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Investigating the glacial history of the northern sector of the Cordilleran Ice Sheet with cosmogenic ^{10}Be concentrations in quartz

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Abstract

Exposure durations of glacial landforms in widely separated areas of central Yukon Territory affected by the northern sector of the Cordilleran Ice Sheet (CIS) and alpine glaciers have been determined using cosmogenic ^{10}Be in quartz. The aim of our research is to test previous reconstructions of glacial history and to begin to address the paucity of chronological control for the lateral and vertical extent of the northern CIS. Chronological evidence for CIS expansion predating the Last Glacial Maximum comes from minimum surface exposure durations of c. 100 ka for two bedrock samples within the Reid glacial limit, indicating a possible marine oxygen isotope stage (OIS) 6 age for this event, and from minimum exposure durations of about 40 ka for boulders on moraines constructed by alpine glaciers on a nunatak within the McConnell glacial limit (OIS 2), indicating a possible OIS 4 age. High elevation minimum surface exposure durations within the McConnell limit indicate that some areas formerly mapped as nunataks were covered by cold-based ice prior to 30 ka. Montane glaciation in the Mackenzie Mountains, outside the McConnell glacial limit, was contemporaneous with nearby CIS advance at 17 ka, with CIS retreat by 15 ka. Deglaciation of the Tintina Trench, a major ice discharge route, was completed by 12 ka. At this time ice in an adjacent discharge route to the south was still entering higher-elevation valleys in the Pelly Mountains. A Late Glacial readvance may have peaked at ca. 10 ka in the Ogilvie Mountains. Considerable variation in ages from individual landforms, and possible complex histories, require additional cosmogenic nuclide measurements to confirm interpretations.

Key words: Surface exposure duration, Cordilleran Ice Sheet, Yukon Territory, nunataks, Reid glaciation, McConnell glaciation

1. The Cordilleran Ice Sheet

The Canadian Cordillera consists of a series of largely northwest-trending mountain ranges with intervening large plateaus and lowland areas (Fig. 1). Several of the mountain ranges, notably the Coast and St. Elias Mountains, currently support ice fields, and valley- and cirque glaciers. On several occasions during the Pleistocene, the Cordilleran Ice Sheet (CIS) nucleated in these mountain regions, grew outward from high mountain valleys and coalesced to form a sheet of ice up to about 2 km thick over the plateau areas of British Columbia and Yukon Territory (Booth et al., 2003; Fig. 1).

Southern Yukon Territory was repeatedly covered by the northern sector of the CIS, producing an irregular, digitate, horseshoe-shaped glacial limit on the plateau area between the St. Elias and Mackenzie Mountains (Jackson et al., 1991). Based on geomorphic expression and stratigraphic evidence, this glaciated area has been subdivided into surfaces of three successively younger glaciations – the oldest and most extensive pre-Reid glaciation, the intermediate Reid glaciation, and the youngest and most restricted McConnell glaciation (Fig. 2; Bostock, 1966; Vernon and Hughes, 1966; Campbell, 1967; Muller, 1967). Although the maximum areal extents of the McConnell and Reid glaciations are established (Duk-Rodkin, 1999), their vertical limits are not well constrained, and furthermore pre-Reid limits are poorly known. The times of Reid and pre-Reid glaciations are also poorly constrained due to a paucity of absolute ages. Work by Froese et al. (2000) has shown that several ice sheet glaciations in the Yukon are older than the Reid glaciation and not just the two events (Klaza and Nansen) originally defined by Bostock (1966) . Reid glaciation was originally assigned to marine oxygen isotope stage (OIS) 8 (Huscroft et al., 2004), based on its relation to the Sheep Creek tephra and its inferred stratigraphic relation to dated basalts. However, a recent re-evaluation of the age of Sheep Creek and Old Crow tephras (Ward et al., 2008; Westgate et al., 2008) now indicates that the Reid glaciation in central Yukon probably dates to OIS 6.

Cosmogenic nuclide concentrations in erratic boulders in the Aishihik Lake area of southwest Yukon, however, indicate an OIS 4 (Early Wisconsin) age for the penultimate glaciation in that area (Ward et al., 2007). The McConnell glaciation is firmly dated to OIS 2 (Late Wisconsin). Radiocarbon ages from wood and fossils underlying McConnell till indicate that the McConnell glaciation began after 29,600±300 ^{14}C yr BP (Matthews et al., 1990), but glaciers did not advance into major valleys before 26,350±280 ^{14}C yr BP (Jackson and Harington, 1991), and a fully developed CIS did not exist until after 23,900±1140 ^{14}C yr BP (Lowdon and Blake, 1981). Published radiocarbon ages indicate that the St. Elias lobe of the CIS was in retreat by 13,660±180 ^{14}C yr BP (Rampton, 1971) and the Selwyn lobe by 12,590±120 ^{14}C yr BP (Ward, 1989) (Fig. 2).

The paucity of absolute age control for Yukon glacial events and the disparity in age between what had previously been thought to be the same penultimate glacial surface point to the need for critical re-mapping combined with robust chronologic control, not just for areas affected by different ice discharge routes of the CIS, but also within the same ice discharge route (Ward et al., 2007). Here we present 43 new cosmogenic ^{10}Be surface exposure durations of samples from several areas within central Yukon Territory and western Northwest Territories (Fig. 2). We undertook this study to test previous reconstructions of glacial history and to begin to address the paucity of chronological control on ice limits at the northern margin of the CIS. Our site selection was guided by existing literature and new geomorphological mapping (Kleman et al., in press).

2. Methods

Cosmogenic ^{10}Be concentrations in quartz were used to determine the exposure duration of bedrock, boulder and cobble samples collected in 2006 from flat surfaces using hammer and chisel. A reliable exposure duration for a rock surface in a formerly glaciated setting requires that glacial erosion removes >3 m of rock, leaving behind a surface with virtually no ^{10}Be. Ideally, the surface to be dated will have been minimally eroded since formation. If the sampled surface has been eroded subsequent to exposure, the calculated exposure duration will underestimate the age of the event because erosion physically removes cosmogenic nuclides and brings to the surface material that had been partially shielded during its period of exposure (see Gosse and Phillips, 2001 and Bierman and Nichols, 2004 for comprehensive reviews of the cosmogenic nuclide surface exposure dating method).

Sample locations were recorded using a hand-held GPS (Garmin GPSMAP60CSx). Sample elevation, measured using the barometric altimeter of the GPS unit, was checked on 1:50,000-scale topographic maps. Geometric shielding corrections were calculated (Dunne et al., 1999) for each sample to account for partial shielding of samples by local and distant topography. The thickness of the individual samples was recorded because the production of terrestrial cosmogenic nuclides varies exponentially with depth and therefore the production rate for any sample must be integrated over the sample thickness that is processed for accelerator mass spectrometry (Table 1). Quartz separation and purification was carried out in the Department of Geographical and Earth Sciences at the University of Glasgow. Beryllium extraction was done in the Glasgow Cosmogenic Isotope Laboratories using standard methods (Kohl and Nishiizumi, 1992; Child et al., 2000). Beryllium isotope ratios in the samples and six procedural ^{10}Be blanks were measured at the Scottish Universities Environmental Research Centre Accelerator Mass Spectrometry Laboratory (Freeman et al., 2004; Maden et al., 2007). The procedural blanks contained <6 x 10^4 atoms, representing <2% of the total atoms in the samples. Table 1 shows sample details and exposure durations calculated with the CRONUS-Earth exposure age calculator v2.2 (http://hess.ess.washington.edu/math; Balco et al., 2008). We use the Lm scaling scheme for our reported exposure durations, however, it should be noted that for the measured samples all schemes (Lm, Du, Li, De; Balco et al., 2008) yield statistically indistinguishable results at 1 sigma. Calculated exposure durations are given with 1 sigma systematic uncertainty, which includes the analytical measurement uncertainty and the uncertainty in the reference cosmogenic nuclide production rate of 4.39±0.37 atom/g(SiO_2)/yr (http://hess.ess.washington.edu/math). Calculated exposure durations are minima because they have not been corrected for surface erosion, isostatic rebound, and snow or vegetation shielding, because we do not have independent estimates of any of these factors over the exposure duration.

3. Sample sites and results

In the following sections we deal with each sampled area separately, progressing approximately from oldest (Reid glaciation) to youngest (McConnell glaciation). Calculated cosmogenic nuclide exposure durations are detailed in Table 1 and arranged by sample region.

3.1. Stewart River

We collected two bedrock samples from a large crag-and-tail landform on a mapped Reid surface (Figs. 2 and 3). Sample YK45 was taken from a weathered summit (1240 m a.s.l.) approximately 3.5 km north of Stewart Crossing, and sample YK46 is from a bedrock outcrop 200 m lower and 2.4 km east of the summit sample. Unconsolidated sediment interpreted to be till is present between the two sites, indicating that ice covered the hill in the past. The bedrock outcrops yielded minimum exposure durations of 91.4±8.4 ka and 102.0±9.4 ka. The shorter exposure duration for the summit sample, although statistically indistinguishable, may indicate a slightly higher erosion rate, as reflected by the more weathered appearance of the bedrock at this location.

