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**Paper:**

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1 **Deglacial rapid sea level rises caused by ice sheet saddle collapses**

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10

11 **Several meltwater pulses occurred during the last deglaciation (21-7 ka), sometimes**  
12 **causing significant climate change<sup>1,2</sup>. Around 14 ka, Meltwater Pulse 1a (MWP1a), the**  
13 **largest of these events, produced a sea level rise of 14-18 m in 350 years<sup>3</sup>. This great**  
14 **amount of water came from the retreat of ice sheets, but there is currently no consensus**  
15 **on the source or the cause of this rapid sea level rise<sup>4-6</sup>. We present an ice sheet**  
16 **modelling simulation during which the separation of the Laurentide and Cordilleran ice**  
17 **sheets in North America produces a meltwater pulse, which correlates with MWP1a.**  
18 **Another meltwater pulse is produced when the Labrador and Baffin domes around**  
19 **Hudson Bay separate, which could be associated with the ‘8,200 year’ event, the most**  
20 **pronounced abrupt climate event of the past 9,000 years<sup>7</sup>. For both events, the saddle**  
21 **between two ice domes becomes subject to surface melting because of a general surface**  
22 **lowering, caused by climate warming. The melting then rapidly accelerates as the saddle**  
23 **between the two domes continues to lower, producing 9 m of sea level rise in 500 years.**

24 **This mechanism of an ice ‘saddle collapse’ explains MWP1a and the ‘8,200 year’ event**  
25 **and could help us better understand the consequences of these events on climate.**

26 North America has been cited as the most probable source of MWP1a, because the  
27 Laurentide ice sheet that was covering Canada retreated significantly at that time<sup>8</sup>. However,  
28 despite the evidence of freshening of the North Atlantic at the time of MWP1a<sup>9,10</sup>, one study  
29 estimated the contribution of the Laurentide ice sheet to MWP1a to be less than 5.3 m based  
30 on the chemical composition of seawater near the ice sheet’s southern, eastern and northern  
31 runoff outlets<sup>4</sup>. Glacio-isostatic adjustment models disagree on the hemispherical origin of  
32 MWP1a<sup>5,6</sup> and glaciological evidence from Antarctica is currently insufficient to rule out a  
33 potential contribution from East Antarctica. Disagreements in the source and difficulties in  
34 estimating the timing and duration of MWP1a make it difficult to link this event with  
35 recorded climate changes<sup>11–13</sup> and determine if the large amount of freshwater released into  
36 the oceans during this event had a similar climate impact as other ocean freshening events  
37 such as Heinrich Event 1<sup>2</sup>.

38 In a series of ice sheets model simulations of the North American deglaciation, we observed  
39 two meltwater pulses that can be associated with MWP1a and the ‘8,200 year event’, caused  
40 by a common mechanism. We simulated the deglaciation of the North American with the  
41 Glimmer-CISM ice sheet model<sup>14</sup> driven offline with a state of the art transient simulation of  
42 the last deglaciation. The climate simulation was itself forced with greenhouse gas  
43 concentrations, insolation and freshwater fluxes and prescribed ice sheet extent<sup>8</sup> (Figure S1).  
44 Although the climate forcing does not simulate the Bølling-Allerød rapid warming event nor  
45 the Younger-Dryas cold period (Figure S2), it does reproduce well the range of warming of  
46 the last 21,000 years reconstructed from Greenland ice cores. Our ice sheet simulations  
47 reproduce well the extent of ice over North America at the Last Glacial Maximum and during  
48 the deglaciation compared to the Ice-5G ice sheet reconstructions<sup>15</sup> (Figure 1). This close

49 match in ice sheet extent is partly due to the set up of our experiment; the ice sheet extent  
50 follows that of Ice-5G because our climate forcing is dependent on that reconstruction. Our  
51 ice sheet thickness is, however, independent from Ice-5G and consistent with more recent  
52 reconstructions (see Supplementary Text). The decoupling between our results and Ice-5G is  
53 most evident in the evolution of the modelled ice volume (Figure 1), which diverges from the  
54 reconstruction after 15 ka. The mismatch in ice volume is due to a 2,000 years delay in the  
55 separation of the Cordilleran and Laurentide ice sheets in our experiments<sup>8</sup>. This delay could  
56 be explained by uncertainties in our climate forcing or some missing dynamical processes  
57 (see Supplementary Text). Despite the inaccuracy in the chronology of our simulations, the  
58 overall change of ice volume and extent and the rate of our deglaciation is consistent with the  
59 Ice-5G reconstruction (Figure 1), giving us confidence in the amplitude and causes of the  
60 events observed (see Supplementary Text).

