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Timing of terminal Pleistocene deglaciation at high elevations in southern and central British Columbia constrained by ^{10}Be exposure dating

Martin Margold [a,*], Arjen P. Stroeven [b,1], John J. Clague [c,2], Jakob Heyman [b]

[a] Durham University, Department of Geography, Lower Mountjoy, South Road, Durham DH1 3LE, UK
[b] Stockholm University, Department of Physical Geography and Quaternary Geology, and Bolin Centre for Climate Research, 106 91 Stockholm, Sweden
[c] Simon Fraser University, Department of Earth Sciences, 8888 University Drive, Burnaby, British Columbia V5A 1S6, Canada

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ABSTRACT

The Cordilleran Ice Sheet (CIS) covered most of British Columbia and southern Yukon Territory at the local Last Glacial Maximum (lLGM) during Marine Oxygen Isotope Stage 2. However, its subsequent demise is not well understood, particularly at high elevations east of its ocean-terminating margin. We present ^{10}Be exposure ages from two high-elevation sites in southern and central British Columbia that help constrain the time of initial deglaciation at these sites. We sampled granodiorite erratics at elevations of 2126–2230 m a.s.l. in the Marble Range and 1608–1785 m a.s.l. in the Telkwa Range at the western margin of the Interior Plateau. The erratics at both sites are near ice-marginal meltwater channels that delineate the local ice surface slope and thus the configuration of the ice sheet during deglaciation. The locations of the erratics and their relations to meltwater channels ensure that the resulting ^{10}Be ages date CIS deglaciation and not the retreat of local montane glaciers. Our sample sites emerged above the surface of the CIS as its divide migrated westward from the Interior Plateau to the axis of the Coast Mountains. Two of the four samples from the summit area of the Marble Range yielded apparent exposure ages of 14.0 ± 0.7 and 15.2 ± 0.8 ka. These ages are 1.8–3.0 ka younger than the well-established lLGM age of ca 17 ka for the Puget lobe of the CIS in Washington State; they are 1.7 ka younger than the lLGM age for the Puget lobe if a snow-shielding correction to their uncertainty-weighted mean age is applied. The other two samples yielded much older apparent exposure ages (20.6 ± 1.4 and 33.0 ± 1.5 ka), indicating the presence of inherited isotopes. Four samples collected from the summit area of the Telkwa Range in the Hazelton Mountains yielded well clustered apparent exposure ages of 10.1 ± 0.6, 10.2 ± 0.7, 10.4 ± 0.5, and 11.5 ± 1.1 ka. Significant present-day snow cover introduces a large uncertainty in the apparent exposure ages from this site. A snow-shielding correction based on present-day snow cover data increases the uncertainty-weighted mean exposure age of the Telkwa Range erratics to 12.4 ± 0.7 ka, consistent with deglacial ^{14}C ages from areas near sea level to the west. Our exposure ages show a thinning of the southern portion of the CIS shortly after the lLGM and persistence of a remnant mountain ice cap in the central Coast Mountains into the Younger Dryas Chronozone. Our data also show that the summit area of the Marble Range was ice-covered during the lLGM. The presence of an ice body of considerable dimension in north-central British Columbia until, or possibly even after, the Younger Dryas highlights the need for geomorphological and geochronological studies of the ice dispersal centre over the Skeena Mountains in northwest British Columbia and the need for better understanding of the response of the CIS to Lateglacial climate fluctuations.

1. Introduction

The evolution of Earth's climate during the Pleistocene was the result of the interplay between known, hypothesised, and yet undiscovered feedbacks in the climate system and has long been a focus of scientific study. An important aspect of this scientific

* Corresponding author. Tel.: +44 191 33 41829.
E-mail address: martin.margold@durham.ac.uk (M. Margold).
[1] +46 8 16 42 30.
[2] +1 604 291 4924.

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Fig. 1. (a) Location of the study area. Outlined are the lLGM extents of the Cordilleran Ice Sheet (CIS) and the Laurentide Ice Sheet (LIS), which includes the Innuitian Ice Sheet (after Dyke et al., 2003; Kleman et al., 2010; generalised). (b) Physiography of the study area and ice geometries at the local Last Glacial Maximum (lLGM; dark blue ice divide after Clague and Ward, 2011) and early during deglaciation (grey ice divide after Margold et al., 2013b). Locations of the sample sites (Figs. 2a and 3a) and the area shown in Fig. 5 are indicated by black rectangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

endeavour is the study of receding ice sheets that once covered large areas of the mid-latitudes of the Northern Hemisphere. The Cordilleran Ice Sheet (CIS), which covered British Columbia and southern Yukon Territory and extended into Alaska, Northwest Territories, the conterminous United States, and Alberta, is one of the least understood of the Pleistocene ice sheets, and relatively little is known about the pattern and timing of its demise at the end of the Pleistocene (Clague, 1981; Jackson et al., 1991; Ryder and Maynard, 1991; Ryder et al., 1991; Menounos et al., 2009; Margold et al., 2013a, 2013b). In this paper, we build on our recent efforts to reconstruct and date retreat of the CIS in southern and central British Columbia based on geomorphological evidence and cosmogenic exposure ages from relatively unexplored mountain settings.

The CIS covered all of British Columbia, except for mountain nunataks, at the peak of the last glaciation, termed the Fraser Glaciation in British Columbia (Marine Oxygen Isotope Stage (MIS) 2; Fig. 1; Clague, 1981, 1989; Clague and Ward, 2011). It advanced over the northeast Pacific continental shelf and reached the eastern and northern shores of the Queen Charlotte Islands shortly after 21 ^{14}C ka[3] (Blaise et al., 1990). Its southwest margin reached the shelf edge southwest of Vancouver Island at about 19.5 cal ka (Cosma et al., 2008). The local Last Glacial Maximum (lLGM) has been dated to about 17 ka in Yukon Territory (Stroeven et al., 2010, 2014) and to about 17.0–16.6 cal ka at its limit in southern Puget Lowland, Washington (Porter and Swanson, 1998). The relatively sparse chronological information for the eastern sector of the CIS indicates that it coalesced with the Laurentide Ice Sheet sometime between

[3] ^{14}C ka – non-calibrated radiocarbon age; cal ka – calibrated radiocarbon age; ka – cosmogenic exposure age.

about 25.6 ka (Smith, 2004) and 22 ka (Duk-Rodkin et al., 1996) in the Mackenzie Mountains, and shortly after 17.6 ka east of the Rocky Mountains in southwest Alberta (Jackson et al., 1997). More recent work by Kennedy et al. (2010) indicates that the Laurentide Ice Sheet achieved its maximum extent near the Yukon-Northwest Territories boundary sometime between 18 and 19.5 cal ka, which is substantially later than previously thought.