3.2. Glenlyon Range

During the Pleistocene, the western margin of the Glenlyon Range (Figs. 2 and 4) was flanked by the CIS, which extended up many valleys in the range but left much of the uplands ice-free (Campbell, 1967; Ward and Jackson, 1992, 2000). Based on descriptions (Campbell, 1967), surficial geology maps (Ward and Jackson, 1992, Fig. 2) and aerial photographs in Jackson et al. (1991, Fig. 6), we located two moraines at the head of Lyon Creek (Figs. 4 and 5). The higher moraine (ca. 1501 m a.s.l.) has been interpreted by Jackson et al. (1991) as recording the limit of an alpine glacier in Lyon Creek during the McConnell glaciation; the lower moraine (ca. 1492 m a.s.l.) may record an older, Reid-age glacier (moraine E of Ward and Jackson, 1992).

The higher moraine is flat with a few undulating ridges and a sharp down-valley margin (Fig. 5). No large high-standing boulders are present on this feature. We collected three samples from the tops of boulders protruding 20 cm from the surface of the moraine near its down-valley margin (YK39-41). The lower moraine lies a few hundred metres down-valley of the upper moraine and is a more subdued feature. We collected two samples from the tops of two boulders protruding 20 cm above its surface (YK36-37). We also processed a cobble (10 x 8 x 8 cm) partly embedded in the surface sediments of this moraine (YK38). Three additional samples were collected from very competent rounded, coarse-grained granite boulders on a prominent ridge 5 km southwest of the sampled moraines and about 300 m above the floor of Lyon Creek valley (YK42-44). We interpret the ridge to be a lateral moraine of the CIS in the Tintina Trench (Figs. 2 and 4). Samples YK42 and YK43 came from large (1 m x 1 m x 1 m) boulders, whereas YK44 was collected from a smaller, but otherwise similar boulder 10 cm above of the moraine surface.

Two samples from the upper moraine yielded surface exposure durations of 13.7±1.2 ka and 13.2±1.2 ka, confirming the McConnell age postulated by Jackson et al. (1991) and Ward and Jackson (1992). A third sample (YK39) collected from this moraine yielded a surface exposure duration of 5.5±0.5 ka. The calculated surface exposure durations for the outer, more subdued moraine are 37.0±3.4 ka, 43.6±3.9 ka, and 30.6±2.8 ka. The ^{10}Be concentrations in the samples from the CIS lateral moraine yield a large range of exposure durations – the two large boulders yielded 14.3±1.3 ka and 21.3±2.0 ka, whereas the small boulder gave 117.4±11.0 ka.

3.3. Anvil Range

The Anvil Range, located east of the Glenlyon Range, was similarly influenced by CIS ice extending up its valleys, interpreted by Jackson et al. (1991) to have rendered large upland areas as nunataks at the peak of the McConnell glaciation. We collected samples from two moraines located on the flank of one of the mapped nunataks (Figs. 6 and 7). The moraines were noted by Jackson et al. (1991, Fig. 9); they concluded that they formed at the margin of the CIS. The lower southern moraine has a clearly defined ridge and a steep ice-contact slope (Fig. 7). The two moraines may have been deposited by ice from different sources flowing into the low col between the nunatak and higher ground to the west (Figs. 2, 6 and 7). The southern moraine was deposited by ice flowing northward into the Anvil Range from the Tintina Trench, whereas the higher northern moraine may be related to ice flowing southwest past the Anvil Range. We infer that the moraines are approximately the same age and are related to two bodies of ice that were part of one confluent ice drainage system.

We collected three samples from the southern (lower) moraine – two small granitic boulders (YK27 and 29) and a cobble (YK28) – and three samples from the northern (higher) moraine – larger, more resistant quartz monzonite boulders (YK33-34) and cobble (YK35). The sampled boulders on the northern moraine appear largely unweathered and 'ring' when struck with a hammer. However, they are surrounded by coarse-grained grus and the moraine appears to be degraded.

The calculated exposure durations of the competent boulders and cobble on the more degraded, northern moraine increase with increasing size from 7.4±0.7 ka for the cobble (<0.2 m high) to 9.5±0.9 ka for the mid-size boulder (<0.4 m high), and to 16.2±1.5 ka for the largest boulder (<0.5 m high). The boulders of the southern moraine yielded exposure durations of 10.2±0.9 ka and 12.7±1.2 ka; the cobble gave an exposure duration of 40.1±3.6 ka.

We also collected two small erratics (YK31-32, 15 x 15 x 10 cm) and a sample of bedrock (YK30) from near the summit of the hill just east of, and about 130 m above, the moraines. The erratics are granodiorite cobbles that were wedged in cracks in the local fractured phyllite bedrock. The erratics clearly indicate that this hill was overridden by ice some time in the past. A string of boulders sourced at the north end of the hill extends to the south along the flank of the hill, indicating ice flow from north to south.

The cobbles from near the summit of the hill yielded statistically indistinguishable minimum surface exposure durations of 27.6±2.5 ka and 29.5±2.7 ka indicating that the summit of this hill became exposed prior to ca. 30 ka. The nearby bedrock yielded, however, unexpectedly, a shorter exposure duration of 17.0±1.6 ka. This disparity could be due to (i) differential erosion, equivalent to ~38 cm more erosion of the bedrock than the cobbles since exposure, (ii) a cosmogenic nuclide inheritance in the cobbles equivalent to roughly 10 ka of exposure, or (iii) exhumation of the cobbles and the bedrock from beneath a layer of till.

3.4. Ross River region

The Pelly Mountains were influenced by thin, slow-flowing ice located between two major discharge routes towards the northwest (Figs. 2 and 8). There is a lack of evidence of basal sliding in the uplands of the Pelly Mountains compared to adjacent areas (Fig. 8; Kleman et al., in press). Similar areas devoid of ice-flow traces in Sweden and Norway ("relict areas") are interpreted to have been regions of cold-based ice within the Fennoscandian Ice Sheet that protected the underlying landscape from glacial modification (Kleman and Stroeven, 1997; Kleman and Hättestrand, 1999; Fabel et al., 2002; Stroeven et al., 2002; Fjellanger et al., 2006; Goehring et al., 2008). To test the applicability of this hypothesis to the CIS, we collected three bedrock samples from weathered surfaces and tors exposed along ridges within the Pelly Mountains (Fig. 9) and one bedrock sample from the highest point (1950 m a.s.l.) of a smaller 'relict' area north of the Tintina Trench (YK1, YK2, YK5 and YK7; Fig. 9). We also took a sample from a large (1.2 m x 0.8 m x 1.0 m) granitic erratic lying near one of the bedrock samples at an elevation of 1936 m a.s.l. (YK6). Unfortunately, the erratic contained insufficient quartz for a measurement to be made, although it does indicate that this surface has been covered by ice in the past. The apparent surface exposure durations for the bedrock samples range from 20.8±1.9 ka to 29.1±2.7 ka.

Features associated with the presence of warm-based ice dominate the landscape below the high ridges and plateaux of the Pelly Mountains. To determine the time of valley glaciation in this region, we collected three samples from boulders on a lateral moraine in the St. Cyr Range ~260 m above the local valley floor and sloping down 2-5° into the Pelly Mountains (Fig. 9, lower right panel). The slope of the moraine indicates deposition at the margin of a glacier flowing northwesterly into the valley (Fig. 8). The calculated surface exposure durations for these three boulders (YK23-25) are statistically indistinguishable at 1 sigma, with a mean of 12.2±1.1 ka and are interpreted as the stabilisation age of this lateral moraine during deglaciation.

3.5. Mackenzie Mountains

The history of glaciation in the Mackenzie Mountains is based on alpine moraines and Laurentide Ice Sheet (LIS) moraines on the eastern edge of the range (Fig. 2; Duk-Rodkin et al., 1996). We collected the top of a large granitic erratic (YK9) to the east of Keele Peak, within the source area of the CIS near the topographic divide separating the watersheds of the Yukon River to the west and Mackenzie River to the east (Fig. 2, box 5). We furthermore sampled a granitic erratic (YK16) lying on a limestone bench ~600 m above the Twitya River, 80 km northeast of YK9 and 50 km west of the mapped maximum LIS limit in the Keele River drainage (Figs. 2 and 10). We use this sample to date the furthest northeast extent of CIS ice sourced in the Selwyn Range around Keele Peak. The calculated minimum exposure duration of YK16 is 18.3±1.7 ka, and YK9 yielded a minimum exposure duration of 15.0±1.4 ka.

To determine the age of montane glaciation in the Mackenzie Mountains, we sampled six boulders from two closely spaced moraines impounding a small lake at the head of a tributary of Trout Creek (Fig. 10A). Three samples from the outer moraine (YK13-15) yielded consistent exposure histories with a mean duration of 16.5±1.6 ka. Three boulders from the inner moraine (YK10-12) gave exposure durations of 15.5±1.5, 19.3±1.8 and 21.5±1.9 ka. The youngest of the three exposure durations from the inner moraine is statistically indistinguishable from the mean duration derived for the outer moraine, perhaps indicating that the older two ages reflect inherited nuclide concentrations. Alternatively, the age spread could be due to rapid moraine degradation processes with apparent moraine stability since ca. 16 ka.

3.6. Tintina Trench deglaciation

Even during the maximum of the McConnell glaciation, ice flow was controlled by underlying topography – ice streamed along major valleys such as the Tintina Trench (Figs. 2 and 9), separated around areas that were either cold-based or nunataks, rejoined, and finally terminated along a digitate margin on the Yukon Plateau (Jackson et al., 1991). Ice-flow directions are provided by glacially streamlined features such as crag-and-tails and whalebacks (Fig. 8; Jackson et al., 1991; Kleman et al., in press).

