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LETTERS

Identification of Younger Dryas outburst flood path from Lake Agassiz to the Arctic Ocean

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The melting Laurentide Ice Sheet discharged thousands of cubic kilometres of fresh water each year into surrounding oceans, at times suppressing the Atlantic meridional overturning circulation and triggering abrupt climate change[1–4]. Understanding the physical mechanisms leading to events such as the Younger Dryas cold interval requires identification of the paths and timing of the freshwater discharges. Although Broecker *et al.* hypothesized in 1989 that an outburst from glacial Lake Agassiz triggered the Younger Dryas[1], specific evidence has so far proved elusive, leading Broecker to conclude in 2006 that "our inability to identify the path taken by the flood is disconcerting"[2]. Here we identify the missing flood path—evident from gravels and a regional erosion surface—running through the Mackenzie River system in the Canadian Arctic Coastal Plain. Our modelling of the isostatically adjusted surface in the upstream Fort McMurray region, and a slight revision of the ice margin at this time, allows Lake Agassiz to spill into the Mackenzie drainage basin. From optically stimulated luminescence dating we have determined the approximate age of this Mackenzie River flood into the Arctic Ocean to be shortly after 13,000 years ago, near the start of the Younger Dryas. We attribute to this flood a boulder terrace near Fort McMurray with calibrated radiocarbon dates of over 11,500 years ago. A large flood into the Arctic Ocean at the start of the Younger Dryas leads us to reject the widespread view that Agassiz overflow at this time was solely eastward into the North Atlantic Ocean.

Widespread fluvial erosion and deposition punctuated the last glacial–interglacial transition near the mouth of the Mackenzie River on the Canadian Arctic Coastal Plain (Fig. 1 and Supplementary Figs 1 and 2). Onshore, we have observed a regional erosion surface and gravel to elevations of 30 metres above sea level (m.a.s.l.) in the northeast Richards Island area[5]—an intervalley region bordered by the East Channel–Kugmallit Trough valley system to the east and the Middle Channel–Mackenzie Trough system to the west (Fig. 2). Our field investigations on northeastern Richards Island have revealed that fluvial erosion has stripped off much of the pre-existing till and terminated the building of large aeolian dunes and sand sheets that characterized non-glacial periods of Marine Isotope Stage 2 (ref. 6). The erosion produced an unconformity that truncates remnant till patches and aeolian sand deposits, and underlies a pebble–boulder lag or gravel reworked from the till[5].

Offshore, beneath the eastern Beaufort Shelf, the erosion surface occurs as a regional unconformity[7] and forms part of an undulating surface that includes submerged valleys 30–50 m deep that cross the shelf to a depth of ~70 m below the present sea level[8]. Valley incision has been attributed to a major increase in discharge across the emergent shelf during the Sitidgi glacial stade[9] in the Mackenzie Trough at ~15,000 calibrated years before present (15 cal. kyr BP), when relative sea level was ~70 m or more below the present level[9] and extensive proglacial drainage delivered water to the Beaufort Sea coast[10]. Later, the Holocene marine transgression trimmed and buried part of the unconformity[7].

We determined the age of intervalley erosion and gravel deposition by optically stimulated luminescence dating of eleven samples above and below the erosion surface at six locations (Table 1; Fig. 2). Aeolian sand from 0.2–5.0 m below the erosion surface provides seven ages between 13.4 ± 0.9 kyr and 12.7 ± 0.9 kyr (weighted mean by inverse variance is 13.0 ± 0.2 kyr). Fluvial and aeolian sand from above the gravel provides ages of 11.8 ± 1.0 kyr, 11.9 ± 1.0 kyr and 11.5 ± 0.7 kyr (mean = 11.7 ± 0.1 kyr), the latter two separating two gravelly layers. Aeolian sand that post-dates all fluvial gravelly sediments and channels that we have observed provides an age of 9.3 ± 0.7 kyr. From these data, we identify two major high-energy fluvial episodes, indicated by the two gravelly beds shown in Supplementary Fig. 3A and C. The first was deposited between 13.0 ± 0.2 kyr and 11.7 ± 0.1 kyr ago, and the second between 11.7 ± 0.1 kyr and 9.3 ± 0.7 kyr ago.