61 A large meltwater pulse is produced in our experiment around 11.6 ka (Figure 2b) with up to  
62  $10 \times 10^3 \text{ km}^3/\text{yr}$  of ice loss (0.3 SV of freshwater), twice the background melting. This  
63 meltwater pulse represents  $3.8 \times 10^6 \text{ km}^3$  of water discharged over 500 years, producing a  
64 global sea level rise of 9 m in 500 years (Figure 2a). This event coincides with the separation  
65 of the Cordilleran ice sheet, over the Rocky Mountains in the west of North America, and the  
66 Laurentide ice sheet, covering the plains of Canada (Figure 2c). At 11.6 ka, 80 % of the total  
67 North American meltwater flux comes from the Cordilleran-Keewatin region (red box in  
68 Figure S3). The Cordilleran and the Laurentide ice sheets separate within 400 years of the  
69 start of the meltwater pulse. The Cordilleran ice sheet then significantly thins and disappears  
70 over the following 600 years.

71 The modelled separation of the Laurentide and Cordilleran ice sheets, and its associated  
72 meltwater pulse, can be correlated to the MWP1a. Radiocarbon and Luminescence dating  
73 indicate that the Ice-Free Corridor between the Laurentide and Cordilleran ice sheets opened

74 sometime between 15.7 ka and 14 ka (13.5 to 12  $^{14}\text{C}$  ka)<sup>8,16</sup>, and not at 11.6 ka as in our  
75 model. The separation of the two ice sheets in our model coincides with the production of 9  
76 m of sea level rise in 500 years. This corresponds to 50 to 60 % of the amplitude of MWP1a,  
77 which occurred between 14.6 ka and 13.8 ka<sup>3,13,17-19</sup>. It is therefore likely that this freshwater  
78 pulse, produced in our model by the opening of the corridor between the Laurentide and  
79 Cordilleran ice sheet, corresponds to the MWP1a event (see discussion in Supplementary  
80 Text). This result is in agreement with North American deglacial chronologies calibrated with  
81 sea level data and evolution of ice extent<sup>6</sup>, where the North American ice sheet is estimated to  
82 have produced 9.4 to 13.2 m of sea level rise between 14.6 and 14.1 ka. Contributions from  
83 the background melting of the Eurasian and Antarctic ice sheet could explain the remaining  
84 part of the pulse.

85 The separation of the two ice sheets in our model induces a lowering of the Cordilleran ice  
86 sheet (Figure 3), which results in the deglaciation of the Cordilleran ice sheet within 600  
87 years of the separation of the two ice sheets (supplementary materials). Although in reality,  
88 the extent of the Cordilleran ice sheet did not significantly reduce until 11.5 ka<sup>8</sup>, field  
89 evidence reveals an extreme and widespread thinning of the ice sheet before 12.8 ka (11  $^{14}\text{C}$   
90 ka)<sup>20</sup>, and sediment cores suggest a high freshwater input to the North Pacific from 14.7 ka to  
91 12.9 ka<sup>21</sup>. Our results therefore suggest that the thinning of the Cordilleran ice sheet could  
92 have thus contributed to MWP1a, which is consistent with a reconstruction of ice sheet  
93 drainage chronology<sup>22</sup>. In this case meltwater would have been routed not only towards the  
94 Arctic Ocean, the Gulf of Mexico and perhaps the St Lawrence<sup>1,23,24</sup>, but also towards the  
95 Pacific Ocean. We estimate that about a third of MWP1a could have been routed toward the  
96 Pacific (Figure S3). The potential distribution of meltwater between the North Atlantic, the  
97 Arctic and the North Pacific oceans could have potentially dampened the climate impact of  
98 MWP1a on the climate<sup>18</sup>. It could also have influence the pattern of sea level rise observed

99 throughout the world. Hence, fingerprinting the pattern of MWP1a sea level rise may need to  
100 be revised.

101 The large meltwater pulse observed in our model is caused by a simple mass balance  
102 mechanism associated with the separation of the Cordilleran and Laurentide ice sheets. In our  
103 model experiment, progressive warming occurs throughout the deglaciation (Figure S2),  
104 which slowly elevates the upper altitude at which surface melting occurs and simultaneously  
105 produces a general ice surface lowering. When surface melting starts occurring in the saddle  
106 between the Cordilleran and Laurentide ice domes, the ablation zone considerably expands  
107 (Figure 3). This then triggers a mass-balance elevation feedback<sup>25</sup>, which accelerates surface  
108 melting as the saddle lowers and reaches warmer altitudes (Figure 3b). Surface melting peaks  
109 when the corridor between the two ice domes opens, it then slows down as a new  
110 equilibrium geometry is reached. This meltwater pulse is also produced in simple warming  
111 experiments (see Supplementary Text), which confirms that it is a non-linear response of the  
112 ice sheet to climate.