To determine the time of final deglaciation of the Tintina Trench, we collected two samples from striated bedrock on a whaleback along the northern shore of Little Salmon Lake (YK21-22; Fig. 2, box 7), a bedrock sample from a streamlined granite outcrop in the Tintina Trench northeast of Ross River (YK8; Fig. 9), and three samples from erratics ~300 m above the trench floor on the top of a streamlined limestone hill between Ross River and Faro (YK17-19; Fig. 9). The three bedrock samples yielded consistent exposure durations with an average of 12.6±1.2 ka. In contrast, the three erratics yielded a larger spread in minimum exposure durations – 11.7±1.2 ka for a granite boulder, and 14.5±1.3 ka and 19.7±1.8 ka for a granite cobble and a vein-quartz cobble, respectively. Although the exposure duration of the youngest erratic (YK17) is equivalent to the bedrock exposure durations, the sampled surface had lost 3 cm due to exfoliation. Correcting for this erosion yields an exposure duration of 12.2±1.2 ka, indicating that this streamlined hill became ice-free at the same time as the bedrock samples and that the apparently older erratic cobbles likely contain inherited nuclides.

3.7. Ogilvie Mountains

The Ogilvie Mountains were last covered by a series of Late Pleistocene coalescent valley glaciers that did not merge with the CIS (Fig. 2). Two samples were collected from small boulders that barely protruded above the surface of the southern margin of the North Fork Moraine adjacent to the Dempster Highway at North Fork Pass (YK47-48; Fig. 11). Duk-Rodkin (1999) interpreted this moraine to be a McConnell-age feature. The minimum surface exposure durations of the two samples are 9.8±1.1 ka and 9.5±0.9 ka.

4. Discussion

The ^{10}Be data are summarised in Figure 12. The considerable spread in exposure durations reflects the large geographic area covered and the different objectives of our study. These objectives included testing a number of hypothesised glacial histories for specific areas affected by the CIS and alpine glaciers (Jackson et al., 1991; Duk-Rodkin et al., 1996; Beierle, 2002) and assessing the suitability of different types of samples for addressing specific chronological problems.

4.1. Reid glaciation

Two of the oldest exposure durations come from bedrock samples collected at two sites on a large, glacially streamlined feature within the Reid glacial limit near Stewart Crossing. The exposure durations place this glaciation either in OIS 5 or OIS 6. They are younger than the currently accepted OIS 6 age for the Reid glaciation (Ward et al., 2008; Westgate et al., 2008). Perhaps the bedrock was exhumed from beneath a layer of Reid glaciation till, although it seems unlikely that till was deposited on the sharp summit ridge where the samples were collected. Alternatively, the bedrock may have suffered some erosion following the Reid glaciation. If, for example, Reid ice removed all inherited cosmogenic nuclide concentrations and the sampled bedrock became exposed at the OIS 6 termination (~130 ka), the nuclide concentration in the two summit samples record steady-state bedrock erosion rates of 2.3±0.2 mm.ka^{-1} (YK46) and 3.4±0.3 mm.ka^{-1} (YK45) since exposure. This hypothesis indicates that the CIS during the OIS 4 Gladstone glaciation (Ward et al., 2007) did not reach this site, or did not erode sufficient bedrock to remove inherited cosmogenic nuclides.

4.2. McConnell glaciation

4.2.1. Constraints on vertical extent: nunataks or not?

Reconstructions of the Late Wisconsin CIS indicate that some of the highest mountains protruded through the ice sheet as nunataks (Clague, 1989; Duk-Rodkin, 1999). However, it is also possible that some of these high mountains may have been covered by cold-based ice, and thus available glacial evidence does not constrain the maximum height of the CIS (Fig. 1). Evidence to support or refute the presence of nunataks plays a major role in delimiting the upper limit of the CIS for ice sheet modeling and estimating the total volume of the CIS.

Erratics collected at ~1780 m a.s.l. from a mapped nunatak in the Anvil Range (YK31-32, Fig. 12) indicate that this high ground was overridden by the CIS in the past. If the cosmogenic nuclide concentrations in the erratics are entirely due to a single exposure event, their deposition occurred during an ice advance older than ca. 30 ka. Similar cosmogenic nuclide concentrations were obtained from weathered bedrock samples at 1680 to 1950 m a.s.l. in the Ross River area (YK1, 2, 5, 7; Fig. 12). Together, the apparent exposure durations indicate that there was a glacial advance that covered these areas and subsequently retreated to below the sampled elevations prior to ca. 30 ka.

Although the surfaces in the Ross River area south of the Tintina Trench may have been ice covered during the McConnell glaciation (Jackson et al., 1991; Duk-Rodkin, 1999), we did not find erratics, and the sampled surfaces appear glacially unmodified, with castellated tors and blockfields (Fig. 9). The ice height in the Anvil Range to the west was >1780 m a.s.l., and CIS surface reconstructions between postulated nunataks indicate increasing ice elevation towards the east, with a slope of 0.2° (Jackson et al., 1991). Hence, we would expect the high elevation sites sampled in the Ross River area to have been ice covered at the same time. Ice cover is confirmed by the erratic found at 1936 m a.s.l. near YK7 (Fig. 9). The geomorphology of the sampled surfaces precludes the simple interpretation that the exposure durations of the bedrock samples provide the age of their emergence from under erosive McConnell glaciation ice during decay of the northern CIS. The castellated tors and blockfields we sampled are unlikely to have survived overriding warm-based ice or to have developed since McConnell glaciation (cf. McConnell, 1906). The measured cosmogenic nuclide concentrations in the samples likely reflect a complex history, with burial of the previously exposed surfaces under non-erosive, cold-based ice, leading to cosmogenic nuclide inheritance, and therefore older than expected ages, and re-exposure and erosion after deglaciation. Measurement of a shorter-lived cosmogenic radionuclide, such as ^{26}Al, might reveal some of this complexity (Fabel et al., 2002; Stroeven et al., 2002), but at present the data cannot resolve between a complex and a simple exposure history.

The apparent surface exposure duration of bedrock sample YK30, associated with the two Anvil Range erratics, 17.0±1.6 ka, cannot be interpreted as a deglaciation age because it would require >3 m of ridge erosion under probable cold-based conditions at a site with >800 m of relief to the valley bottom. Furthermore, a deglaciation age interpretation would only be valid if the nearby erratics, whose apparent exposure durations are consistent with each other and are older than the bedrock sample by about 10 ka, were deposited with similar inherited nuclide concentrations. We cannot discount the possibility that these erratics were sourced and transported from bedrock areas with complex exposure histories similar to that of the bedrock surface sampled in the Ross River area. However, given differences in source area nuclide concentrations and variable glacial erosion, transport and deposition of clasts, it seems unlikely that the erratics would have been deposited with statistically identical inherited nuclide concentrations. Another possible explanation is that the difference in cosmogenic nuclide concentrations between the erratics and the bedrock reflects different surface erosion rates. The maximum steady state erosion rates derived from the cosmogenic nuclide concentrations in the bedrock (YK30) and the older erratic (YK32) are 39±3 mm/ka and 22±2 mm/ka, respectively. These rates are high, equivalent to erosional losses of ca. 66 cm from the bedrock and ca. 37 cm from the erratic in 17 ka. The erratics did not appear to be remnant cores of much larger boulders and there was no evidence of material eroded from the erratics at their base. It is possible that material was lost from the bedrock by fracturing, but this would still require a minimum recent loss of ca. 38 cm from the bedrock surface and no erosion of the erratics. A final possible explanation is that the erratics are remnants of a till that was soliflucted off the slope, exposing the bedrock surface. Estimates of the thickness of till that would have to be removed to explain the surface exposure durations require assumptions about the till density, depositional age and the rate of till removal. For a maximum estimate we assume deposition during the Reid glaciation (ca. 140 ka), a till density of 2.2 g/cm^3, and constant erosion to the present. With these assumptions, the required till exhumation depths for the erratic (YK32) and bedrock (YK30) are 3.9 m and 6.7 m, respectively. For a minimum estimate, we assume the same till density, but an age of till deposition equal to the apparent exposure age of the oldest erratic (ca. 29 ka) and removal of the till over the past few hundred years. In this case, the minimum thickness of till removed is ca. 40 cm. We conclude that none of the hypotheses for explaining the ^{10}Be concentrations in samples YK30-32 is satisfactory; the only certain statement we can make at this time is that the minimum exposure duration for the sampled bedrock surface is 17.0±1.6 ka.

Apparent exposure durations for the two moraines in the Anvil Range (YK27-29 and YK33-35) have a large spread (7.4 – 16.2 ka). The consistent trend of increasing age with increasing boulder height on the northern moraine, together with the degraded nature of the moraine, indicates that the distribution in exposure duration is due to moraine degradation (Duk-Rodkin et al., 1996; Putkonen and Swanson, 2003) and thus that the longest exposure duration of 16.2±1.5 ka may be nearest the true age of the deposit. The interpretation of the southern moraine is complicated by the fact that the cobble sample has a minimum exposure duration of 40.1±3.6 ka and clearly has a prior exposure history compared to the boulder samples from the same moraine. Degradation of the moraine means that the boulder exposure durations only provide a minimum age for the deposit. The results are consistent with a thickening of the CIS around 17 ka, either at the peak of the McConnell glaciation or during a readvance during deglaciation.