Shortly after the lLGM, the western, shelf-based margin of the ice sheet was destabilized by eustatic sea level rise and retreated rapidly towards the fjords and sounds of the rugged mainland coast of British Columbia (Clague, 1981, 1985; Blaise et al., 1990; Booth et al., 2003; Cosma et al., 2008; Hendy and Cosma, 2008). Late-glacial advances of the southwest margin of the ice sheet in Puget and Fraser lowlands and near the head of Howe Sound north of Vancouver (Fig. 1) span the period 14.5–11.0 cal ka (Clague et al., 1997; Kovanen, 2002; Kovanen and Easterbrook, 2002; Friele and Clague, 2002a, b; Menounos et al., 2009). The valley north of Kitimat on the northern mainland coast of British Columbia (Fig. 1) was deglaciated between 12.6 and 12.1 cal ka (Clague, 1985).

Latest Pleistocene advances of valley glaciers up to 10 km beyond their Little Ice Age limits have been described in mountain ranges in central and northern British Columbia and are referred to as the "Finlay Advance" by Lakeman et al. (2008) and Menounos et al. (2009). Geomorphological evidence shows that the Finlay Advance coincided with the latest stage of CIS deglaciation. Lakeman et al. (2008) concluded that the advance is Younger Dryas in age.

Attempts to reconstruct the pattern and timing of CIS deglaciation at a regional scale have been hampered by a lack of recessional moraines and patchy chronological data. Most published chronological information comes from the southwestern and western margins of the CIS; little data are available for the large area of the Interior Plateau and the Rocky and Mackenzie mountains farther east. Moreover, ice retreat dynamics have generally been considered using a conceptual model developed initially for the southern portion of the ice sheet (Fulton, 1967, 1991). The chronology of deglaciation, especially that of the early phase of deglaciation, has received scant attention. Ice thicknesses also remain poorly constrained.

In this manuscript, we present new ^{10}Be exposure ages from summit areas of two mountain ranges near the ice divide of the thinning and retreating CIS in southern and central British Columbia. By combining inferences on CIS configuration derived from geomorphology (Margold et al., 2011, 2013b) and new chronological data, we aim to advance knowledge of ice sheet recession in British Columbia. We discuss our data in the context of previously published radiocarbon- and surface exposure ages from other, mainly low-elevation sites.

2. Study sites

We collected samples for surface exposure dating in the Marble Range and the Hazelton Mountains, both of which are located at the western margin of the Interior Plateau (Fig. 1). We chose sample sites based on the presence of high-elevation, ice-marginal meltwater channels that clearly delineate the direction of meltwater flow and thus the configuration of the ice sheet surface when the sites first became ice-free (Figs. 2 and 3; Margold et al., 2011, 2013b). The ice-marginal channels were eroded by meltwater flowing between the edge of the CIS and an adjacent rising slope. The pattern of the channels thus records the surface slope of the ice sheet, from which regional ice sheet configurations can be reconstructed (Mannerfelt, 1945; Greenwood et al., 2007).

The Marble Range extends over 30 km in a northwest direction at the southwest margin of the Interior Plateau in southern British