113 MWP1a may not be the only event caused by this saddle collapse mechanism. A smaller  
114 meltwater pulse is observed in our simulation around 8.8 ka, reaching a maximum flux of 0.2  
115 Sv and producing  $9 \times 10^6 \text{ km}^3$  of freshwater (2.5 m of sea level rise) in 200 years (Figure 4).  
116 This freshwater event happens as the three ice domes around Hudson Bay separate (Figure 4).  
117 This event coincides with another freshwater event, the '8200 year event', attributed to the  
118 sudden discharge of the proglacial Laurentide lakes (Lake Agassiz and Lake Ojibway)<sup>7</sup>. The  
119 amount of meltwater released in our model in 200 year is 4 times greater than the estimates of  
120 discharge from the two lakes<sup>7</sup> during the 8200 year event and is consistent with the latest  
121 estimates of sea level rise associated with this event of 0.8 m to 2.2 m within 130 years<sup>26</sup>.  
122 Glaciological reconstruction suggest that the Fox dome over Baffin island and the Labrador  
123 dome over Quebec were disconnected from 9 ka, but the Labrador dome was still connected

124 to the Keewatin Dome and the Fox Dome, through an ice dam<sup>8</sup>. It is the collapse of this ice  
125 dam that is thought to have produced a sudden discharge of the proglacial lakes via the  
126 Hudson Strait<sup>7</sup>. In our model, most of the meltwater pulse is caused by the melting of the  
127 saddle between the Keewatin, Labrador and Fox Domes (Figure 4). Our results suggest that  
128 the collapse of the saddle, or ice dam, between the Keewatin and Labrador domes produced a  
129 meltwater pulse, which contributed to the freshening of the Labrador Sea. Halfway through  
130 this meltwater pulse, the opening of channel between the ice domes would have enabled the  
131 sudden discharge of the lakes. This could explain the two stages of this cooling event<sup>27</sup>, with  
132 the ‘saddle collapse’ pulse responsible for the longer century time scale climate response and  
133 the discharge from Lake Aggasiz being the more rapid cooling occurring halfway through the  
134 event.

135 The mechanism of ‘saddle collapse’ that produced two meltwater pulses in our simulations of  
136 the North American deglaciation reveals the role of multi-dome ice sheet geometries in  
137 producing large meltwater pulses in the context of a deglaciation. This can be seen as the  
138 reversal mechanism to the one described in the growth of ice caps in Scotland<sup>28</sup> where the  
139 topography plays an important role in accelerating the growth. Dynamical processes not yet  
140 present in our ice sheet model, involving for example subglacial hydrology or ice streams,  
141 could have played a role in facilitating the saddle collapse, thus influencing the timing and  
142 potentially the duration of the meltwater pulses. However, the amplitude and the triggering of  
143 the pulses can be explained by simple mass balance processes. For the first time, we have  
144 associated mass balance processes with specific events of rapid sea level rise of the last  
145 deglaciation, MWP1a and the ‘8,200 year event’. The saddle collapse mechanism could also  
146 help identify other rapid sea level rise and ocean freshening events. Moreover, understanding  
147 the glaciological cause of meltwater pulses can help determine the routing of meltwater,  
148 improve the dating of these events and put the events into the context of climate change.

149

## 150 **Method Summary**

151 We simulated the deglaciation of the North American with the Glimmer-CISM ice sheet  
152 model with shallow ice approximation<sup>14</sup>. We drove the ice sheet model offline with a state of  
153 the art transient simulation of the last deglaciation, performed with the FAMOUS climate  
154 model<sup>29</sup>. The climate simulation was itself forced with greenhouse gas concentrations,  
155 insolation and freshwater fluxes, which varied continuously throughout the simulation, and  
156 geographical changes, which were applies every 1,000 years (Figure S1). Because of high  
157 computational demand of the climate model and technical challenges, the ice sheet model  
158 could not feedback to the climate model. Ice sheet geometry in the climate model was instead  
159 prescribed every 1,000 years based on the Ice-5G reconstruction<sup>15</sup> (Figure S1). We smoothed  
160 out the climate forcing to remove artificial steps in the temperature and precipitation forcing,  
161 caused by the discontinuous change of ice sheets for each interval (Figure S2). We started our  
162 simulation of the deglaciation with spun-up LGM North American ice sheet state, built-up  
163 through the last glacial-interglacial cycle using the standard climate-index interpolation  
164 technique<sup>30</sup>. Ice sheet mass balance was calculated from the monthly temperature and  
165 precipitation fields using an annual Positive Degree Day (PDD) scheme. The temperatures  
166 were downscaled onto the Glimmer topography, by using a constant lapse rate of 5 °C km<sup>-1</sup>.  
167 Model parameters shown in Table S1 were adjusted to improve the LGM ice volume, the  
168 LGM extent and the rate of uplift throughout the deglaciation compare to reconstructions<sup>8,15</sup>.