The lateral moraine constructed by Cordilleran ice flowing northeast up the valley of Lyon Creek, Glenlyon Range, may be the same age as the upper of the two moraines deposited by the alpine glacier farther up the valley (ca. 14 ka, see below, section 4.3.1.), but the age constraint is poor. The spread in ages of the samples from the lateral moraine (YK42-44) may be best explained as resulting from cosmogenic nuclide inheritance in the oldest, or perhaps the two oldest, boulders. It is surprising, however, that there is no discernable difference in weathering of the sample with an apparent exposure duration of 117 ka and the two that are much younger. Assuming inheritance is present, the shortest exposure duration is closest to the true age of the lateral moraine. This interpretation favours a late McConnell age for the lateral moraine, immediately prior to the final deglaciation in this region (see below, section 4.2.2.). Another interpretation of the disparate exposure durations for samples from the lateral moraine would be to only regard the longest exposure duration as erroneous due to inheritance, and explain the difference in exposure duration of the other two samples (14.3±1.3 and 21.3±2.0 ka) as arising from moraine degradation. In this scenario, the minimum age of the moraine would be 21.3±2.0 ka. A maximum advance of the CIS to ca. 1500 m a.s.l. along this flank of the Glenlyon Range (cf. Jackson et al., 1991, Fig. 5) at the peak of the McConnell Glaciation would then confirm this range to have been a large nunatak region.

4.2.2. Constraints on lateral extent

The samples from the Mackenzie Mountains provide some insight into the eastern margin of the CIS. We found no landforms or erratics to indicate an extension of the CIS in the Backbone Ranges beyond our YK16 sample, consistent with the maximum CIS ice limit mapped by Duk-Rodkin and Hughes (1992). The minimum exposure duration of erratic YK16 (18.3±1.7 ka) may represent a CIS advance broadly coincident with the advance of the LIS during the Katherine Creek phase ca. 19 ka (Duk-Rodkin et al., 1996) and with possible thickening of the CIS and deposition of lateral moraines in the Anvil Range. The eastern margin of the CIS retreated back to near the crest of the Selwyn Mountains by ca. 15 ka (YK9).

Final deglaciation of the Tintina Trench occurred at ca. 12 ka. Although the distance between the samples collected at Little Salmon Lake and near Ross River is 100 km, there is no difference in the apparent deglaciation ages. Although consideration must be given to the uncertainties in the dating technique, the near-coincident ages suggests rapid final deglaciation. Ice may have still been present at an elevation of 1360 m a.s.l. in the St. Cyr Range to the south at 12.2±1.1 ka (YK23-25), highlighting the need for caution in attempts to extrapolate chronological information from one ice discharge route to others.

4.3. Alpine glaciation

4.3.1. Above former ice sheet levels: on nunataks

Disparate exposure durations from the same moraine are also a feature of the data from the Glenlyon Range. The spread in ages may be due to an exhumation of boulders as the moraine degraded to its present subdued form. If exhumation is the cause of the disparate ages, the oldest apparent exposure age would be closest to the true age of the deposit (Putkonen and Swanson, 2003). Furthermore, the two datasets from the alpine moraines (YK36-38 and YK39-41) suggest that the older moraines have associated larger spreads in ages, which would be an expected consequence of moraine degradation (Duk-Rodkin et al., 1996). Finally, although the upper of the two Glenlyon alpine moraines has an apparent formation age of ca. 14 ka, the lower moraine is clearly not associated with the McConnell glaciation.

The outer of the two alpine moraines at the head of Lyon Creek (moraine E of Ward and Jackson, 1992) must predate the McConnell glaciation. If the spread in exposure durations of the samples from this moraine is due to moraine degradation, the oldest exposure duration (43.6±3.9 ka) is closest to the age of the deposit. This age would still be a minimum because the oldest boulder could itself have been exhumed and because boulder surface erosion has not been taken into account in the age calculation. The exposure duration range from the outer Lyon Creek moraine is consistent with the results from the Mountain River moraine in the Mackenzie Mountains, which has a minimum age of 32 ka (Duk-Rodkin et al., 1996). Both moraines may date to the early Wisconsin (55-50 ka) Gladstone glaciation of Ward et al. (2007).

4.3.2. Beyond the limit of ice sheet glaciation

Our data indicates that OIS 2 alpine glaciers in the Mackenzie Mountains advanced prior to

17-22 ka, depending on whether the dataset is regarded as skewed by inheritance or by moraine degradation. The timing is coincident with the Gayna River glacial advance 75 km northwest of our site, dated at 17-22 ka using cosmogenic ^{36}Cl (Duk-Rodkin et al., 1996).

Finally, our data from North Fork Pass in the Ogilvie Mountains support a Late Glacial readvance in this area, as proposed by Beierle (2002). Wood fragments in basal silt and gravel from a lake inside the glacial limit and 3 km north of our samples yielded a calibrated radiocarbon age of 10,500±240 cal yr BP (Beierle, 2002). The radiocarbon age is only slightly older than our two moraine boulder minimum exposure durations of 9.8±1.1 ka and 9.5±0.9 ka. Together the available data indicate formation of the moraine during the Late Glacial rather than at the peak of the McConnell Glaciation. Beierle (2002) suggested that the Chapman Lake moraine to the north, which Duk-Rodkin (1999) mapped as a Reid-age deposit, may be of McConnell age. This interpretation must be tested with further dating because it has been disputed by Lacelle et al. (2007), who propose a pre-Late Wisconsin age for a massive ground ice body near Chapman Lake.

4.4 Suitability of samples for glacial reconstruction

The new ^{10}Be data from the northern sector of the CIS allow us to reflect on the suitability of different sample types for surface exposure dating in the Yukon. The samples collected in the Tintina Trench clearly show the effect of inheritance in this region. The bedrock samples yielded exposure durations of ca. 12 ka, in contrast to exposure durations of up to 19 ka for the erratics. Nevertheless, erratics and moraines remain the preferred sampling targets because they more clearly relate to both upper and lateral glacier margins than eroded bedrock. In cases where all or most of the moraine samples yield similar exposure durations, they provide important information on moraine stabilisation or deposition age. In two cases where boulders and cobbles were sampled from the same features, cobbles came out older. We also sampled cobbles in the absence of large boulders, but to minimise the effect of moraine degradation on exposure duration and to minimise the chance of inheritance, it would be advantageous to sample large, tall, boulders if they are available. Resolution of some of the uncertainties in the exposure durations presented in this paper requires that more samples be analysed from the same landforms. For the case where there is inheritance in bedrock samples, measurement of a second cosmogenic nuclide with a different half-life in the same mineral phase may provide further information about potential complex histories.

5. Conclusion

Cosmogenic ^{10}Be minimum surface exposure durations were obtained for 43 samples of bedrock, erratics, and moraine boulders in eight areas affected by the northern sector of the

Cordilleran Ice Sheet (CIS) and alpine glaciers. The surface exposure durations for samples from some sites have considerable spread, particularly those obtained from boulders and cobbles from individual moraines. Bedrock surface exposure ages of samples collected outside the McConnell limit, but within the Reid glacial limit near Stewart Crossing indicate pre-OIS 4 glaciation and are not at odds with an OIS 6 age for the Reid glaciation. An alpine glacier advance in the Glenlyon Range possibly is older than 40 ka. Data from high-elevation sites in the Anvil Range and in the Pelly Mountains south of the Tintina Trench in the Ross River area indicate that these areas were ice covered before the McConnell glaciation and probably became deglaciated prior to 30 ka. Moraines below a nunatak in the Anvil Range have previously been interpreted as marking the upper limit of the CIS during the McConnell glaciation, but they may also date to an early stage of McConnell deglaciation. Data from the Mackenzie Mountains indicates that the CIS achieved its maximum extent there ca. 18 ka. Montane glaciation in an area of the Mackenzie Mountains that was not affected by ice-sheet glaciation reached a maximum extent prior to 17-22 ka, broadly contemporaneously with (i) the maximum of the CIS in this region, (ii) with thickening of the CIS in the Anvil Range, (iii) with the time of the Gayna River glacial advance, and (iv) with the advance of the LIS during the Katherine Creek phase. The eastern margin of the CIS retreated back to its source area in the Selwyn Mountains by ca. 15 ka. Alpine glaciers in the Glenlyon Range retreated from their maximum position at ca. 14 ka. Deglaciation of the Tintina Trench was complete by 12 ka at Little Salmon Lake and Ross River. At this time, glacier ice appears to have still been present in the St. Cyr Range to the south. Finally, minimum surface exposure durations support radiocarbon evidence for Late Glacial ice in the Ogilvie Mountains.

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Table captions

Table 1: Cosmogenic ^{10}Be data and minimum surface exposure duration.

Figure captions

Figure 1: Stylised east-west topographic profiles at different stages of Cordilleran glaciation. LIS denotes Laurentide Ice Sheet.

Figure 2: Map showing the location of glacial limits in northwestern Canada and flow directions of major ice discharge routes. Numbered boxes show locations of sample sites. (Modified from Duk-Rodkin et al., 1996; Duk-Rodkin, 1999; Ward et al., 2007.)

Figure 3: Map showing the location of Stewart River bedrock samples (Fig. 2, box 1).

Figure 4: Map showing the location of Glenlyon Range samples (Fig. 2, box 2). Defined (solid lines) and approximate (dashed lines) glacial limits and capital letter labels are from Ward and Jackson (1992, Fig. 2). See also Figure 5.

Figure 5: Moraines at the head of Lyon Creek (dashed white lines) sampled in this study. The upper moraine impounds a small lake. Ward and Jackson (1992) interpreted this upper moraine (their moraine D) as representing an alpine glacial advance during the McConnell glaciation; they interpreted the outermost moraine (their moraine E) as older, potentially a Reid glaciation moraine.