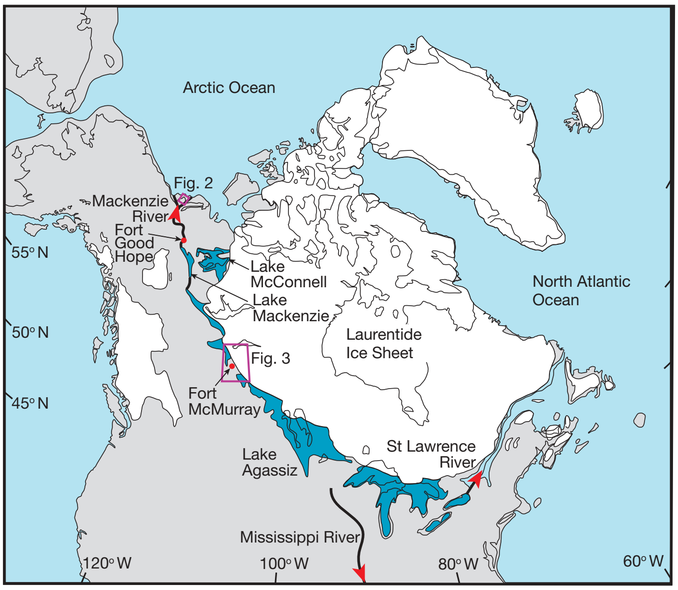

Figure 1 | Large proglacial lakes along the retreating Laurentide Ice Sheet at ~12.65–12.75 cal. kyr BP, near the start of the Younger Dryas. Three outlets are indicated: (1) northwest along the Mackenzie River to the Arctic Ocean, (2) east along the St Lawrence River to the North Atlantic Ocean, and (3) south along the Mississippi River to the Gulf of Mexico. The distribution of glacial ice (white), proglacial lakes (dark blue) and land (grey) is from ref. 11. Purple boxes mark the location of Figs 2 and 3.

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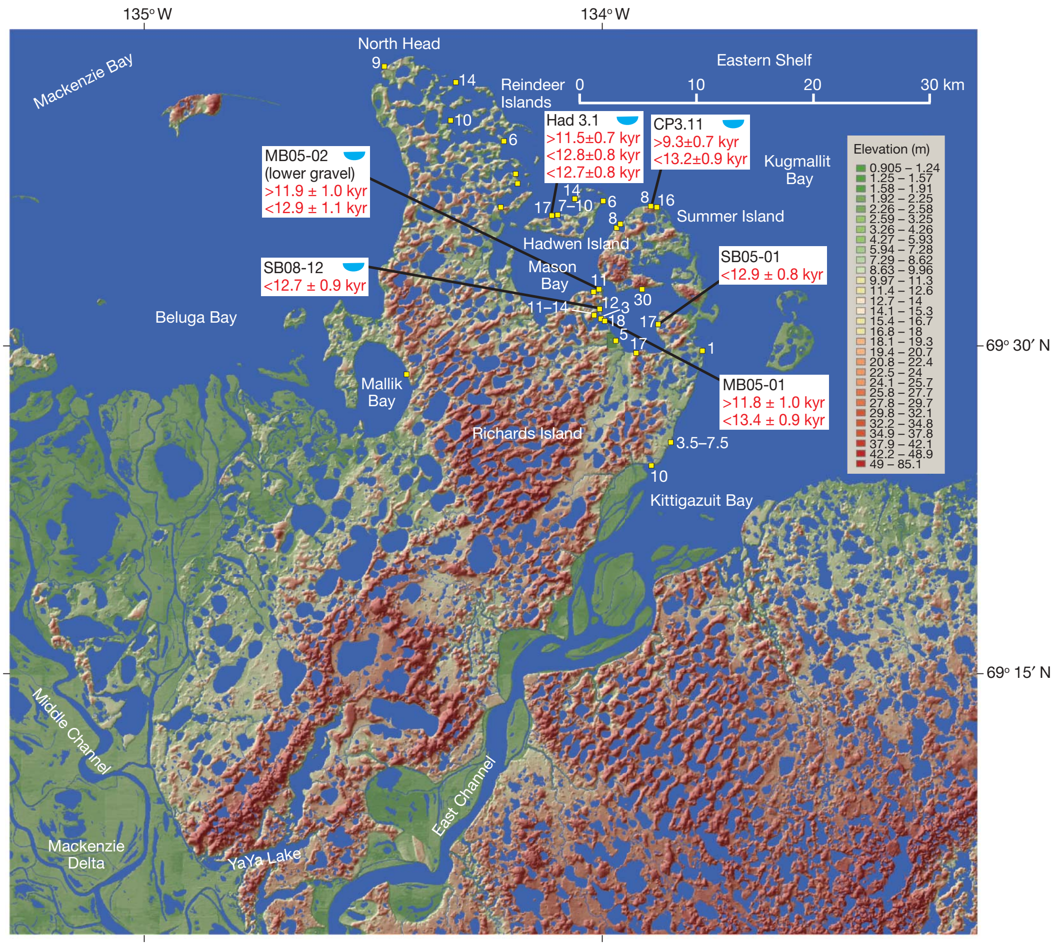