169

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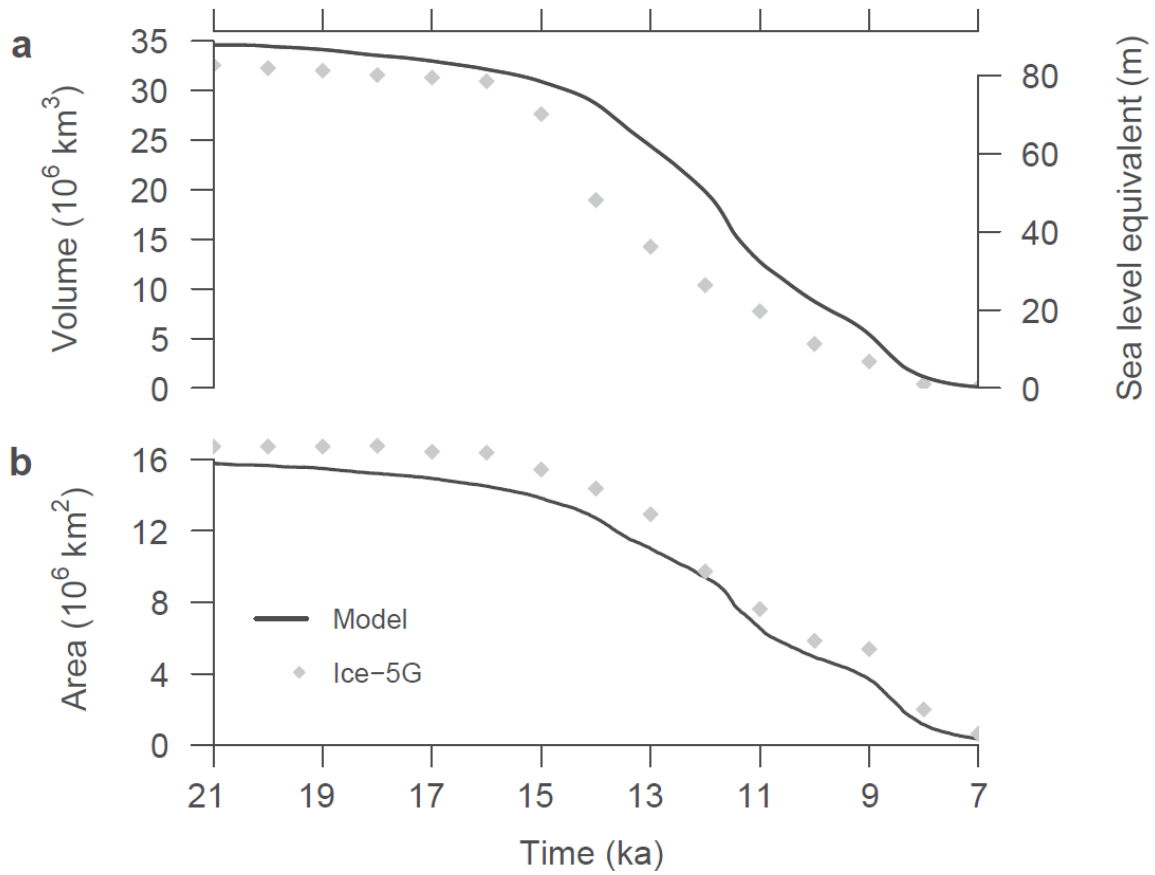
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- 243
- 244 **Supplementary Information** is linked to the online version of the paper at  
245 [www.nature.com/nature](http://www.nature.com/nature).

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254 **Author Contributions** LJG performed the experiments, the analysis and wrote the  
255 manuscript. PJV provided the input climate. All authors contributed to designing the  
256 experiments, discussed the results and implications and commented on the manuscript at all  
257 stages.