Figure 6: Map showing the location of Anvil Range samples (Fig. 2, box 3). The solid lines mark moraine crests. See also Figure 7.

Figure 7: View of Anvil Range moraines (dashed white lines), showing bedrock and erratic sample locations. This area is shown in an oblique air photo in Jackson et al. (1991, Fig. 9).

Figure 8: Map of ice flow traces and major ice discharge routes for southeastern Yukon Territory (adapted from Kleman et al., in press). Symbols show sample locations.

Figure 9: Map showing locations of Ross River (YK1, 2, 5, 7, 23, 24, 25) and Tintina Trench

(YK8, 17, 18, 19) samples (Fig. 2, box 4). The photograph shows the location of sample YK1, which was collected from a typical tor in the Pelly Mountains.

Figure 10: Map showing the location of an erratic (YK16) and moraine boulder samples (YK10-15) in the Backbone Ranges, Mackenzie Mountains (Fig. 2, box 6).

Figure 11: Map showing the location of moraine boulder samples in the Ogilvie Mountains (Fig. 2, box 8). Late Pleistocene glacial limit based on Duk-Rodkin (1999).

Figure 12: ^{10}Be apparent exposure ages for the different regions of this study. Sample numbers are the same as those denoted YK in the text, figures, and in Table 1. Filled symbols denote alpine glaciation, open symbols Cordilleran ice sheet glaciation.

Table 1. Cosmogenic ^{10}Be data and minimum surface exposure durations

Sample location	Material[(a)] and dimensions (LxWxH m)	Sample no.	Latitude (degrees)	Longitude (degrees)	Altitude (m asl)	Thickness factor[(b)]	Topographic shielding factor [(c)]	[^{10}Be] (10^5 at g^{-1})[(d)]	^{10}Be minimum exposure duration (kyr)[(e)]
Stewart River									
Stewart River	B	YK45	63.413	136.685	1240	0.975(3)	1	14.07 ± 0.43	91.4 ± 8.4
Stewart River	B	YK46	63.415	136.733	1033	0.992(1)	0.999	13.30 ± 0.41	102.0 ± 9.4
Glen Lyon Range									
Glenlyon Ra.	M (0.7x0.7x0.2)	YK36	62.463	134.620	1490	0.967(4)	0.997	6.94 ± 0.24	37.0 ± 3.4
Glenlyon Ra.	M (1.0x0.7x0.2)	YK37	62.463	134.620	1492	0.975(3)	0.997	8.25 ± 0.24	43.6 ± 3.9
Glenlyon Ra.	M (cobble)	YK38	62.463	134.619	1496	0.935(8)	0.997	5.59 ± 0.19	30.6 ± 2.8
Glenlyon Ra.	M (1.2x1.2x0.3)	YK39	62.466	134.624	1492	0.967(4)	0.994	1.03 ± 0.04	5.5 ± 0.5
Glenlyon Ra.	M (0.6x0.4x0.2)	YK40	62.466	134.626	1497	0.967(4)	0.994	2.60 ± 0.08	13.7 ± 1.2
Glenlyon Ra.	M (0.5x0.5x0.3)	YK41	62.466	134.628	1501	0.935(8)	0.994	2.43 ± 0.08	13.2 ± 1.2
Glenlyon Ra.	M (1.8x1.3x1.2)	YK42	62.421	134.686	1463	0.983(2)	0.999	2.68 ± 0.08	14.3 ± 1.3
Glenlyon Ra.	M (0.9x0.8x0.8)	YK43	62.422	134.686	1464	0.983(2)	0.999	3.99 ± 0.14	21.3 ± 2.0
Glenlyon Ra.	M (0.6x0.4x0.2)	YK44	62.422	134.685	1458	0.983(2)	0.999	21.43 ± 0.73	117.4 ± 11.0
Anvil Range									
Anvil Ra.	M (1.3x1.0x0.2)	YK27	62.528	133.714	1648	0.975(3)	0.999	2.75 ± 0.10	12.7 ± 1.2
Anvil Ra.	M (cobble)	YK28	62.528	133.713	1650	0.967(4)	0.999	8.55 ± 0.25	40.1 ± 3.6
Anvil Ra.	M (0.6x0.4x0.1)	YK29	62.527	133.710	1657	0.992(1)	0.999	2.25 ± 0.08	10.2 ± 0.9
Anvil Ra.	B	YK30	62.530	133.702	1795	0.983(2)	0.997	4.15 ± 0.15	17.0 ± 1.6
Anvil Ra.	E (cobble)	YK31	62.529	133.701	1782	0.935(8)	0.990	6.26 ± 0.22	27.6 ± 2.5
Anvil Ra.	E (cobble)	YK32	62.529	133.701	1783	0.967(4)	0.986	6.88 ± 0.22	29.5 ± 2.7
Anvil Ra.	M (0.5x0.5x0.2)	YK33	62.533	133.715	1663	0.967(4)	1	3.51 ± 0.10	16.2 ± 1.5
Anvil Ra.	M (0.5x0.5x0.2)	YK34	62.533	133.717	1666	0.983(2)	1	2.10 ± 0.07	9.5 ± 0.9
Anvil Ra.	M (cobble)	YK35	62.533	133.716	1665	0.967(4)	1	1.60 ± 0.06	7.4 ± 0.7
Ross River									
Pelly Mts. tor	B	YK01	61.376	132.963	1686	0.975(3)	1	6.42 ± 0.23	29.1 ± 2.7
Pelly Mts. tor	B	YK02	61.377	132.959	1688	0.975(3)	1	5.42 ± 0.17	24.5 ± 2.2
Pelly Mts.	B	YK05	61.819	132.543	1838	0.975(3)	1	5.17 ± 0.19	20.8 ± 1.9
Anvil Ra.	B	YK07	62.252	131.934	1950	0.959(5)	1	7.06 ± 0.22	26.5 ± 2.4
Pelly Mts. lateral	M (0.5x0.4x0.5)	YK23	61.367	132.034	1381	0.967(4)	0.985	2.05 ± 0.09	12.1 ± 1.1
Pelly Mts. lateral	M (0.5x0.4x0.1)	YK24	61.364	132.036	1386	0.975(3)	0.984	1.92 ± 0.07	11.2 ± 1.0
Pelly Mts. lateral	M (0.3x0.2x0.1	YK25	61.364	132.037	1388	0.975(3)	0.981	2.27 ± 0.08	13.3 ± 1.2
Mackenzie Mountains									
Keele Peak	E (4.0x3.0x1.5)	YK09	63.428	130.048	1571	0.975(3)	1	3.05 ± 0.11	15.0 ± 1.4
Mackenzie Mts.	M (0.8x0.8x0.5)	YK10	64.299	128.171	1438	0.967(4)	0.994	3.50 ± 0.13	19.3 ± 1.8
Mackenzie Mts.	M (1.0x0.8x0.3)	YK11	64.298	128.175	1416	0.959(5)	0.994	2.75 ± 0.11	15.5 ± 1.5
Mackenzie Mts.	M (1.1x0.9x0.3)	YK12	64.300	128.166	1437	0.983(2)	0.990	3.94 ± 0.89	21.5 ± 1.9
Mackenzie Mts.	M (1.5x1.0x0.6)	YK13	64.301	128.170	1417	0.967(4)	0.990	2.91 ± 0.09	16.4 ± 1.5
Mackenzie Mts.	M (1.1x0.8x0.4)	YK14	64.302	128.168	1422	0.975(3)	0.990	2.97 ± 0.11	16.5 ± 1.5
Mackenzie Mts.	M (1.0x0.7x0.2)	YK15	64.302	128.164	1438	0.967(4)	0.990	3.02 ± 0.15	16.7 ± 1.7
Mackenzie Mts.	E (0.5x0.4x0.2)	YK16	64.100	128.811	1389	0.975(3)	0.993	3.21 ± 0.11	18.3 ± 1.7
Selwyn Lobe deglaciation									
Tintina Trench	B	YK08	62.139	131.992	1184	0.975(3)	1	1.90 ± 0.09	12.8 ± 1.2
Tintina Trench	E (0.3x0.2x0.2)	YK17	62.026	132.735	1003	0.975(3)	0.999	1.49 ± 0.07	11.7 ± 1.2
Tintina Trench	E (cobble)	YK18	62.026	132.736	1001	0.951(6)	0.998	1.78 ± 0.06	14.5 ± 1.3
Tintina Trench	E (cobble)	YK19	62.026	132.736	1001	0.959(5)	0.999	2.44 ± 0.09	19.7 ± 1.8
Little Salmon La.	B	YK21	62.192	134.894	680	0.975(3)	0.992	1.19 ± 0.04	12.5 ± 1.1
Little Salmon La.	B	YK22	62.192	134.893	679	0.983(2)	0.992	1.18 ± 0.04	12.3 ± 1.1
Ogilvie Mountains									
Ogilvie Mts.	M (0.4x0.3x0.1)	YK47	64.565	138.246	1307	0.975(3)	0.998	1.62 ± 0.12	9.8 ± 1.1
Ogilvie Mts.	M (0.3x0.3x0.1)	YK48	64.565	138.246	1307	0.967(4)	0.998	1.57 ± 0.06	9.5 ± 0.9

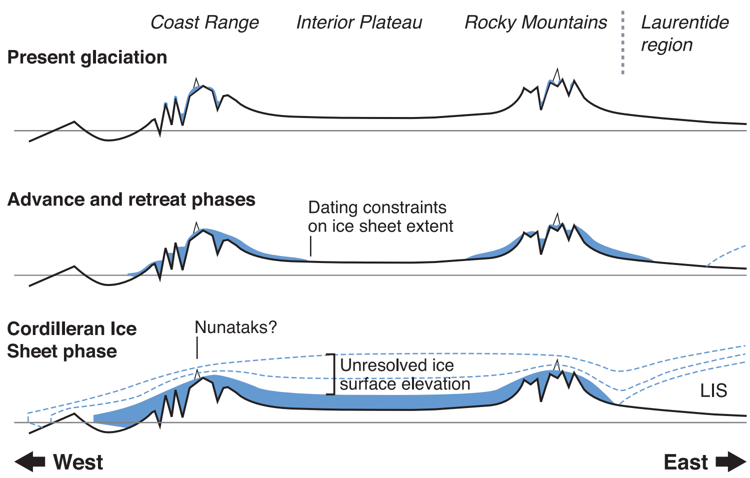
[a] B- bedrock, E- erratic, M- moraine boulder and/or cobble. LxWxH is LengthxWidthxHeight with Height measured above the surface. Cobbles were lying on the surface and were completely processed. Cobble thickness is given in the thickness scaling column.