Figure 2 | Digital elevation model of Richards Island region. Shown are luminescence dates (red numbers, in kyr with 1σ uncertainties) constraining the age of a regional erosion surface and overlying gravelly deposits (yellow squares) relating to the first flood event. Numbers in white next to yellow squares are approximate elevations of fluvial features in m.a.s.l. Blue half-moons indicate channelled erosion surfaces. See Supplementary Discussion for details about fluvial sediments and stratigraphy.

The distribution of the coarse gravel and the spatially extensive yet narrowly timed fluvial erosion are exceptional. We discount non-glacial fluvial activity because the post-glacial Mackenzie River delivers mostly silt and clay to its low-lying delta, rather than the pebble–boulder gravel that we observe to elevations up to 30 m.a.s.l. in a region lacking evidence for glacio-isostatic uplift. Instead, the water source must have been glacial meltwater. A local glaciofluvial source from the Sitidgi ice margin is also unlikely. First, meltwater issuing from glacier margins tends to flow along the lowest parts of landscapes, rather than over topographic highs such as northeast Richards Island. To submerge it and transport cobbles and boulders over it would have required a huge amount of water washing over and inundating the entire area. Second, the erosion post-dates 13.0 ± 0.2 kyr ago (Table 1), a time when the nearest actively retreating ice margin—according to the recent reconstruction of Laurentide deglaciation[11]—was in the vicinity of Great Bear Lake, $\sim$600 km southeast of Richards Island (Fig. 1). We infer two vast, yet rapid fluvial events, with the most likely water source being a distant glacial lake such as Agassiz or McConnell. Outburst floods from such massive lakes could reasonably explain the age, wide spatial extent and elevation of the erosion surface and gravel.

We envisage that the flooding events significantly affected the palaeogeography of the Mackenzie Delta area and the Beaufort Shelf. While the active glacial ice margin moved south, cold permafrost conditions on the coastal plain preserved large amounts of stagnant glacial ice[12]. Thus initial flow was probably affected by glacial drainage systems. Our field studies suggest flow northeastward across

Table 1 | Optically stimulated luminescence ages on aeolian and fluvial sand

Sediments and stratigraphy	Section number	Sample number	Elevation (m.a.s.l.)	Age (kyr)	Palaeoenvironmental significance
Aeolian sand above channel base	CP3.11*	Shfd02066	8.2	9.3 ± 0.7	Postdates fluvial activity
Aeolian sand between two gravelly layers	Had 3.1†	Shfd02041	17.6	11.5 ± 0.7	Separates two episodes of flood deposition
Fluvial sand (MB05-02 separates two gravel layers)	MB05-01	Shfd06118	18.2	11.8 ± 1.0	Dates fluvial deposition (MB05-02 separates two episodes of flood deposition)
	MB05-02	Shfd06119	11.5	11.9 ± 1.0	
Gravel					Flood deposition
Unconformity					Flood erosion
Aeolian sand below fluvial gravel or channel base	MB05-01	Shfd06117	17.5	13.4 ± 0.9	Predates fluvial activity
	MB05-02	Shfd06120	10.6	12.9 ± 1.1	
	SB05-1	Shfd06066	16.5	12.9 ± 0.8	
	Had 3.1*	Shfd02042	16.7	12.8 ± 0.8	
	CP3.11*	Shfd02067	7.8	13.2 ± 0.9	
	Had 3.1†	Shfd02047	11.9	12.7 ± 0.8	
	SB08-12	Shfd08147	10.0	12.7 ± 0.9	

Sample locations and depths, water content, dose rate data (based on either *in situ* gamma-spectroscopy or inductively coupled plasma mass spectrometry), dose rates, equivalent doses and ages with associated 1σ uncertainties are given in Supplementary Table 1.
* Ref. 6.
† Sample reported in ref. 6 but revised according to methodology in the Supplementary Information.