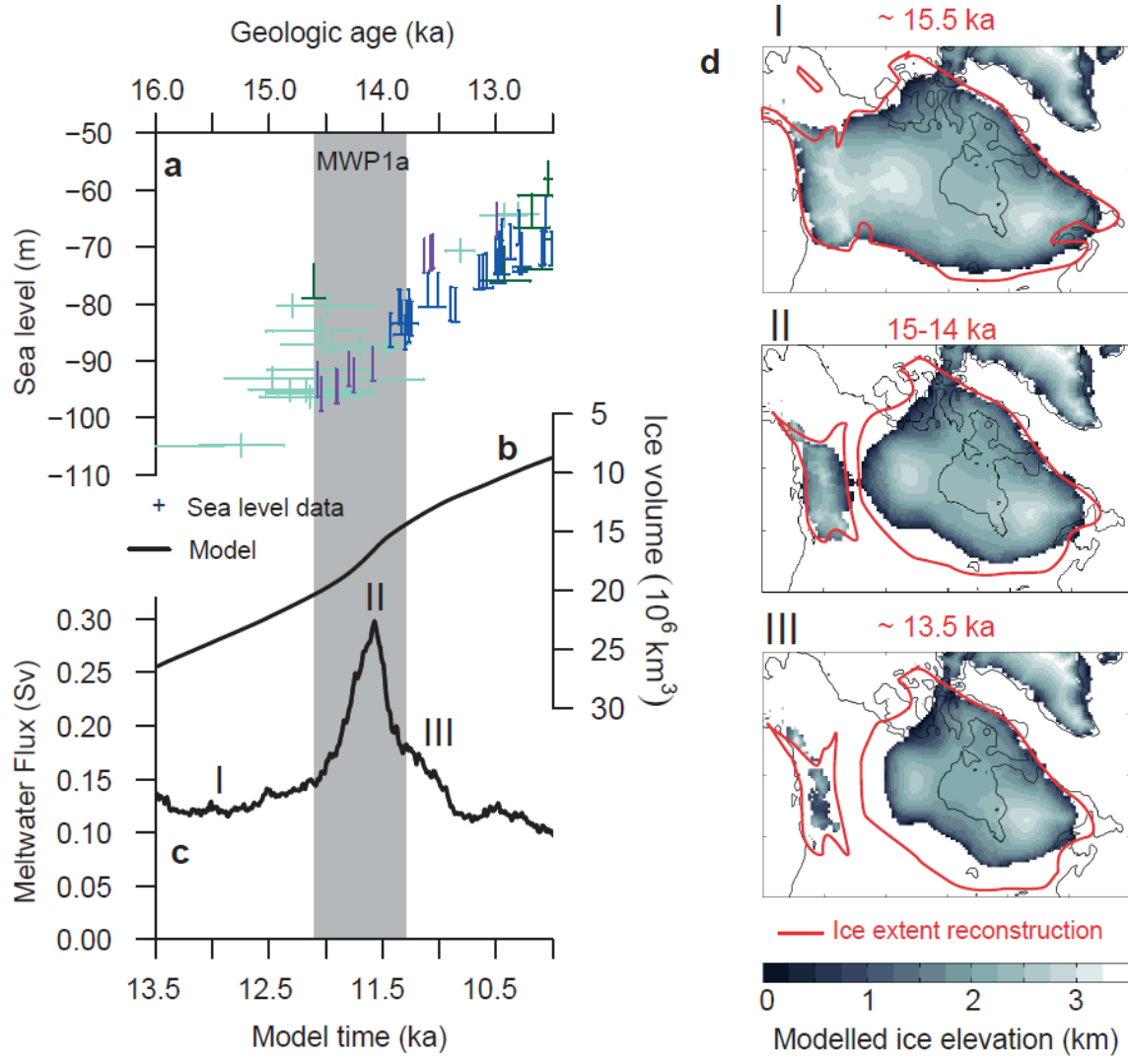
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260 interests. Correspondence and requests for materials should be addressed to LJG  
261 ([lauren.gregoire@bristol.ac.uk](mailto:lauren.gregoire@bristol.ac.uk)).



263

264 **Figure 1: The deglaciation of North America.** Evolution of ice volume **a** and area **b** of the  
 265 North American ice sheet from 21 ka to 7 ka in our model (solid black line) compared to the  
 266 Ice-5G reconstruction<sup>15</sup>(grey diamonds). The delay in our modelled deglaciation could be due  
 267 to missing dynamical processes or uncertainties in the climate forcing.