[b] Sample thickness values are provided in brackets and are in cm

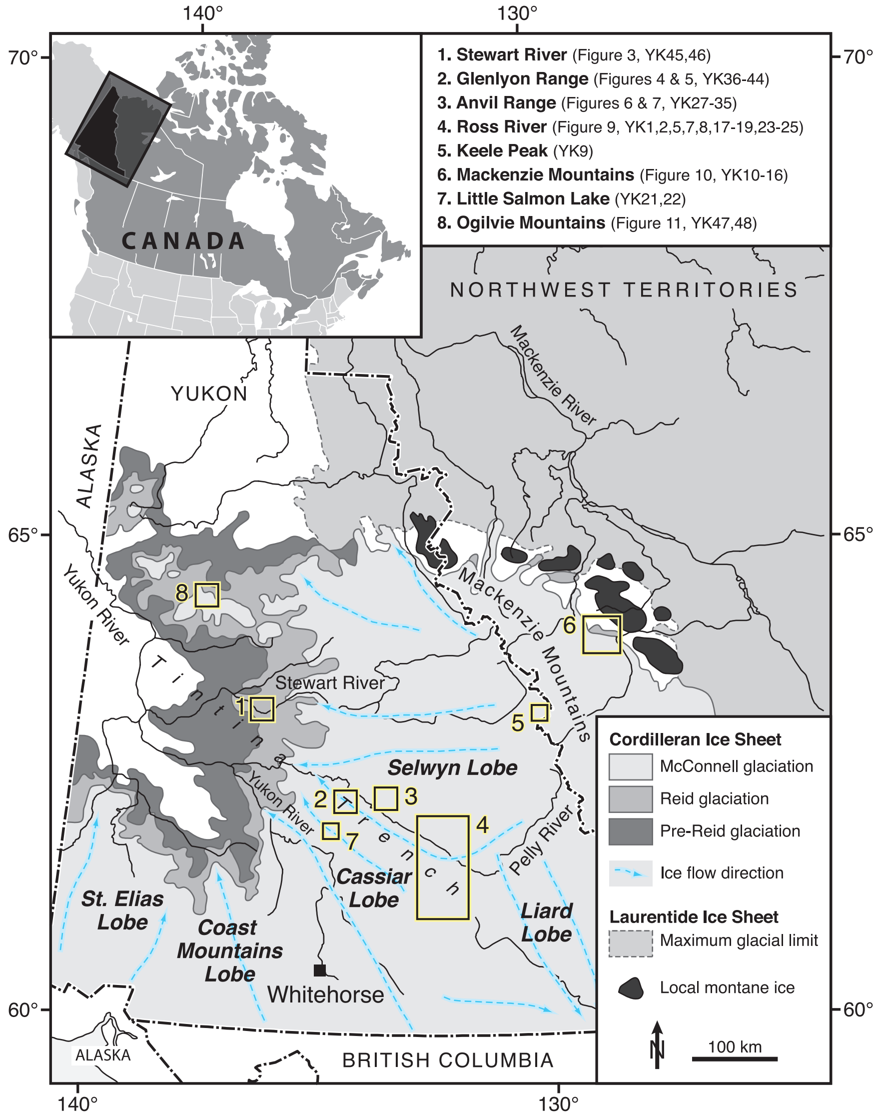
[c] Calculated according to Dunne et al. (1999)

[d] Data are normalised to NIST SRM 4325 using $^{10}Be/^{9}Be = 3.06 \times 10^{-11}$.

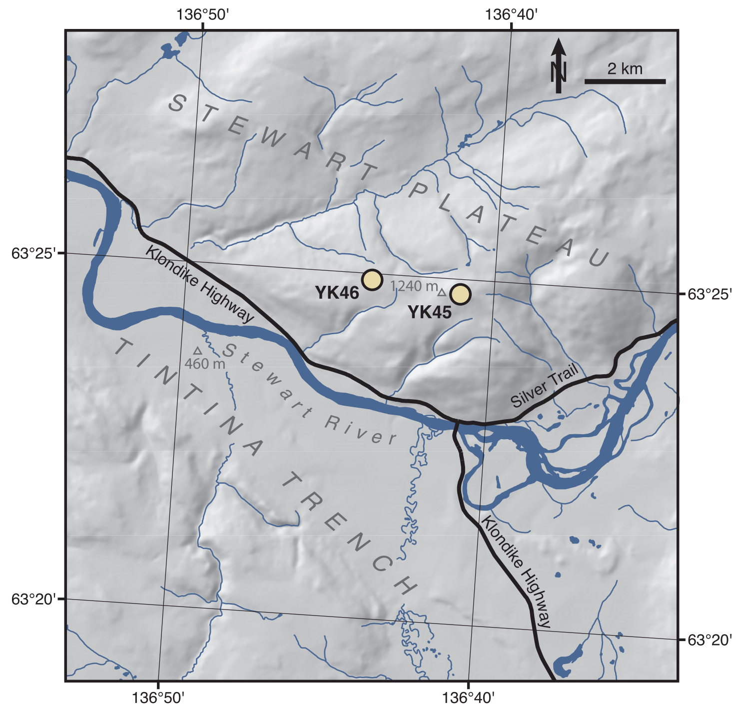
[e] Ages are calculated using the Lm scaling scheme in the CRONUS-Earth online exposure age calculator (version 2.2)

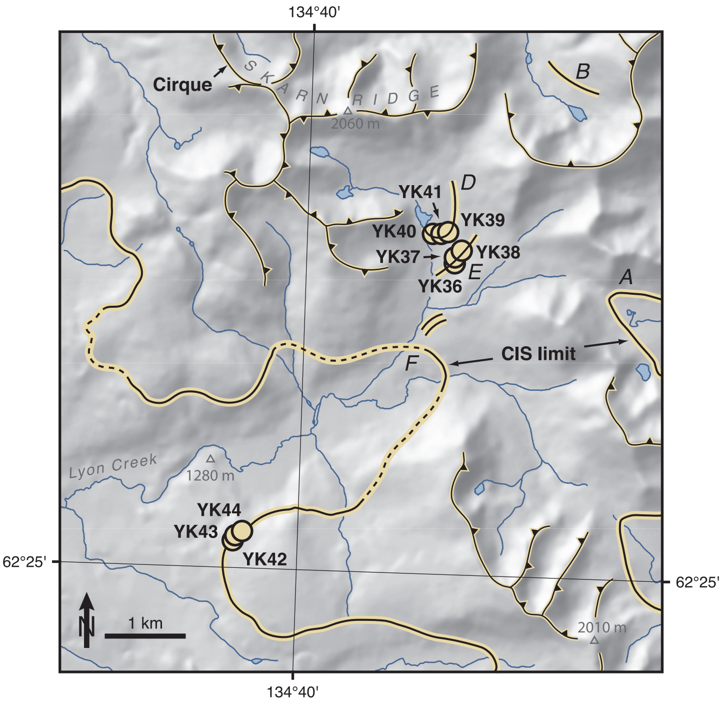


Coast Range
Interior Plateau
Rocky Mountains
Laurentide region
Present glaciation
Advance and retreat phases
Dating constraints on ice sheet extent
Cordilleran Ice Sheet phase
Nunataks?
Unresolved ice surface elevation
LIS
West
East

