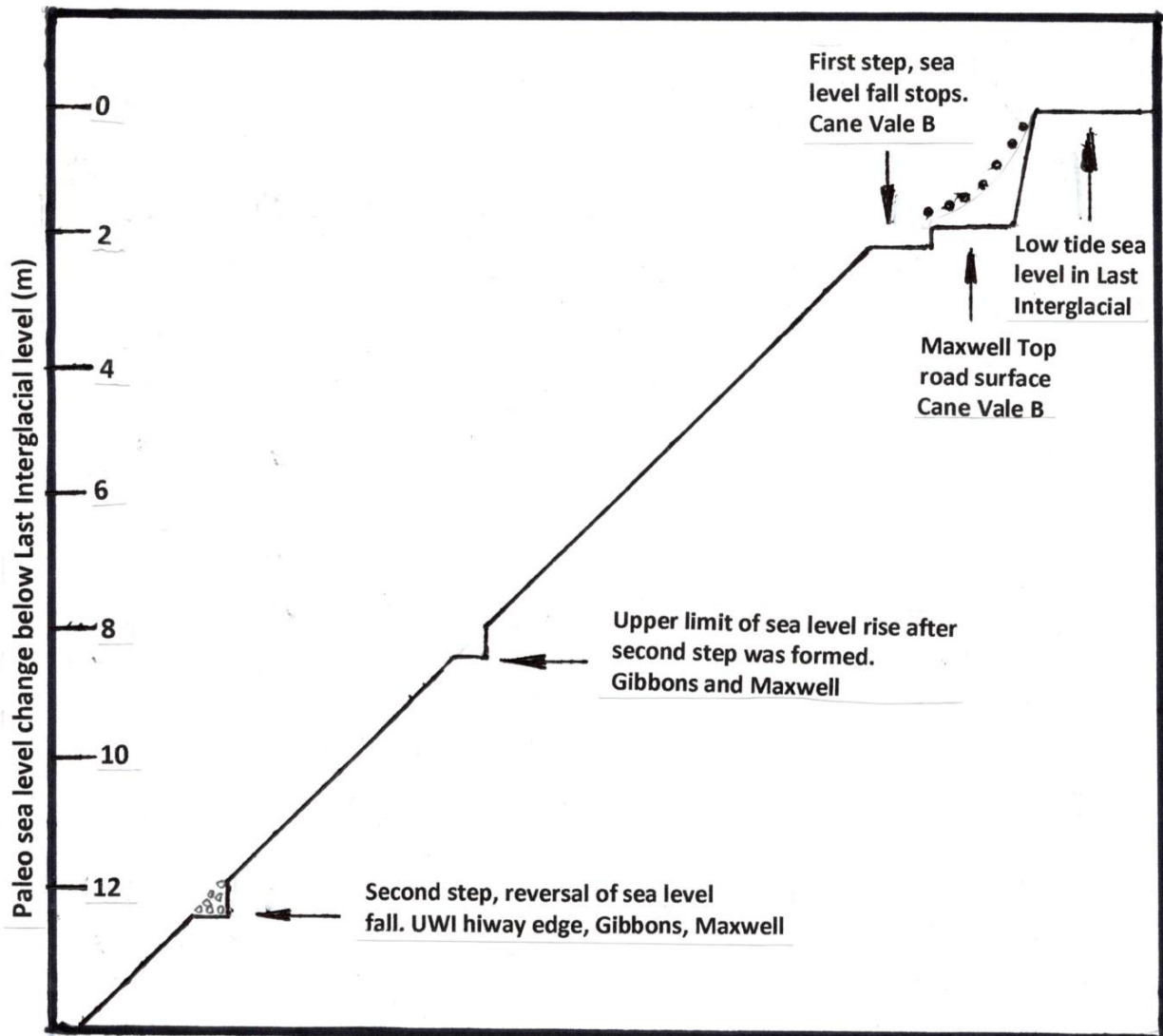


Figure 7 World sea level changes at the beginning of the Wisconsin Glaciation as displayed on a hypothetical First High Cliff profile. Sea level differences were derived from surveys on Barbados. Dotted line is the assumed coral debris surface before construction of the Maxwell Top road.