Richards Island following the palaeo-East Channel, or an esker system northwest of Ya Ya Lake (Fig. 2). Ultimately the entire northern Richards Island area was inundated with significant flow almost certainly to the shelf edge via Kugmallit Bay and Kugmallit Trough (Supplementary Fig. 1). The modern elevation of the palaeo-East Channel between Tununuk and the sea is ~15 m.a.s.l. (ref. 13), which means that floodwaters would readily have spilled out across Richards Island to an elevation of at least 17.5 m.a.s.l., inferred from the highest elevation amongst the seven pre-flood optically stimulated luminescence ages (Table 1), and probably to 30 m.a.s.l. or more (Fig. 2). The elevation range (7.8−17.5 m.a.s.l.) of these ages suggests a minimum water depth of ~10 m. Flooding across northeast Richards Island and the emergent continental shelf to the north eroded till and terminated aeolian deposition, leaving a pebble–boulder lag at widely varying elevations. We correlate the fluvial erosion surface beneath this lag with a regional flooding surface in the sequence stratigraphy of the Mackenzie Delta[9]. The flooding surface—which cuts across sediments attributed to delta progradation during the Sitidgi Stade[9]—is located in the centre of the main flood route along the Mackenzie Trough.

The erosion surface and gravel suggest that at least two glacial outburst floods swept into the Arctic Ocean between ~13.0 and 9.3 kyr ago. We infer that the earlier flood is associated with the Younger Dryas (12.9–11.5 cal. kyr BP) based on the concordance of the pre-erosion optically stimulated luminescence ages from across the area and their mean age (13.0 ± 0.2 kyr): the ages are within analytical errors from six locations that span an area of >70 km^2 and an elevation range of ~8−18 m.a.s.l. and underlie a single, regional erosion surface that truncates aeolian deposits. This evidence suggests that fluvial erosion abruptly terminated aeolian deposition during a single event shortly after 13.0 kyr ago. A Mackenzie outburst at the onset of the Younger Dryas is consistent with one hypothesized from numerical modelling[14], geological interpretations in northern Alberta[15,16] and palaeoceanographic data from the Chukchi margin of the Arctic Ocean[17]. A later flood sometime between 11.7 ± 0.1 kyr and 9.3 ± 0.7 kyr ago may correspond to a catastrophic outburst from Lake Agassiz along the Mackenzie system at 11.3 cal. kyr BP, previously inferred from palaeoceanographic data from the Beaufort and Chukchi[17] margins and geological data in northern Alberta[18,19].

The available geomorphic evidence, radiocarbon dates and palaeotopographic modelling upstream in the Mackenzie basin are consistent with our inferences about catastrophic outburst flooding between ~13.0 and 9.3 kyr ago. Some 400 km southeast of Richards Island, near Fort Good Hope, in the Northwest Territories, Mackay and Mathews reported a 25-km-long and 1.5–2-km-wide spillway at the northeast end of glacial Lake Mackenzie (Fig. 1) that "is swept almost completely clear of all loose sediment"[20] and the terrain of which resembles the Channelled Scabland in the northwest USA, which was scoured by catastrophic flooding[21]. Although the precise age of the Fort Good Hope flooding is unknown, radiocarbon dates from deltaic and floodplain sediments that accumulated on the floor of the adjacent Mackenzie basin between ~13.4 and 13.1 cal. kyr BP (11,530 ± 170 and 11,140 ± 160 ^{14}C yr BP)[20]—when water spilled over a bedrock ridge near Fort Good Hope, cutting a number of spillways—also terminate near the start of the Younger Dryas.