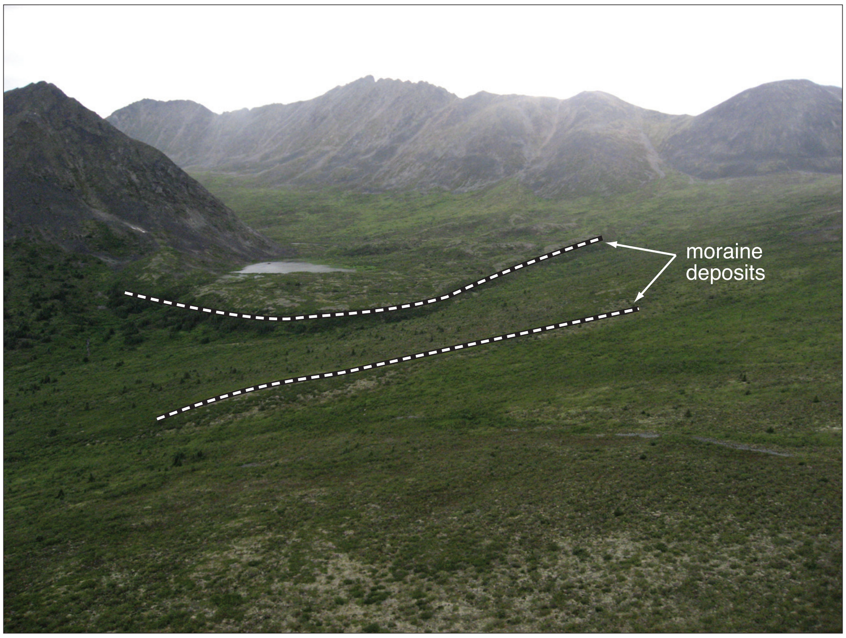


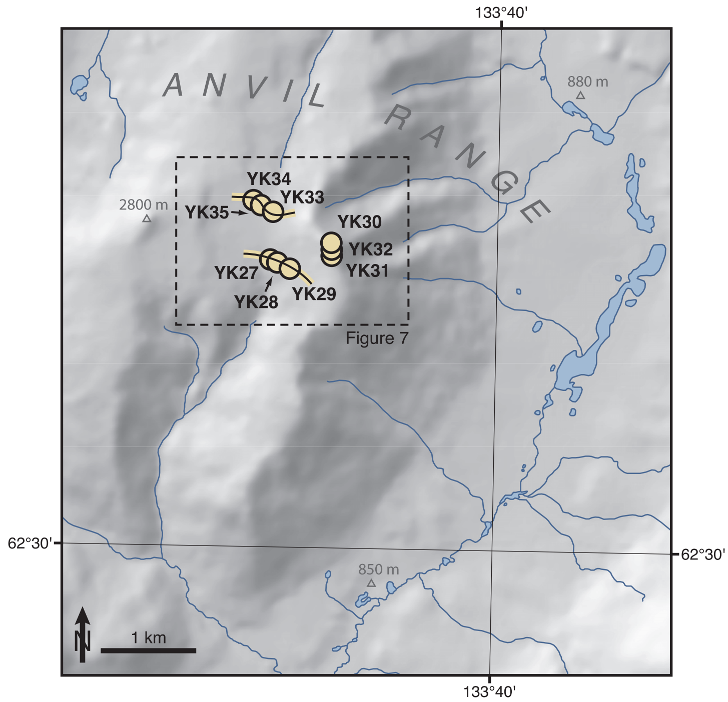
140°
130°
70°
65°
60°
CANADA
1. Stewart River (Figure 3, YK45,46)
2. Glenlyon Range (Figures 4 & 5, YK36-44)
3. Anvil Range (Figures 6 & 7, YK27-35)
4. Ross River (Figure 9, YK1,2,5,7,8,17-19,23-25)
5. Keele Peak (YK9)
6. Mackenzie Mountains (Figure 10, YK10-16)
7. Little Salmon Lake (YK21,22)
8. Ogilvie Mountains (Figure 11, YK47,48)
NORTHWEST TERRITORIES
Mackenzie River
YUKON
ALASKA
Yukon River
Mackenzie Mountains
Tintina Trench
Stewart River
Selwyn Lobe
Yukon River
Pelly River
Cassiar Lobe
Liard Lobe
St. Elias Lobe
Coast Mountains Lobe
Whitehorse
ALASKA
BRITISH COLUMBIA
Cordilleran Ice Sheet
McConnell glaciation
Reid glaciation
Pre-Reid glaciation
Ice flow direction
Laurentide Ice Sheet
Maximum glacial limit
Local montane ice
N
100 km


136°50'
136°40'
2 km
N
STEWART PLATEAU
63°25'
Klondike Highway
YK46
1240 m
YK45
TINTINA TRENCH
460 m
Stewart River
Silver Trail
Klondike Highway
63°20'
136°50'
136°40'

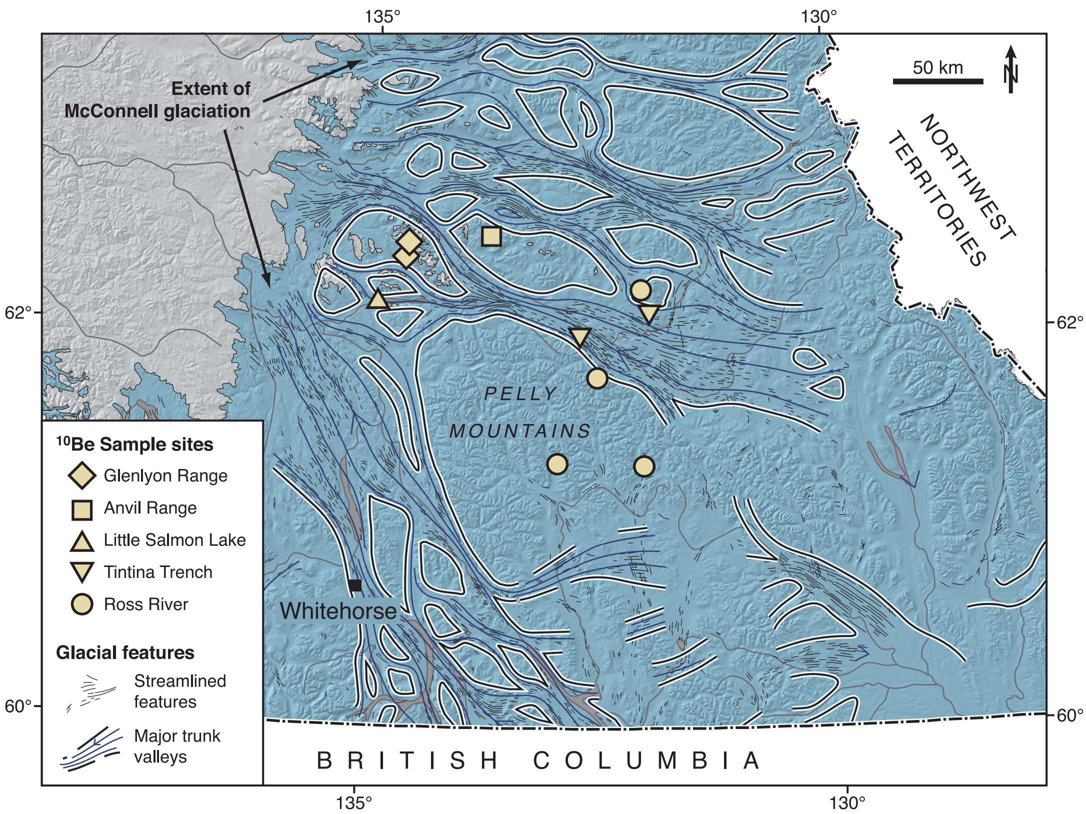


134°40'
Cirque
SKARN RIDGE
2060 m
B
D
YK41
YK40
YK39
YK37
YK38
E
YK36
A
CIS limit
F
Lyon Creek
1280 m
YK44
YK43
YK42
62°25'
62°25'
N
1 km
2010 m
134°40'


moraine
deposits

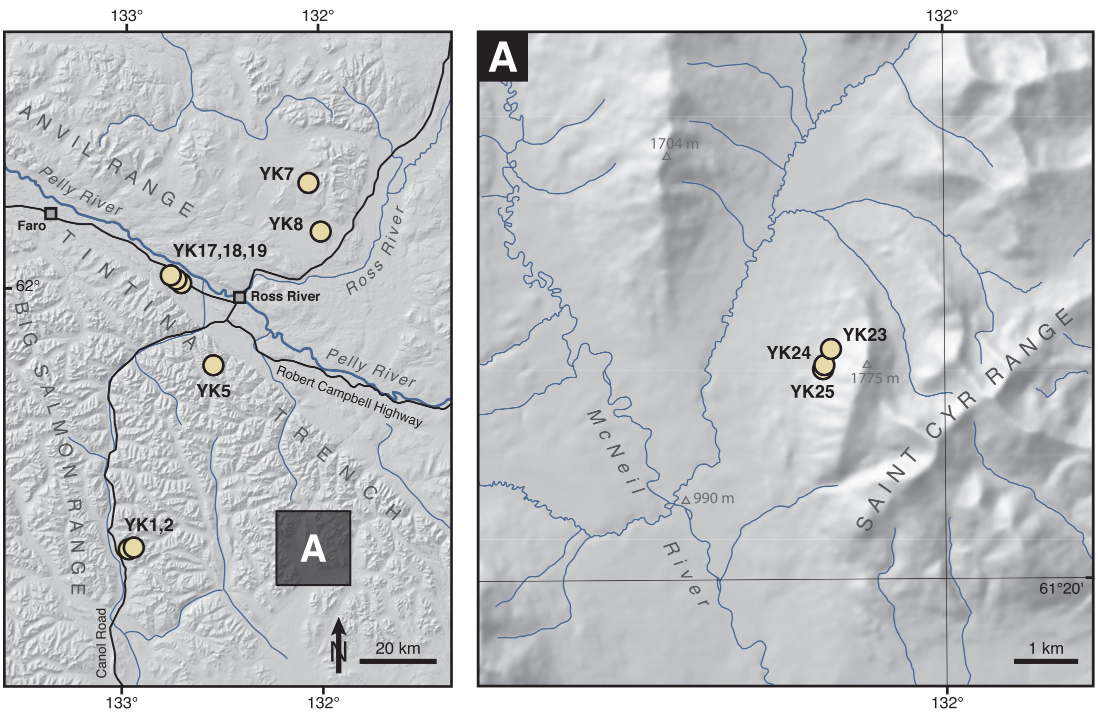

133°40'
A N V I L
R A N G E
880 m
2800 m
YK34
YK33
YK35
YK30
YK32
YK31
YK27
YK28
YK29
Figure 7
62°30'
62°30'
850 m
N
1 km
133°40'