circulation and climate. The AMOC flow was greatly reduced, and the zonal circulation brought an arctic climate to western Europe. However, the cause of each event was quite different. The more recent event began with the abrupt collapse of the ice dam in only one year[6], a time that would have been too short to form wave-cut steps on Barbados, but the result was 1,300 years of arctic climate in northwestern Europe and a deglaciation with a large world sea level rise from -70 m to -59 m relative to present[13]. The cause of the collapse was the melting of ice at the sea bed in Hudson Strait by highly saline water from a subglacial lake. The process was driven by the hydrostatic pressure of a thick accumulation of glacial ice in the Hudson Bay-Foxe Basin area of central Canada[7]. The melting and undercutting occurred over an area many tens of kilometers in width, and the collapse was catastrophic. On the other hand, the early ice dam was slowly destroyed by the erosion of the overflow of the giant fresh-water Lake Zissaga[14], which was impounded by the large ice sheets on Baffin Island, northern Quebec, and Labrador. The erosion, as inferred from the Barbados evidence (Fig. 4), was a slow process occurring over many decades, and the resulting world sea level rise was 3.8 m, consistent with an ice accumulation in central Canada.

6.2 The wave-cut step on Barbados made at the time of the reversal.

The noteworthy aspects of the flat step exposure pictured in Figure 4 are the large size of the two cobbles retrieved from the holes at the surface of the step and the ~0.4 m thick layer of small cobbles that later engulfed them. The large size implies a sufficiently long period of growth at a depth well below the reach of falling sea level and violent waves of storms. But eventually as sea level fell, the waves of occasional hurricanes were

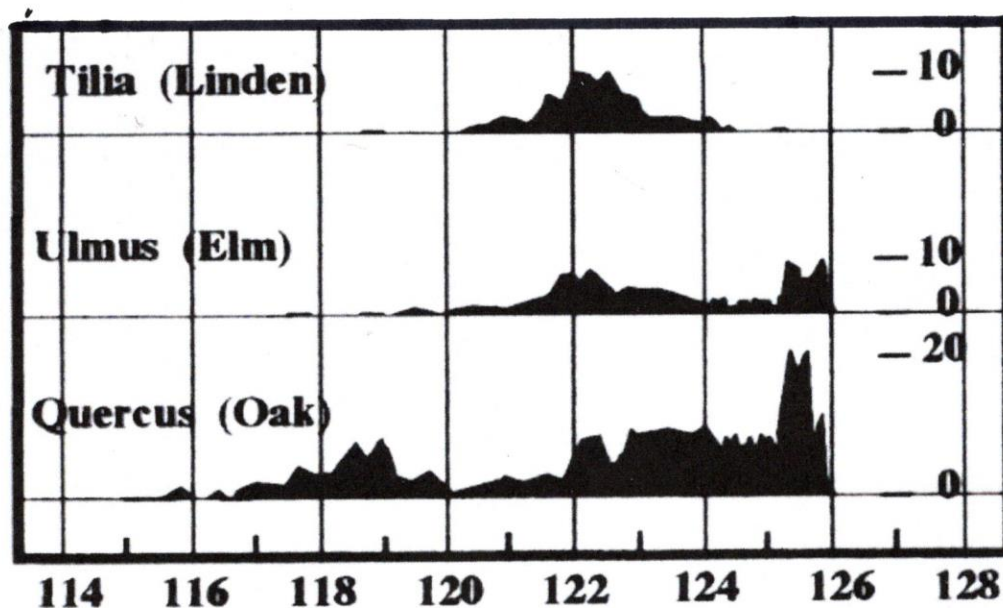


Figure 8: Percent pollen abundance record for three species of temperate climate trees showing the persistence of a temperate climate in western Europe for about 3.5 ka after the last glacial climate began in Canada. See text. Data from Field et al.[8], used with permission.

able to break them away from their parent colony and convert them into large cobbles resting on the eroded step. The small cobbles began their growth in the shallow water above the step after the reversal as sea level was slowly rising. Therefore, those pieces could never become large pieces before the violent breaking waves of occasional storms tore them away from the sea bed and washed them down the slope into the shelter of the step. A similar layer of cobbles is visible above the step level at the Gibbons site pictured in Figure 6. In this early ice dam, its slow destruction was caused by fresh water erosion.