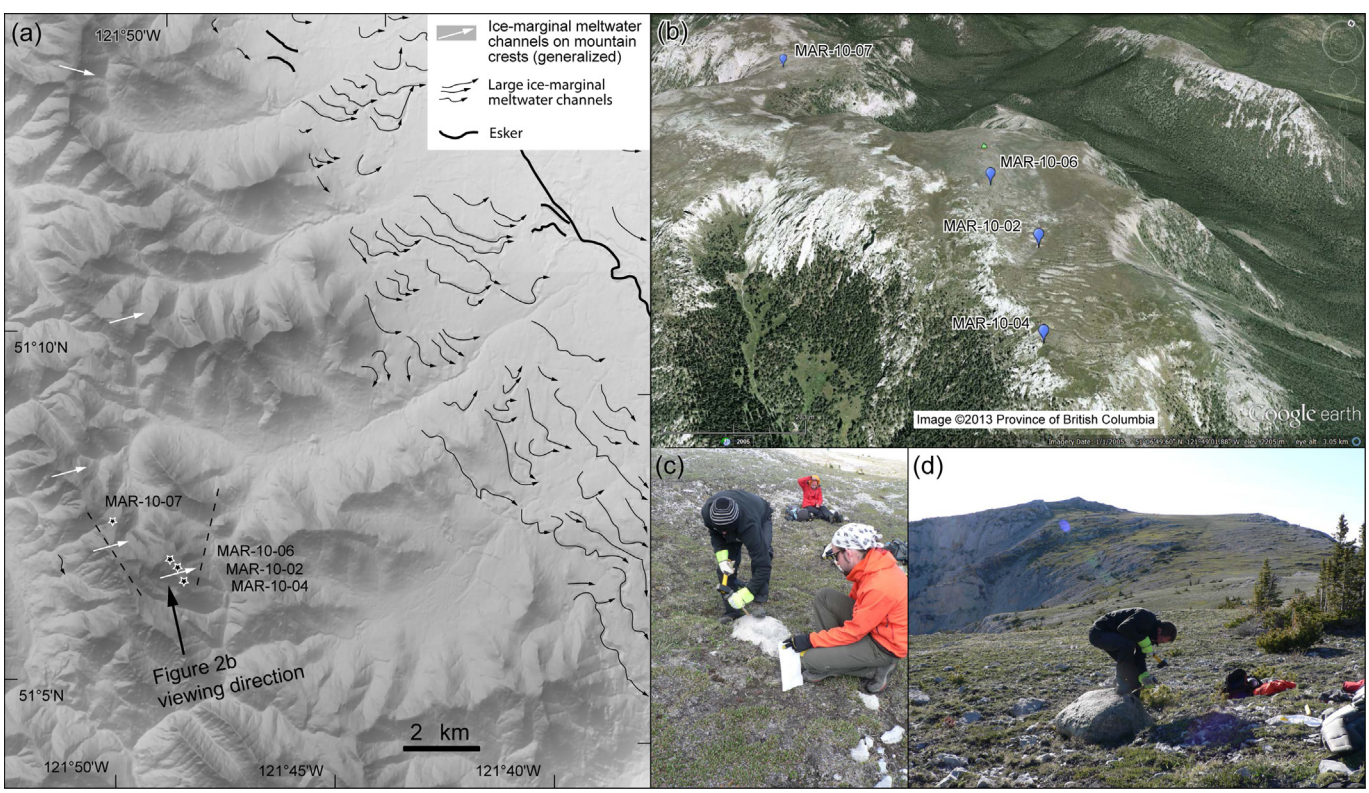

Fig. 2. Marble Range. (a) Topography; ^{10}Be exposure sample sites are marked by stars, ice-marginal meltwater channels with arrows, and eskers with dark black lines. (b) Oblique Google Earth view of the Marble Range summit area, showing a series of ice-marginal meltwater channels in the foreground and locations of the ^{10}Be exposure samples. (c) and (d) Photographs showing the collection of, respectively, samples MAR-10-02 and MAR-10-07.

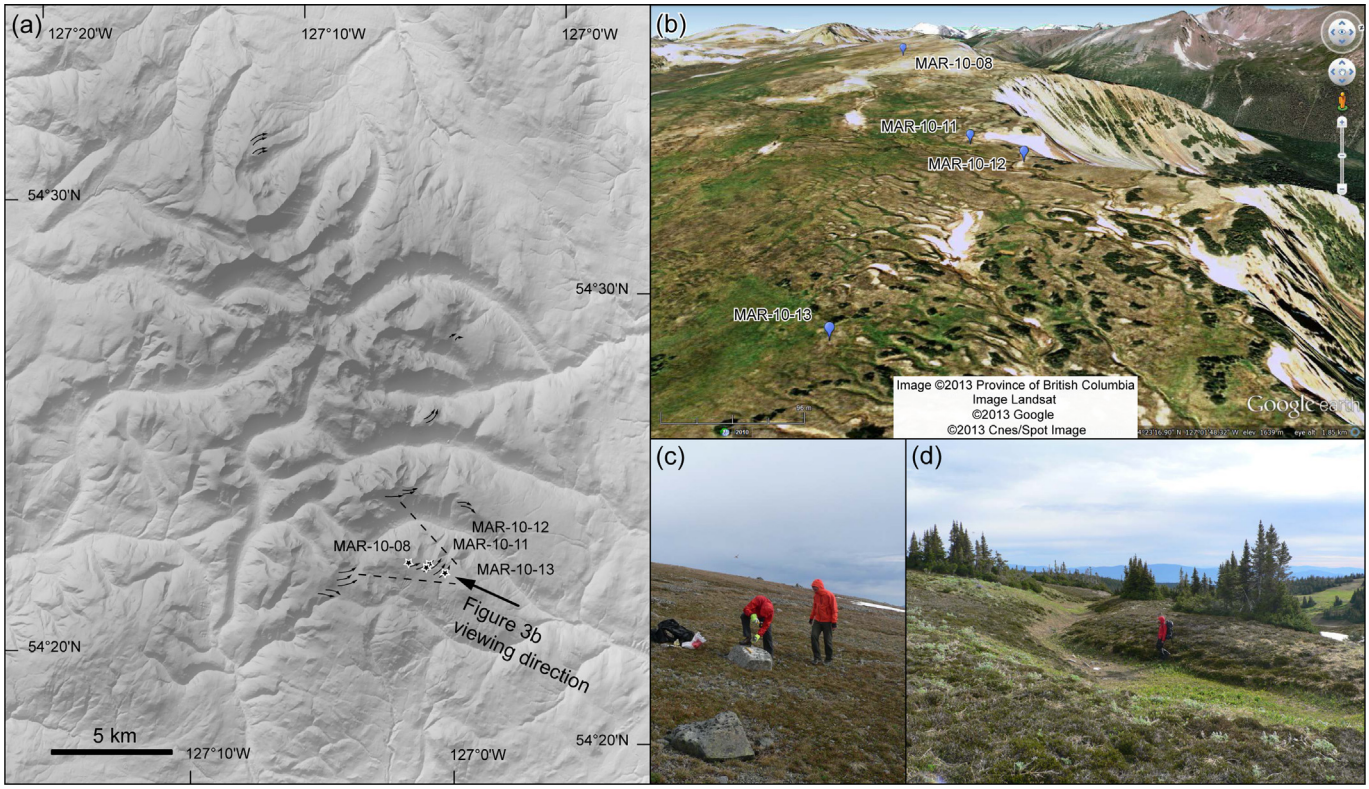

Fig. 3. Telkwa Range, Hazelton Mountains. (a) Topography; ice-marginal meltwater channels are marked by black arrows; ^{10}Be exposure sample locations are marked by stars (samples that yielded insufficient quartz for analysis are not shown). (b) Oblique Google Earth view of the sampling site in the summit area of the Telkwa Range, showing a series of ice-marginal meltwater channels in the foreground (between samples MAR-10-12 and MAR-10-13) and locations of the ^{10}Be exposure samples. (c) Photograph showing the collection of sample MAR-10-08. (d) Photograph of one of the ice-marginal meltwater channels; person for scale.

Columbia (Fig. 1). The summit area is about 2200 m above sea level (a.s.l.), about 1000 m above the plateau to the east and 1900 m above the Fraser River to the west. Ice-marginal channels oriented east to east-northeast are common at and near the summits of the Marble Range (Fig. 2). Granodiorite erratics are scattered on limestone bedrock in the summit area of the range. We collected samples of four erratics from the summit area for ^{10}Be exposure dating. Two of the four sampled erratics (MAR-10-02 and MAR-10-04) are located within the area of the best-developed, ice-marginal meltwater channels; one (MAR-10-06) is near a low summit above the meltwater channels; and one (MAR-10-07) is about 2 km northwest of the others, on the main ridge (Fig. 2). All the sampled boulders, with the exception of MAR-10-07, are small and partially embedded in regolith soil. The adjacent flights of well preserved, small ice-marginal meltwater channels have changed little since deglaciation. We further noted the presence of only a thin layer of soil developing from the carbonate regolith and an absence of substantial amounts of till. Although all of the samples are of the same lithology, their degree of weathering differs considerably – sample MAR-10-04 is considerably more weathered than the others.