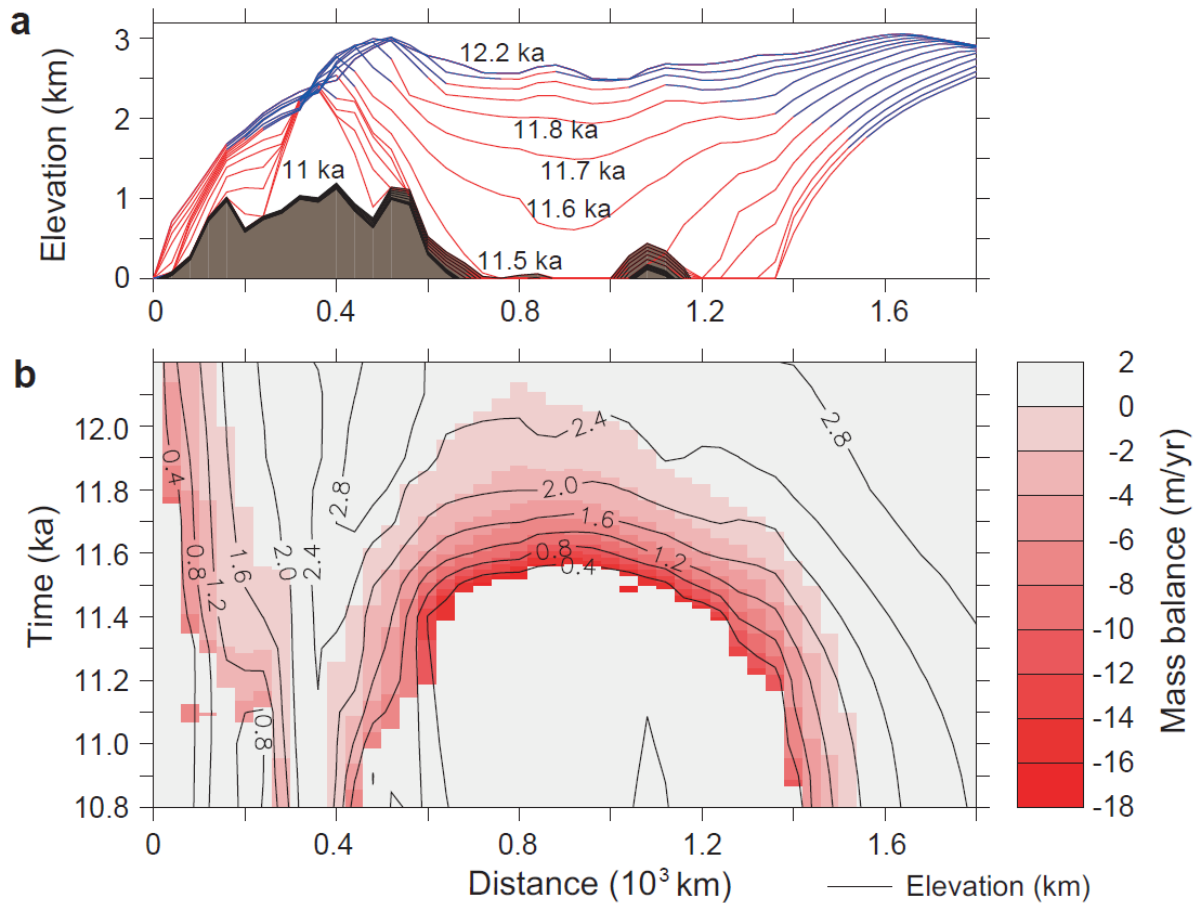
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269

270 **Figure 2: MWP1a in model and data.** **a**, Relative sea level data from the Sunda Shelf (light  
 271 blue), New Guinea (green), Tahiti (blue) and Barbados (purple). Vertical error bars show the  
 272 typical depth uncertainty ranges of  $\pm 2$  m for Sunda Shelf data and  $+6$  m for other data  
 273 (corals)<sup>11</sup>. Horizontal error bars denote  $\pm 1$  s.e.m. around the mean age<sup>11</sup>. The vertical grey  
 274 band denotes the range in MWP1a timing<sup>13,17-19</sup>. Modelled ice volume **b** and meltwater flux **c**  
 275 ( $0.1 \text{ Sv} = 3.2 \times 10^3 \text{ km}^3/\text{yr}$  of water =  $0.8 \text{ m}/\text{century}$  of sea level rise). **d**, Modelled ice sheet  
 276 elevation, before (**I**), during (**II**) and after (**III**) the pulse as labelled in **c**, and ice sheet extent  
 277 reconstruction<sup>8</sup> before, during and after the Ice-Free Corridor opening, with corresponding  
 278 dates in red. The pulse happens in our model when the corridor between the Laurentide and