Farther southeast, in the Fort McMurray region of northern Alberta (Fig. 1)—where the last vestige of the Laurentide Ice Sheet dam remained over the northwest outlet of Lake Agassiz[11]—there are few early-deglacial radiocarbon dates. The scarcity of datable organics from the flood-scoured spillway here—which lies north of the junction of the Clearwater spillway leading from Lake Agassiz and the Athabasca–Mackenzie system (Fig. 3)—is not surprising in a newly deglaciated area. Importantly, however, several dates exceed 10 ^{14}C kyr BP or ~11.5 cal. kyr BP (Fig. 3; Supplementary Table 2), suggesting a Younger Dryas connection between Lake Agassiz and the Arctic Ocean.

Our Geographic Information System (GIS) palaeotopographic modelling of the Fort McMurray region (Fig. 3), based on adjusting modern digital-elevation-model surface elevations for differential isostatic rebound at a specific time, indicates that overflow from Lake Agassiz into the Mackenzie system would have occurred during the Younger Dryas, if the Laurentide Ice Sheet had retreated from the Clearwater–Athabasca valley system. The volume of water abruptly released from Lake Agassiz at the start of the Younger Dryas was calculated as 9,500 km^3 (ref. 22), based on the elevation difference between the highest (Herman) beach in the Agassiz basin—formed near the start of the Younger Dryas—and the low-water level there shortly after an abrupt drawdown of the lake. For a flood with a hypothetical duration of one year, this would represent a flux of 0.30 Sv, plus an additional baseline flow from the basin of 1,577 $km^3 yr^{-1}$ (0.05 Sv), related to melting of the Laurentide Ice Sheet[4]. The upper boulder gravel terrace in the Athabasca River Valley north of Fort McMurray[23] may have been deposited by this outburst[16], before the outburst swept through glacial lakes Mackenzie and McConnell (Fig. 1)—perhaps rapidly eroding their overflow