The Hazelton Mountains comprise several mountain ranges at the northwest margin of the Interior Plateau in west-central British Columbia (Fig. 1). The easternmost of these ranges – the Telkwa Range – rises above the adjacent Nechako Plateau to elevations just above 2000 m a.s.l., creating a local relief of up to 1600 m. Ice-marginal meltwater channels occur below about 1740 m a.s.l., mainly on southeast- and northwest-facing slopes of the range and have a consistent northeast orientation (Fig. 3). The Telkwa Range consists mainly of volcanic rocks, and erratics of both local and distant lithologies are common in the summit area. We sampled six erratic boulders for ^{10}Be exposure dating. Three of the sampled erratic boulders (samples MAR-10-08, MAR-10-09, and MAR-10-10) are located in a flat summit area at an elevation of about 1780 m a.s.l., 40 m above the highest ice-marginal meltwater channel. Samples MAR-10-11, MAR-10-12, and MAR-10-13 were collected from erratics within the area of meltwater channels (Fig. 3). The sampled erratics are boulders of intermediate size (Table 1); the sampled surfaces are 30–60 cm above the ground, with the exception of MAR-10-09, which was collected 170 cm above the ground. As in the case of the Marble Range, the well-preserved character of the ice-marginal meltwater channels implies little surface alteration since deglaciation. The sampled boulders have experienced little, if any, post-depositional modification, thus the derived apparent exposure ages should accurately record the time of deglaciation at the sites. None of the samples was obviously weathered. Isolated patches of snow were present at the sample sites at the time of our visit in mid-July 2010.

3. Methods

We collected samples for exposure dating with a hammer and chisel, and recorded their locations and elevations with a hand-held GPS. We measured the sample thickness and recorded the topographic shielding using a compass and clinometer. Sample preparation was carried out at PRIME Lab, Purdue University, using standard procedures, including quartz separation, Be carrier addition, and conversion to BeO. Ratios of ^{10}Be/^{9}Be were measured at PRIME Lab using accelerator mass spectrometry with normalization to the 07KNSTD standard of Nishiizumi et al. (2007). We corrected ^{10}Be concentrations for blanks corresponding to 0.4–6.1% of the total number of ^{10}Be atoms in a sample. The CRONUS online calculator code (Balco et al., 2008; version 2.2; constants 2.2.1),

Table 1
Cosmogenic ^{10}Be sample data and minimum apparent surface exposure ages.

Location sample code	Dimensions[a] $L \times W \times H$ (m)	Latitude (degrees)	Longitude (degrees)	Altitude (m a.s.l.)	Sample thickness (cm)	Topographic shielding factor	[^{10}Be] (atoms/g)[b]	Exposure age ± external uncertainty (years)[c]	Internal uncertainty (years)
Marble Range									
MAR-10-02	0.9 × 0.5 × 0.2	51.11366	−121.81593	2184	3	0.9982	341,993 ± 11,318	13,952 ± 704	464
MAR-10-04	0.7 x 0.4 x gr. surf	51.11089	−121.81400	2161	4	0.9998	493,050 ± 27,014	20,550 ± 1376	1137
MAR-10-06	0.5 x 0.5 x gr. surf	51.11526	−121.81908	2230	3	0.9999	839,734 ± 19,172	32,988 ± 1471	767
MAR-10-07	1.0 × 0.7 × 0.5	51.12329	−121.84145	2126	3	0.9969	357,064 ± 11,424	15,193 ± 756	489
Telkwa Range									
MAR-10-08	0.9 × 0.7 × 0.4	54.38760	−127.04717	1785	3	0.9998	194,113 ± 11,985	10,235 ± 743	637
MAR-10-11	1.0 × 1.0 × 0.3	54.38813	−127.03533	1675	3	0.9996	176,311 ± 8567	10,111 ± 625	495
MAR-10-12	1.0 × 1.0 × 0.5	54.38869	−127.03350	1661	3	0.9996	198,625 ± 17,538	11,519 ± 1110	1025
MAR-10-13	1.3 × 1.3 × 0.6	54.38630	−127.02705	1608	5	0.9997	168,627 ± 6054	10,354 ± 542	374

[a] $L \times W \times H$ is Length × Width × Height, with Height measured above the surface.
[b] Data are normalised to 07KNSTD and corrected for blank measurements corresponding to 0.4–6.1% of the total number of measured ^{10}Be atoms (total number of blank ^{10}Be atoms: 213163 ± 41382).
[c] Exposure ages are calculated using the Lm scaling scheme in the CRONUS-Earth online exposure age calculator code (version 2.2, constants 2.2.1; Balco et al., 2008) with the updated Arctic spallation ^{10}Be reference production rates from Young et al. (2013). We assume a sample density of 2.7 g cm^{-3} and zero erosion. Both external and internal uncertainty is 1σ.

with updated Arctic reference ^{10}Be production rates of Young et al. (2013), was used to calculate apparent exposure ages. We report apparent exposure ages using the time-dependent CRONUS Lm production rate scaling of Lal (1991) and Stone (2000) with a reference spallation production rate of 3.96 ± 0.15 atoms g^{-1} yr^{-1} (Young et al., 2013). This production rate is 10% lower than the global CRONUS production rate of 4.39 ± 0.37 atoms g^{-1} yr^{-1}. The Arctic production rate of Young et al. (2013) is based on ^{10}Be production rate data from calibration sites in northeastern North America (Balco et al., 2009), Norway (Fenton et al., 2011; Goehring et al., 2012), western Greenland (Briner et al., 2012; Young et al., 2013), and Baffin Island (Balco et al., 2009; Young et al., 2013).