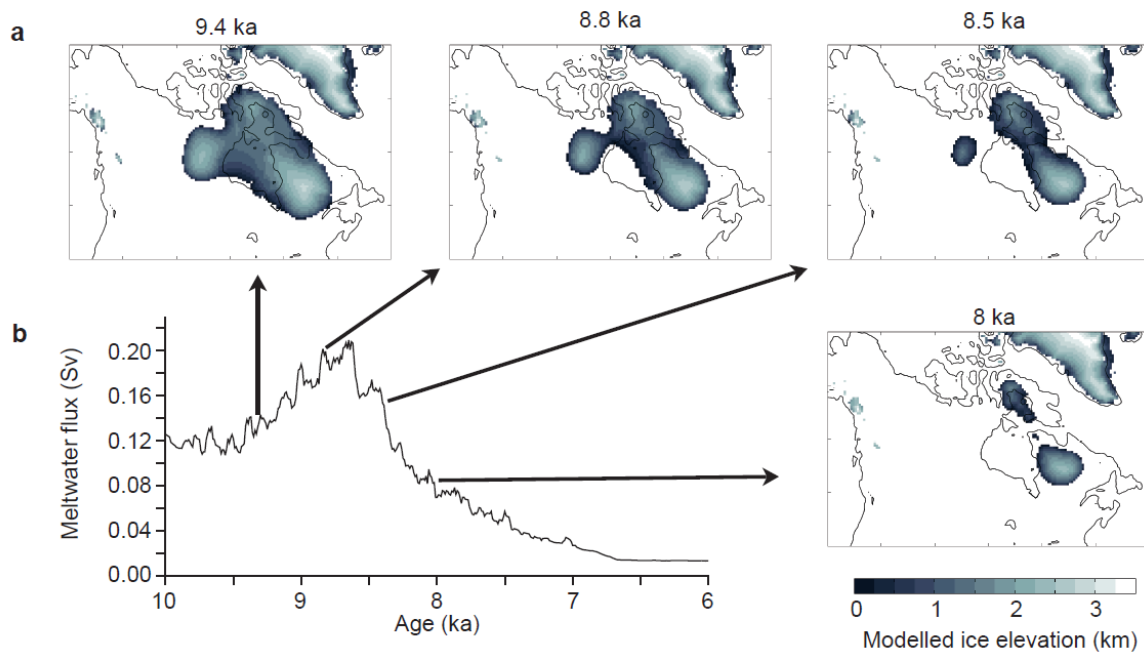
279 Cordilleran ice sheets opens. The opening of this corridor happened between 15 and 14 ka<sup>8,16</sup>,  
 280 which corresponds to the time of MWP1a.  
 281



282

283 **Figure 3: Mechanism of Saddle Collapse.** a, Ice sheet elevation (lines) and topography  
 284 (shaded area) on the cross section (shown in Figure S4) at 100 years interval during the  
 285 separation of the Cordilleran and Laurentide ice sheet between 12.1 ka and 11 ka in model  
 286 time. Red lines indicate surface ablation (negative mass balance) and blue lines area of  
 287 surface accumulation. b, Surface mass balance through time along the cross section in shades  
 288 of red with contours of ice elevation superimposed showing that the mass balance increases  
 289 primarily because of surface lowering.

290



291

292 **Figure 4: The 8,200 year event in our model. a,** Evolution of ice sheet elevation and  
 293 topography in North America before, during and at the end of the second meltwater pulse. **b,**  
 294 Time series of the meltwater flux (in Sv) from the North American ice sheet between 10 ka  
 295 and 6 ka. The ages correspond to model time.

296

## 297 **Methods**

298 **Ice Sheet model description:** The ice sheet model used in this study is Glimmer-CISM<sup>14</sup>  
 299 version 1.0.14, a 3D-thermomechanical ice sheet model based on the shallow ice  
 300 approximation. The model includes isostatic adjustment, basal sliding and a simple  
 301 parameterisation for calving. It does not simulate ice shelves and does not include higher  
 302 order physics, but thanks to its speed, it is well suited for simulating evolution of continental  
 303 scale ice sheets over glacial-interglacial time-scales and is comparable to the models used to  
 304 simulate Quaternary ice sheets<sup>31-34</sup>.

305 **Initial conditions:** We started our simulation of the deglaciation with spun-up LGM North  
 306 American ice sheet state, built-up through the last glacial-interglacial cycle using the standard  
 307 snapshot interpolation technique<sup>31-33</sup>. This technique consists of interpolating present day and



308 Last Glacial Maximum (LGM ; 21 ka) equilibrium runs with a climate index proportional to  
309 the NGRIP  $\delta^{18}\text{O}$  record<sup>35</sup>. This spinning-up of the ice sheet was initiated from the last  
310 interglacial period at 120 ka with present day topography and ice thickness<sup>36</sup>. We then used  
311 the LGM ice thickness, velocity, temperature and the bedrock topography obtained to  
312 initialise our deglaciation experiment.