6.3 The overflow of giant Lake Zissaga and the slow destruction of the ice dam.

The seasonal flood of meltwater from the central half of Canada therefore would have remained on top of the lake ice, and repeated seasonal freezing of the flood water would have increased the thickness of the lake ice until the overflow occurred into the stress-induced cavities of the Hudson Strait ice dam, and the destruction of the ice dam began. The altitude of the cross-flowing ice dam surface at the east end of Hudson Strait[7] was likely higher than altitude at the point of overflow. If so, overflow water would have tended to accumulate seasonally in Hudson Strait behind the higher surface of the dam, perhaps 300-400 km west of the east end of the strait. From the point of the overflow, the overflow water may have remained on the ice sheet surface[15] until reaching the highly stressed area of the dam. There it would have entered the cavities and developed tunnels to the sea. Erosion would begin slowly at first, but as the years went by the tunnels would have enlarged. Eventually the increasing discharge of water and icebergs from the strait into the world ocean would have diminished the AMOC flow, increased the zonality of atmospheric circulation, initiated Northern Hemisphere deglaciation, and slowly terminated the sea level fall. Sea level was therefore nearly constant for many decades at the Barbados sites, thus providing the time needed to grow the large *A. palmata* coral heads that were retrieved at the low-tide level of the step at the UWI site in Figure 4. Nevertheless, at that point some of the ice dam would still have been intact. The reason for this is that the tunnels beneath the ice would have been small when compared with the 50-100 km width of the strait and the broad sheets of highly saline sub glacial lake

water at the seabed that caused the abrupt collapse of the Younger Dryas Heinrich event[7]. Consequently, increasing the tunnel sizes would increase the rate of delivery of overflow water and iceberg delivery to the sea, but did not cause a catastrophic collapse because much of the ice was still frozen to the seabed. The fresh water contribution to the AMOC flow would have been proportional to the sum of the overflow water and water from melting icebergs. Therefore, the rise of world sea level as the reversal began would have been slow at first and probably did not reach its maximum rate until later when the drainage of Lake Zissaga reached its maximum rate or when the destruction of the ice dam was nearly complete.

7. Summary

The last major interval of glacial climate in the Northern Hemisphere began about 120 ka BP because of an increase in precipitation by about a factor of eight in northeastern Canada. In that climate transition, two climate change events occurred that affected mainly northwestern Europe. They are proposed to have been caused respectively by the formation and destruction of the Hudson Strait ice dam. These events have now been correlated with the record of paleo sea level on the tectonically uplifting island of Barbados. In the first event, a few hundred years after the transition began, formation of the Hudson Strait ice dam ended a large flood of fresh water through Hudson Strait into the high-latitude North Atlantic, a flood that had been caused by the extremely high rate of precipitation west of Greenland. This low-salinity water had greatly reduced the flow of the warm AMOC and had given northwestern Eurasia an ~400-year arctic climate. In the second event, about 3,500 years after the first, the ice dam was probably destroyed by the ice sheet overflow of the giant Lake Zissaga, which had been impounded behind the ice-blocked Hudson Strait. The overflow and its erosion of the ice dam caused an increase of fresh water discharged through Hudson Strait into the Northern Gyre and on into the AMOC flow. The fresh water addition diminished the sea-surface salinity that drives the AMOC flow, thus cooling the sea north of the eastward-flowing Gulf Stream and increasing the zonality of atmospheric circulation. This process starved the Canadian ice sheets of snowfall, causing a significant deglaciation and a lengthy reversal of the world sea level fall. This progression of events is supported by evidence of paleo sea level change on the island of Barbados. The ice dam destruction was slow relative to the collapse of the ice dam in one year at the start of the Younger Dryas cold interval.

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