4. Results

The four granodiorite erratics collected in the summit area of the Marble Range yielded ^{10}Be apparent exposure ages of 14.0 ± 0.7 ka (MAR-10-02), 20.6 ± 1.4 ka (MAR-10-04), 33.0 ± 1.5 ka (MAR-10-06), and 15.2 ± 0.8 ka (MAR-10-07; Table 1, Figs. 2 and 4). In the absence of reliable surface erosion and burial estimates and corrections, these ages should be considered minimum exposure ages (see Discussion).

Only four of the six boulders sampled in the Telkwa Range yielded sufficient amounts of quartz for extraction and measurement of the ^{10}Be nuclide. The four samples yielded apparent exposure ages of 10.2 ± 0.7 ka (MAR-10-08), 10.1 ± 0.6 ka (MAR-10-11), 11.5 ± 1.1 ka (MAR-10-12), and 10.4 ± 0.5 ka (MAR-10-13; Table 1, Figs. 3 and 4). The uncertainty-weighted mean exposure age of the four samples, using the internal uncertainties (production rate uncertainty added in quadrature using standard uncertainty propagation), is 10.3 ± 0.5 ka. These ages, like those from the Marble Range, are minima; we have applied no corrections for snow cover and surface erosion, but discuss the possible effects of snow shielding in the next section.

5. Discussion

5.1. Implications of ^{10}Be exposure ages from the Marble Range for deglaciation of southwestern British Columbia

The apparent exposure ages from the Marble Range differ significantly from those in the Telkwa Range, in spite of similar topographic settings. Specifically, all Marble Range apparent exposure ages are considerably older than the Telkwa Range ages; the oldest Telkwa Range apparent exposure age (11.5 ± 1.1 ka) is significantly younger than the youngest Marble Range apparent exposure age of 14.0 ± 0.7 ka (Fig. 4).

Two of the four Marble Range apparent exposure ages are significantly older (20.6 ± 1.4 and 33.0 ± 1.5 ka) than the other two. The uncertainty-weighted exposure age of the two younger samples is 14.5 ± 1.0 ka. We interpret the two older exposure ages as resulting from prior exposure (Heyman et al., 2011), because there is no single sample history that can explain the difference in the nuclide concentrations. The two older erratics could have been brought to the site with earlier ice advances, although for this interpretation even older exposure ages would be expected because the Marble Range was ice-free throughout MIS 3 (Clague, 1981). Alternatively, the two older boulders have ^{10}Be inheritance from a period prior to their deposition at the site.

The crest of the Marble Range receives a moderate amount of snow during the winter season, and we therefore explore the possible effects of snow shielding on the apparent exposure ages. We employ a simple equation for spallation production rate at depth (Lal, 1991) with an attenuation length of 160 g/cm,[2] and base our estimates for the duration, thickness, and density of the present-day snow cover on data from nearby Pavilion Mountain (British Columbia Ministry of Environment, Snow Station 1C36), ca 20 km SSE of our study site. Current snow cover reduces the

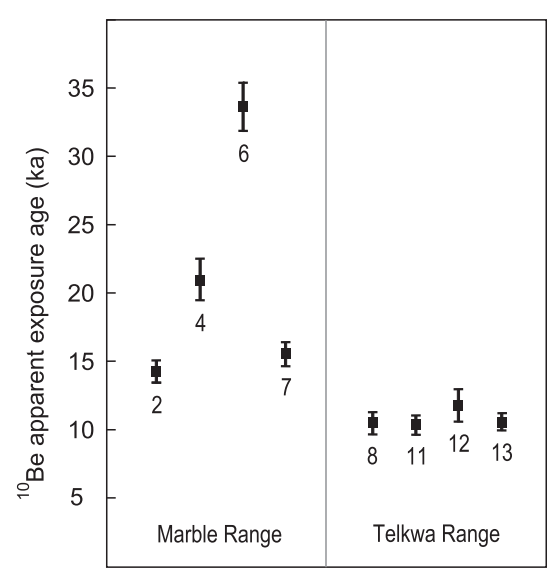

Fig. 4. Cosmogenic ^{10}Be apparent exposure ages.

production rate by 5%, which, when considered as representative on longer timescales, results in an increased uncertainty-weighted mean age of 15.3 ± 1.1 ka for the two younger samples (see Supplementary Data). We acknowledge that possible redistribution of snow by wind and changes in snow cover during the Lateglacial and Holocene introduce large uncertainty in our estimate of the snow-shielding effect.

The uncertainty-weighted exposure age of the two younger samples from the Marble Range is 2.5 ka younger (1.7 ka younger if snow shielding is taken into account) than the lLGM in the Puget Sound (Porter and Swanson, 1998) and slightly younger than, or even contemporaneous with, the time of retreat of the CIS from the Strait of Georgia (Clague, 1981, Fig. 5). We envision ice-marginal retreat and thinning of the southern part of the CIS between the lLGM and about 15–14.5 ka, which is generally in accord with the literature on the timing of deglaciation of southwest British Columbia (summarised in Clague, 1981, 1989; Fulton, 1991; Ryder et al., 1991).

The younger Marble Range exposure ages are also consistent with the evidence provided by ice-marginal meltwater channels at high elevations. Margold et al. (2013b) documented the distribution and form of ice-marginal meltwater channels at high elevations in British Columbia, from which they inferred a reconfiguration of the ice sheet during the earliest stage of deglaciation. Specifically, a northwest-trending ice divide located over the western Interior Plateau in south-central British Columbia at the lLGM shifted westward to a position over the crest of the Coast Mountains early during deglaciation. The ice-marginal meltwater channels near the crest of the Marble Range slope to the east, which indicates that the surface of the CIS at the time the granodiorite erratics were deposited (14.5 ± 1.0 ka, or 15.3 ± 1.1 ka if the correction for snow shielding is applied) also sloped in this direction. This evidence is consistent with an ice divide located west of the Marble Range. The saddle that connected an ice-dispersal centre in the Columbia Mountains to accumulation areas in the west at the lLGM (Ryder et al., 1991) had disappeared by the time the crest of the Marble Range emerged from the ice sheet. The geomorphological evidence and apparent exposure ages also confirm that the summit ridge of the Marble Range was covered by the CIS at the lLGM. This finding is contrary to suggestions by previous researchers that the ice sheet on the plateau surface bordering the Marble Range was only 600 m thick at the lLGM (Huntley and Broster, 1994; Burke et al., 2012a, b). In a later stage of deglaciation, the slope of the ice sheet surface changed to southeasterly over the Interior Plateau east of the Marble Range, and ice retreated to the northwest along the foot of the range, as indicated by a series of large ice-marginal meltwater channels and eskers (Fig. 2; Margold et al., 2013b).