313 **Ice sheet model set-up:** We use a horizontal resolution of 40 km, and 11 unequally spaced  
314 sigma levels to allow for higher resolution towards the bed of the ice sheet. When the basal  
315 conditions allow for melting, water accumulates, and the presence of basal water allows basal  
316 sliding to occur. To account for the presence of deformable sediment on the North American  
317 continent, which is likely to have been associated with high basal velocities, we prescribe a  
318 spatially varying basal sliding parameter. The basal sliding parameter is set to a high value  
319  $B_{\text{sed}}$  where the sediment thickness<sup>37</sup> is greater than 20 m, otherwise it is set to a low value  
320  $B_{\text{rock}}$ . We parameterised calving by cutting off floating ice. The isostatic adjustment of the  
321 bedrock to the ice load is calculated assuming the earth is composed of an elastic lithosphere  
322 (crust) floating on top of a relaxing mantle of time constant<sup>38</sup>. To calculate the mass balance,  
323 we used an annual Positive Degree Day (PDD) scheme<sup>39</sup>. This mass balance scheme works  
324 on the assumption that surface melting is proportional to the sum of positive degree days over  
325 a year. All precipitation is assumed to fall as snow, and up to 60 % of the snow fall can  
326 refreeze in the snow pack after melting. The parameter values we used for this study are  
327 presented in Table S1. Several parameter values were adjusted to improve the LGM ice  
328 volume, the LGM extent and the rate of uplift throughout the deglaciation compare to  
329 reconstructions<sup>8</sup>. These parameters are the relaxation time of the mantle, the basal sliding  
330 parameter and the flow factor of ice. We use a lapse rate of  $5\text{ }^{\circ}\text{C km}^{-1}$  [40]. A detailed  
331 comparison of our model results to observational data and ice sheet reconstruction and some  
332 sensitivity tests are described in Gregoire (2010)<sup>30</sup>.

333 **Climate forcing:** To drive our ice sheet model through the last deglaciation, we used a  
334 transient climate model simulation performed with a low resolution ocean-atmosphere  
335 coupled GCM, called FAMOUS. This simulation was forced by boundary conditions varying  
336 through time with no acceleration factor. The boundary conditions changed through the  
337 climate simulation are the geography, trace gas concentrations, orbit and freshwater input  
338 (Figure S1). To account for changes in the sea level and ice sheets, the orography,  
339 bathymetry, land sea mask and ice sheet extent were updated every 1000 years according to  
340 the Ice-5G reconstruction<sup>15</sup>. The experiment is set up so that the ice sheet extent used  
341 between 21 ka and 20 ka is that of 21 ka, the ice extent used between 20 and 19 ka is that of  
342 20 ka and so on. Except for area covered by ice, the vegetation is held constant at the present  
343 day values. Similarly, aerosols are held constant throughout the run. The atmospheric  
344 concentrations of CO<sub>2</sub>, methane and N<sub>2</sub>O are varied every time step with values taken from  
345 EPICA<sup>41</sup>. The simulation was forced with continuously varying insolation at the top of the  
346 atmosphere<sup>42</sup>. Finally freshwater is input into the ocean to reflect the discharge of ice sheets:  
347 this time varying field, based on a sea level reconstruction<sup>43</sup>, consists of a background flux  
348 from the melting of the ice sheets and three meltwater pulses, Heinrich Event 1, MWP1a and  
349 Meltwater Pulse 1b (MWP1b). Heinrich Event 1 was put the Norwegian Sea and the Ice  
350 Rafter Debris (IRD) belt between 19 ka and 17 ka. For MWP1a, the equivalent of 15 m of sea  
351 level equivalent was released in the North Atlantic from 14.2 ka to 13.6 ka. MWP1b was  
352 mainly put into the Arctic Ocean releasing 5.6 m of sea level equivalent. No abrupt climate  
353 change was simulated over the deglaciation, in particular the Bølling-Allerød warming event  
354 and the Younger-Dryas cold periods are not reproduced in this simulation. The freshwater  
355 pulses input to the climate model had little impact on the climate. However, the climate  
356 simulation reproduces well the LGM and present day temperatures over Greenland and the  
357 overall rate of temperature change observed in Greenland ice cores. We forced the Glimmer

358 ice sheet model with monthly mean temperatures and precipitation. The temperatures are  
359 downscaled from the FAMOUS resolution, on a 7.5° longitude by 5° latitude grid, onto the  
360 Glimmer topography, on a 40 km grid, by using a constant lapse rate of 5 °C km<sup>-1</sup>.  
361 **Smoothing of climate forcing:** Because the climate model was run in 1,000-year intervals,  
362 ice sheet topography and extent in the climate model were changed abruptly at the start of  
363 each interval. This caused discontinuities in North American temperature and precipitation  
364 (Figure S2) that produced steps in the Glimmer ice sheet mass balance. We therefore  
365 transformed the output of the transient climate simulations to produce a smooth climate that  
366 we used to drive our ice sheet model (Figure S2). We first averaged the temperature and  
367 precipitation fields over 1,000 year intervals for each month of the year to produce long term  
368 mean climatologies. We then calculated the climate forcing by linearly interpolating between  
369 the 1,000-year climatological means for each month so that the changes in seasonal cycle are  
370 taken into account. This had the effect of removing artificial steps in the mass balance  
371 produced by the discontinuities in temperature and precipitation in the raw climate output.

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### 373 **Methods References**

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