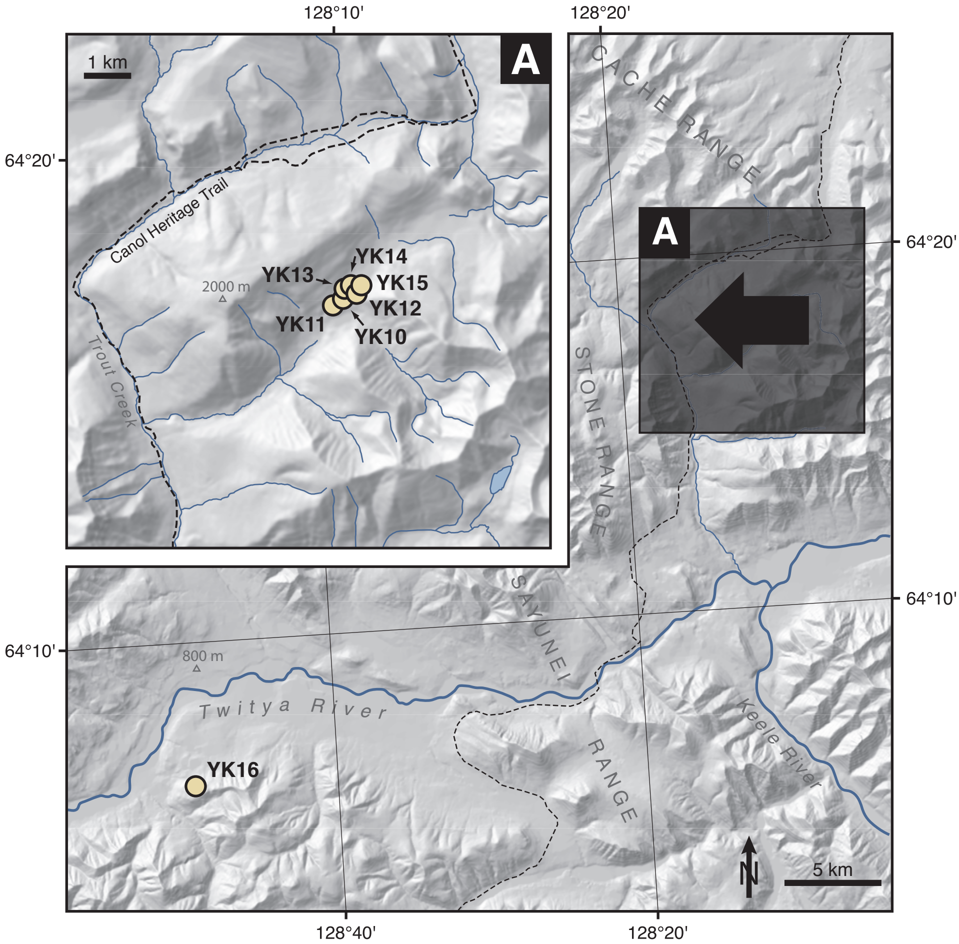

YK27
YK28
YK29
YK34
YK35
YK33
YK30, YK31, YK32
S
N



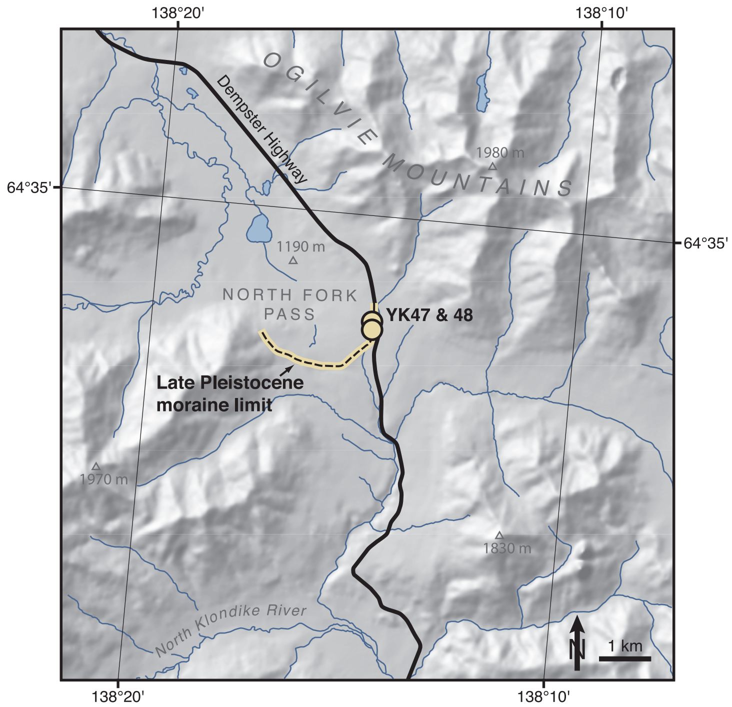
135°
130°
50 km
N
Extent of
McConnell glaciation
NORTHWEST
TERRITORIES
62°
62°
PELLY
MOUNTAINS
Whitehorse
60°
60°
BRITISH COLUMBIA
135°
130°
10Be Sample sites
Glenlyon Range
Anvil Range
Little Salmon Lake
Tintina Trench
Ross River
Glacial features
Streamlined
features
Major trunk
valleys


YK1

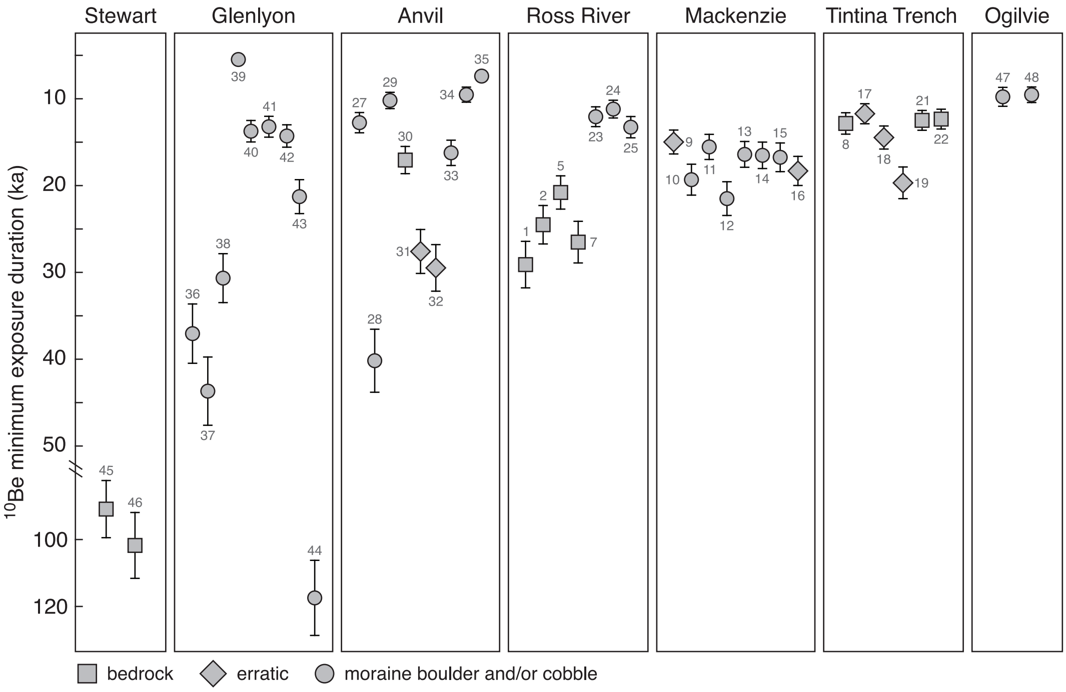

133°
132°
ANVIL RANGE
Pelly River
Faro
YK7
YK8
YK17,18,19
Ross River
Ross River
62°
TINTINA
BIG SALMON RANGE
YK5
Pelly River
Robert Campbell Highway
TRENCH
YK1,2
A
Canol Road
N
20 km
133°
132°
A
132°
1704 m
YK24
YK23
1775 m
YK25
McNeil River
990 m
SAINT CYR RANGE
61°20'
1 km
132°



128°10'
128°20'
A
1 km
64°20'
Canol Heritage Trail
YK14
YK13
YK15
2000 m
YK12
YK11
YK10
Trout Creek
CACHE RANGE
A
64°20'
STONE RANGE
SAYUNEI RANGE
64°10'
64°10'
800 m
Twitya River
Keele River
YK16
N
5 km
128°40'
128°20'



138°20'
138°10'
OGILVIE MOUNTAINS
Dempster Highway
1980 m
64°35'
64°35'
1190 m
NORTH FORK
PASS
YK47 & 48
Late Pleistocene
moraine limit
1970 m
1830 m
North Klondike River
N
1 km
138°20'
138°10'


Stewart
Glenlyon
Anvil
Ross River
Mackenzie
Tintina Trench
Ogilvie
^{10}Be minimum exposure duration (ka)
10
20
30
40
50
100
120
45
46
39
41
40
42
43
38
36
37
44
27
29
30
34
35
33
31
32
28
24
23
25
5
2
1
7
9
10
11
12
13
14
15
16
17
8
18
19
21
22
47
48
bedrock
erratic
moraine boulder and/or cobble