Different exposure ages, with some of apparent deglacial age and others much older such as in the Marble Range, have been reported on relict surfaces of the former Laurentide (Briner et al., 2006), Fennoscandian (Harbor et al., 2006), British-Irish (Phillips et al., 2006), and Cordilleran (Stroeven et al., 2014) ice sheets (cf. Heyman et al., 2011). The range in the Marble Range apparent exposure ages may possibly indicate that high elevation areas were covered by cold-based non-erosive ice, which would have allowed for repeated accumulation of erratics over several glacial periods without the removal of older erratics by subsequent ice advances (Fabel et al., 2002, 2006; Sugden et al., 2005; Briner et al., 2006; Stroeven et al., 2006a, b; Corbett et al., 2013).

5.2. Implications of ^{10}Be exposure ages from the Telkwa Range for deglaciation of west-central British Columbia

The westward shift of the ice divide over central British Columbia during deglaciation was larger than described above from farther south. Stumpf et al. (2000) presented evidence for a lLGM ice divide about 100 km east of the Hazelton Mountains (Fig. 1). Margold et al. (2013b) showed that the divide shifted to a location southwest of the Hazelton Mountains before the ice-marginal meltwater channels in the Telkwa Range had been eroded and the erratic boulders deposited. At the time of channel formation, the CIS probably was restricted to the Coast Mountains and its flanks, forming one or more extensive mountain ice fields or ice caps, although its precise configuration remains unknown.

Apparent exposure ages from the summit area of the Telkwa Range (with an uncertainty-weighted mean exposure age of 10.3 ± 0.5 ka) are younger than expected, given that deglaciation of the Kitimat Trough, about 100 km to the west (Fig. 1), has been dated to 12.6–12.1 cal ka (Clague, 1985, Figs. 1 and 5). However, the derived apparent exposure ages are minima because possible boulder surface erosion and sediment and snow shielding, if incorporated in exposure age calculations, lead to older apparent exposure ages. We have argued that boulder surface erosion and sediment shielding have not significantly affected the resulting ages, but snow shielding may be important in the summit area of the Hazelton Mountains. Using data on present-day snow cover from Hudson Bay Mountain (British Columbia Ministry of Environment, Snow Station 4B03), ca 50 km NNW of our study site, we calculate that snow shielding may cause a ca 17% reduction in the production rate. This shielding results in a significant increase in the apparent exposure ages — the uncertainty-weighted mean exposure age becomes 12.4 ± 0.7 ka after this adjustment (see Supplementary Data). However, as in the case of the Marble Range, snow redistribution by wind and changes in snow cover during the Lateglacial and Holocene introduce a large uncertainty in the estimate of the snow-shielding effect. Nevertheless, the adjusted apparent exposure ages are consistent with the deglaciation chronology developed for the Kitimat-Terrace area in the Coast Mountains to the west (Clague, 1985, Figs. 1 and 5).

We recognize that the ^{10}Be exposure dating method is still in development; further refinements in ^{10}Be production rates and new insights into other factors that affect exposure ages will likely require future corrections of our ages. However, the tight clustering of three of the four ^{10}Be exposure ages strengthens our confidence in them, because exhumation or weathering would likely have affected all samples differently. We conclude that our set of apparent exposure ages from the Telkwa Range, together with the ages reported by Clague (1985) from the Kitimat-Terrace area, indicate that the mountain areas of north-central British Columbia became ice-free at about 12.5–12 ka.

5.3. Ice-sheet surface lowering at the study sites during deglaciation

The existence of ice-marginal meltwater channels at high elevations near ice accumulation areas in the Coast Mountains raises a question about the rate of ice sheet surface lowering at the time the channels formed and the dated erratics were deposited. Mannerfelt (1945, 1949) interpreted similar lateral meltwater channels incised in slopes in the mountains of Sweden to be annual features, although Holdar (1957), Mannerfelt (1960), and Sissons (1961) later questioned this interpretation. Syverson and Mickelson (2009) observed that, on average, two or three small ice-marginal channels formed annually during recent wastage of Burroughs Glacier in Alaska. Although it is not possible to calculate an exact rate of lowering of the CIS surface, we infer by analogy with present-day observations (Maag, 1969; Syverson and Mickelson, 2009) that the ice sheet surface must have lowered rapidly at the time the flights of ice-marginal meltwater channels formed in the Marble and Telkwa ranges. It follows that the CIS was greatly out of balance

with climate, both during the early stage of deglaciation documented in the Marble Range and later during melting of a spatially much reduced ice body in the Telkwa Range.

5.4. Palaeoglaciological summary and suggestions for further research

Available radiocarbon ages (Fig. 5, Table 2) indicate that the western, shelf-based margin of the CIS disappeared about 1–2 ka after the lLGM. The retreat pattern of the eastern margin of the CIS across the Interior Plateau towards the Coast Mountains has been reconstructed by Margold et al. (2013b) using meltwater erosional and depositional landforms. Apparent exposure ages from the Marble and Telkwa ranges, together with the glacial landform record, indicate that recession of the CIS was triggered by thinning and reconfiguration of the accumulation areas of the ice sheet. Whereas only restricted Lateglacial readvances have been reconstructed in the Columbia and the Rocky Mountains (Osborn and Gerloff, 1997; Menounos et al., 2009), ice persisted in the Coast Mountains in sufficient amounts to sustain readvances to near sea level in the Fraser Lowland and Howe Sound into the Younger Dryas Chronozone (12.9–11.6 cal ka (Fiedel, 2011); Friele and Clague, 2002a, b; Kovanen, 2002; Kovanen and Easterbrook, 2002; Menounos et al., 2009) and to allow erosion of meltwater channels on summit ridges below 1740 m a.s.l. in the Telkwa Range before 10.3 ± 0.5 ka (12.4 ± 0.7 ka if a correction for snow shielding is applied).