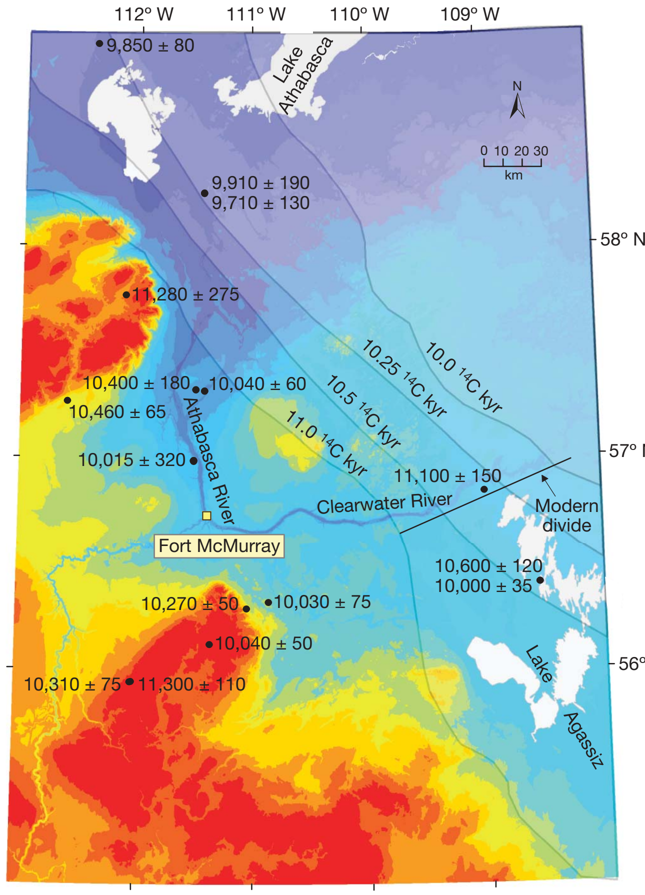

Figure 3 | Modelled palaeotopography of the Fort McMurray region at the Herman beach stage of Lake Agassiz. Stage age ~10.9 ^{14}C kyr BP ≈ 12.9 cal. kyr BP. Selected radiocarbon dates are shown (with 1σ uncertainties), mainly those exceeding 10 ^{14}C kyr (details in Supplementary Table 2); dates on shell carbonate are not included. The glacial boundaries of Dyke[11] are shown in radiocarbon years at several times, with 11.0 ^{14}C kyr BP = 12.9 cal. kyr BP, 10.5 ^{14}C kyr BP = 12.5 cal. kyr BP, 10.25 ^{14}C kyr BP = 12.0 cal. kyr BP and 10.0 ^{14}C kyr BP = 11.5 cal. kyr BP. Yellow to red colours show areas above Lake Agassiz level at 50-m intervals. Blue colours show areas below the level of Lake Agassiz at 50-m intervals down to −600 m; beyond the extent of Lake Agassiz, these contours reflect only the palaeotopographic surface, not the depth of water. Overflow from Lake Agassiz occurred into the headwaters of the Clearwater Valley across the 'Modern Divide', and flowed west to Fort McMurray, where it entered the Athabasca Valley and flowed north to Lake Athabasca and then to the Mackenzie River and Arctic Ocean.

spillways—and then scouring the surface in the Arctic lowland, depositing the coarse lag dated to shortly after 13.0 ± 0.2 kyr ago.

Although the location of the Laurentide Ice Sheet margin in this region during the Younger Dryas is not well constrained, Dyke placed it along the western side of the Athabasca lowland[11] (Fig. 3). A subsequent readvance of the Laurentide Ice Sheet at ~11.5 cal. kyr BP[23] complicates reconstructions. Thus, a shift of <50 km in the currently drawn Laurentide Ice Sheet margin at ~12.9 cal. kyr BP (11 ^{14}C kyr BP) (Fig. 3) would open a corridor from Lake Agassiz to the Arctic Ocean during the Younger Dryas. A Laurentide Ice Sheet readvance at ~11.5 cal. kyr BP—known from much of the region between the Great Lakes and the Rocky Mountains[4,24,25]—would have briefly closed the corridor. When this glacier dam retreated, a second outburst from Lake Agassiz entrenched the older boulder terrace in the Athabasca Valley, depositing a younger and lower boulder terrace[16] and the fluvial gravels downstream in the Richards Island area that are between 11.7 kyr and 9.3 kyr old, as dated by optically stimulated luminescence.

Identification of the two Mackenzie floods elucidates our understanding of meltwater routing and abrupt climate change during the last deglaciation of North America. Our results identify the missing Younger Dryas flood path sought by Broecker[2]. Outburst flooding from Lake Agassiz at the start of the Younger Dryas occurred preferentially to the northwest because this outlet was at a lower elevation than the eastern one. This explains the lack of geomorphic evidence for catastrophic overflow eastward from the lake during the Younger Dryas[2,15], but does not preclude some eastward drainage from Lake Agassiz or other proglacial lakes farther east[26,27]. Thus we reject the prevailing view that the routing of deglacial meltwater from Lake Agassiz at the start of the Younger Dryas switched from the southern (Mississippi) outlet solely to the eastern (St Lawrence) outlet (Fig. 1)[1]. Instead, our data support the hypothesis that the trigger of the Younger Dryas was along the Arctic route[14,16]. After that, a glacial advance probably forced overflow to switch temporarily to a southerly route[15] or, if the Superior basin was ice-free, to pass eastward through the Great Lakes[28]. If this shift occurred during the Younger Dryas and overflow was into the Great Lakes it would have sustained the suppression of the Atlantic meridional overturning circulation[28] initiated by the Mackenzie River routing of Lake Agassiz overflow.

METHODS SUMMARY

Between 1989 and 2008 we examined coastal sedimentary sequences throughout the northeast Richards Island area to determine the stratigraphy of the fluvial gravel, erosion surface and aeolian sand. We logged numerous sections sedimentologically to refine these observations and interpret the origin of sediments (Fig. 2), before collecting eleven sand samples for luminescence dating from six key sections; Supplementary Fig. 3 records three sections. Luminescence dating was carried out using the optically stimulated luminescence signal from extracted quartz (see Supplementary Methods). GIS palaeotopographic modelling of the Fort McMurray region used a model of differential isostatic rebound based on ref. 29.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions J.B.M. and M.D.B. designed the field research in the Mackenzie Delta region; J.B.M. and S.R.D. performed the stratigraphic analyses and interpreted the palaeogeography; M.D.B. collected samples and performed the luminescence dating; J.T.T. and Z.Y. studied and modelled the Fort McMurray region. J.B.M., J.T.T. and M.D.B. drafted the manuscript, with all authors contributing to it.

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