We have presented evidence for an early lowering of the surface of the CIS on the southern Interior Plateau and survival of remnant ice farther north in the Telkwa Range until the Younger Dryas Chronozone. This work, however, highlights the need for further studies, specifically on (1) the timing of ice-marginal retreat on the

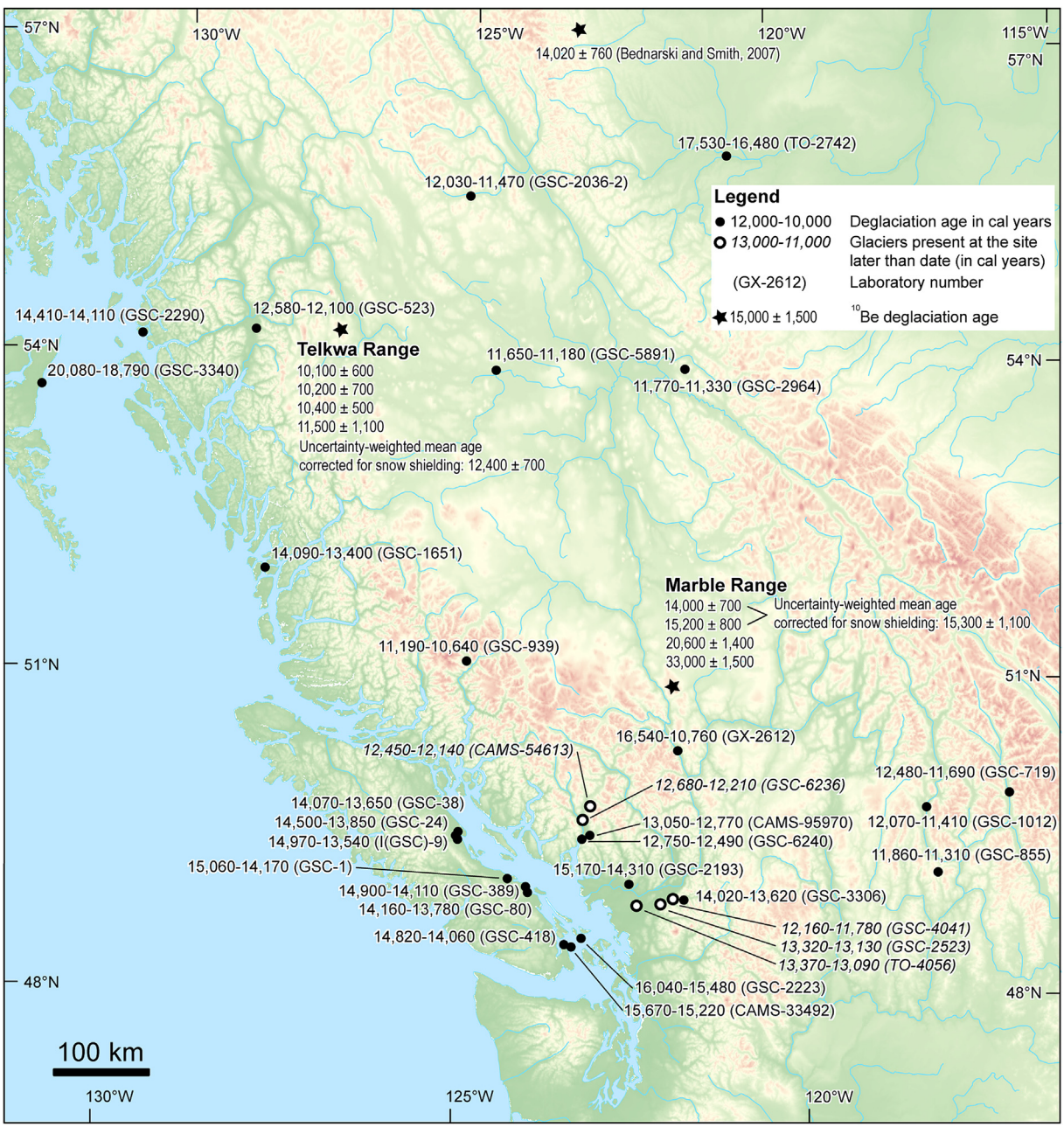

Fig. 5. Closely limiting deglaciation ages in southern and central British Columbia. See Table 2 for references.

Table 2
Selected calibrated radiocarbon ages pertaining to the deglaciation of southern and central British Columbia.

Radiocarbon Age (years)	Calibrated Age range (years)	Laboratory no.	Location Latitude	Longitude	Elevation (m a.s.l.)	Locality[a]	Dated Material	Reference
Coast								
9510 ± 160	11,190–10,640	GSC-939	51°21.0′	124°56.5′	863	Tiedemann Glacier (M)	Peat	Lowdon et al., 1971
10,370 ± 25	12,450–12,140	CAMS-54613	49°58.9′	123°00.6′	1636	Helm Glacier (M)	Wood	Unpublished
10,600 ± 110	12,750–12,490	GSC-6240	49°41.7′	123°08.4′	870	Squamish (M)	Wood	Friele and Clague, 2002a
10,790 ± 110	12,580–12,100	GSC-523	54°25′	128°31′	92	Terrace	Marine shell	Lowdon et al., 1967
10,940 ± 70	13,050–12,770	CAMS-95970	49°43.9′	123°05.3′	87	Squamish	Wood	Friele and Clague, 2002a
11,900 ± 120	14,020–13,620	GSC-3306	49°04.5′	121°41.5′	259	Chilliwack Valley	Wood	Blake, 1983
12,200 ± 160	14,500–13,850	GSC-24	49°41′	125°02′	53	Puntledge River	Wood	Dyck and Fyles, 1962
12,210 ± 330	14,090–13,400	GSC-1651	52°09′	128°06′	11	Shearwater	Marine shell	Lowdon and Blake, 1973
12,360 ± 140	14,070–13,650	GSC-38	49°41′	125°02′	53	Puntledge River	Marine shell	Dyck and Fyles, 1962
12,400 ± 200	15,060–14,170	GSC-1	ca 49°17′	124°16′		Parksville	Wood	Dyck and Fyles, 1962
12,420 ± 150	14,160–13,780	GSC-80	49°09.0′	123°58.2′	108	Nanaimo	Marine shell	Dyck and Fyles, 1963
12,500 ± 450	14,970–13,540	I(GSC)-9	49°38.7′	125°00.3′		Courtenay	Marine shell	Walton et al., 1961
12,700 ± 120	14,410–14,110	GSC-2290	54°17.0′	130°21.3′	11	Prince Rupert	Marine shell	Lowdon and Blake, 1979
12,700 ± 170	14,820–14,060	GSC-418	48°39.5′	123°26.0′	20	Patricia Bay	Marine shell	Dyck et al., 1966
12,740 ± 170	14,900–14,110	GSC-389	49°12.3′	124°00.0′	70	Wellington	Marine shell	Dyck et al., 1966
12,900 ± 170	15,170–14,310	GSC-2193	49°14.0′	122°29.6′	154	Websters Corner	Marine shell	Lowdon et al., 1977
13,100 ± 130	16,040–15,480	GSC-2223	48°43′	123°11	396	Harris Creek	Plant detritus	Alley and Chatwin, 1979
13,270 ± 60	15,670–15,220	CAMS-33492	48°38.0′	123°20.0′	−102	Saanich Inlet	Marine shell	Blais-Stevens and Clague, 2001
16,000 ± 570	20,080–18,790	GSC-3340	53°41.7′	131°52.6′	1	Cape Ball	Plant detritus	Warner et al., 1982
Interior								
9830 ± 130	11,650–11,180	GSC-5891	54°08′	124°35′	815	Fraser Lake	Peat	Plouffe, 2000
10,000 ± 90	11,770–11,330	GSC-2964	54°08.5′	121°31.5′	1215	Wells (M)	Wood	Lowdon and Blake, 1980
10,000 ± 150	11,860–11,310	GSC-855	49°14.7′	117°58.8′	1327	Sheep Lake	Peat	Lowdon and Blake, 1970
10,100 ± 90	12,030–11,470	GSC-2036-2	55°47′	125°05′	946	Omineca valley (M)	Peat	Blake, 1986
10,100 ± 150	12,070–11,410	GSC-1012	49°52.2′	118°05.2′	444	Fauquier	Wood	Lowdon and Blake, 1976
10,270 ± 190	12,480–11,690	GSC-719	49°57.0′	116°51.2′	793?	Leviathan Lake	Peat	Lowdon and Blake, 1975
11,285 ± 1000	16,540–10,760	GX-2612	50°30.1′	121°44.8′		McGillivray Creek	Bone	Ryder, 1978
13,970 ± 170[b]	17,530–16,480	TO-2742	56°10′	120°44′	ca 575	Fort St. John (IP)	Wood	Catto et al., 1996
	14,020 ± 760[c]		57°23.2′	123°17.6′	1870	Northern Rockies (M)	^{36}Cl surface exposure	Bednarski and Smith, 2007
Glacier present at site later than date								
10,370 ± 25	12,450–12,140	CAMS-54613	49°58.9′	123°00.6′	1636	Helm Glacier (M)	Wood	Unpublished
10,500 ± 100	12,680–12,210	GSC-6236	49°51.2′	123°06.7′	1020	Squamish (M)	Wood	Friele and Clague, 2002b
10,200 ± 90	12,160–11,780	GSC-4041	49°04.9′	121°50.6′	310	Chilliwack Valley	Wood	Saunders et al., 1987
11,300 ± 80	13,370–13,090	TO-4056	49°01.3′	122°25.5′	86	Aldergrove	Conifer needles	Clague et al., 1997
11,300 ± 100	13,320–13,130	GSC-2523	49°02.0′	122°01.5′	124	Cultus Lake	Wood	Lowdon and Blake, 1978

[a] M – Montane environment; IP – Interior Plains.
[b] Minimum age for retreat of Laurentide ice sheet at near its maximum limit.
[c] No stratigraphic relation with glacial sediments, but age has been interpreted to postdate maximum Laurentide glaciation. Postglacial rate of surface erosion assumed to be zero.

Interior Plateau (note the paucity of dates in Fig. 5) and (2) the history of deglaciation north of the study area in the region dominated by the ice dispersal centre over the Skeena Mountains (McCuaig and Roberts, 2002; Lakeman et al., 2008; Margold et al., 2013b). Additional dating and geomorphological studies are required to determine how CIS remnants responded to Lateglacial climate fluctuations, which thus far have only been documented on the southwest coast (Clague et al., 1997; Kovanen, 2002; Kovanen and Easterbrook, 2002; Friele and Clague, 2002a, b; Menounos et al., 2009) and in the Finlay River area (Lakeman et al., 2008).

6. Conclusions

We present and discuss ^{10}Be apparent exposure ages on erratics from two high-elevation sites in southern and central British Columbia. Granodiorite erratics on the summit ridge of the Marble Range on the western margin of the Interior Plateau in southern British Columbia yielded exposure ages of 14.0 ± 0.7, 15.2 ± 0.8, 20.6 ± 1.4 and 33.0 ± 1.5 ka. We interpret the two oldest ages as outliers with inheritance and consider the uncertainty-weighted mean exposure age of 14.5 ± 1.0 ka for the two younger erratics to be the best minimum deglaciation age of the crest of the Marble Range. A correction for snow-shielding calculated from present-day snow cover data increases the uncertainty-weighted mean exposure age of the two younger erratics to 15.3 ± 1.1 ka. The corrected age of the time of thinning of the CIS appears to immediately follow deglaciation of the Strait of Georgia to the west shortly after the lLGM. Four exposure ages from the Telkwa Range in the west-central part of the Interior Plateau are clustered around 10.3 ± 0.5 ka. Significant present-day snow cover, however, introduces large uncertainty in the apparent exposure ages from this site. A correction for snow-shielding determined from data on present-day snow cover increases the uncertainty-weighted mean exposure age of the Telkwa Range erratics to 12.4 ± 0.7 ka. We conclude that a remnant mountain ice cap persisted in the central Coast Mountains into the Younger Dryas Chronozone. Ice-marginal meltwater channels at and near the dated erratics indicate rapid lowering of the ice sheet surface during deglaciation. The CIS was clearly out of equilibrium during Lateglacial time and disappeared relatively rapidly. Important future research tasks are to further investigate the chronology of ice retreat across the Interior Plateau and the response of the CIS to Lateglacial climate fluctuations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2014.06.027.

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