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Directly dating post-glacial Greenlandic land-surface emergence at high resolution using *in situ*
 ^{10}Be

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Abstract

Postglacial emergence curves are used to infer mantle rheology, delimit ice extent, and test models of the solid Earth response to changing loads. Such curves are rarely produced by direct dating of land emergence; rather, most rely on the presence of radiocarbon-datable organic material and inferences made between the age of sedimentary deposits and landforms indicative of former sea level. Here, we demonstrate a new approach, ^{10}Be dating, to determine rates of post-glacial land emergence in two different settings. In southern Greenland (Narsarsuaq/Igaliku), we date directly the exposure, as relative sea level fell, of gravel beaches and rocky outcrops allowing determination of rapid, post-Younger Dryas emergence. In western Greenland (Kangerlussuaq), we constrain Holocene isostatic response by dating the sequential stripping of terrace sediment driven by land-surface uplift, relative sea-level fall, and resulting fluvial incision. The technique we employ provides high temporal and elevation resolution important for quantifying rapid emergence immediately after deglaciation as well as less rapid uplift during the middle Holocene. ^{10}Be -constrained emergence curves can improve knowledge of relative sea-level change by dating land emergence along rocky coasts, at elevations and locations where radiocarbon-datable sediments are not present, and without the lag time needed for organic material to accumulate.

Keywords: uplift; isostasy; glacier; ice sheet; emergence; beach; cosmogenic; dating

Introduction

When ice sheets and glaciers melt at the end of glacial periods, sea-level changes in a globally complex pattern, responding both to differences in the distribution of water between ice sheets and the ocean and the isostatic response of land surfaces depressed by the mass of overlying ice (Peltier, 2004). Quantifying relative sea-level rise is important for topics as disparate as parameterizing solid Earth rheology (Roy and Peltier, 2015), the size and shape of ice sheets (Lecavalier et al., 2014; Simpson et al., 2009), and the spatial and temporal response of the linked cryosphere/ocean system to changes in past and future climate (Dutton et al., 2015).

In formerly glaciated areas, there is generally land-surface emergence (relative sea-level fall) during and after deglaciation due to net isostatic rebound. In areas outside the ice margin, there is generally land-surface submergence (relative sea-level rise) due to rising eustatic sea level (increasing ocean water volume). In some places, patterns of relative sea-level change are complex during deglaciation, with periods of both emergence and submergence as both glacial isostatic adjustment and increasing ocean water volume from ice-sheet melting interact dynamically over time (Clark et al., 1978). Around the world, a variety of different field sampling and geochronologic approaches have been used to constrain post-glacial, relative sea-level change over time in formerly glaciated regions. However, with few exceptions (Briner et al., 2006; Gosse et al., 1998; Mauz et al., 2015), relative sea-level curves rely on radiocarbon (^{14}C) analysis of organic material, both marine and terrestrially sourced, for temporal control.

Here, we demonstrate a different approach to dating post-glacial emergence. As a proof of concept, we analyzed cosmogenic ^{10}Be , produced *in situ* by the interaction of cosmic rays with quartz (Lal and Peters, 1967), to generate two post-glacial emergence curves. We chose a pair of sites in Greenland with very different geomorphic settings and histories and collected samples from landforms exposed both directly (Narsarsuaq/Igaliku, south Greenland) and indirectly (Kangerlussuaq, west Greenland) as relative sea level fell during and after deglaciation. The method we use here does not require ^{14}C -datable material and thus can potentially be applied anywhere quartz-bearing rock crops out along coastlines.

Background

Quantifying relative sea-level histories (and thus the magnitude and timing of post-glacial emergence) requires knowledge of relative sea level as a function of time. Emergence curves (local relative sea-level histories) are created by dating paleo-shoreline features and measuring their elevation. Uncertainties in such histories include both imprecision and inaccuracy of ages used to determine the timing of sea-level change as well as geologic inferences needed to tie such chronologic information to past sea levels.

Approaches for defining post-glacial emergence histories

Most commonly, organic macrofossils, often marine bivalves, are radiocarbon dated to establish emergence curves. These fossils are typically found in shallow marine deposits into which landforms indicative of sea level, such as marine terraces (bench-like erosional features), have been cut into the sediment by waves (Ten Brink, 1974). Associating sea-level-indicative landforms (wave cut terraces and beaches) with deeper water deposits in which the dated bivalves were deposited (Briner et al., 2006; Retelle et al., 1989; Washburn, 1962) introduces

paleo sea-level elevation ambiguity; some studies e.g., Storms et al. (2012) and Ten Brink (1974) suggest up to 15 m of uncertainty in associating a radiocarbon age with a paleo sea level, the elevation of the correlative shoreline. Surface material on beach ridges, such as wood, bones of marine mammals, or bivalve shells can also be dated (Forman et al., 2004), but the time between the death of the tree or animal and its deposition on the beach is uncertain, as is the effect of storm reworking of beaches and of datable material (Tamura, 2012). More recently, articulated juvenile bivalves have been dated on raised beaches in order to avoid issues with reworking of older shells (Long et al., 2012).

Emergence curves have been constructed by radiocarbon dating organic matter extracted from sediment cores collected from lakes at different elevations above sea level. Sediment in these lakes, termed “isolation basins”, can be analyzed to determine when the lake basins rose above sea level (salt to freshwater transition) using diagnostic microfauna (Bennike et al., 2002; Briner et al., 2010; Retelle et al., 1989). Isolation basins have the potential to provide a more coherent record of sea level change than other radiocarbon-based approaches (Bennike et al., 2011; Long et al., 2009), but results can be affected by storm surges and tsunami events, which can deposit marine material far above average high water level (Long et al., 2011). There are limitations to the isolation basin approach. Many areas of the arctic have few lakes, lakes that are separated by many kilometers, or lakes only at elevations not appropriate for establishing emergence curves.

Limitations of organic radiocarbon-based chronologies

Radiocarbon dating of organic material has revolutionized the understanding of sea-level change since the last glacial maximum (Stuiver, 1969) but as with all dating techniques, there are methodological constraints that limit its applicability, precision, and accuracy. Starting in the 1950s, radiocarbon was measured by decay counting and typical dates had statistical uncertainties (imprecisions) of a century or more (Taylor et al., 1992). Since the 1990s, most radiocarbon has been measured by accelerator mass spectrometry (AMS) and statistical uncertainties of many such measurements are on the order of only a few decades (Scott et al., 2016). However, radiocarbon measurements need to be calibrated to account for changing concentrations of radiocarbon in the atmosphere and ocean over time (Stuiver and Reimer, 1993); this calibration can increase the uncertainty of even the most precisely measured ages substantially (to $\gg 100$ yrs), particularly between 10 and 12 ka (Reimer et al., 2013) and at other times when the calibration curve flattens (initial ^{14}C incorporated by organisms is decreasing with time). The resulting multiple age intercepts for one measured radiocarbon concentration during the latest Pleistocene mean that many post-glacial emergence curves are imprecise during this period of rapid ice melting and glacier retreat.

Radiocarbon dating of marine organisms can be biased (high or low) by the assumed correction to radiocarbon ages for inclusion of old carbon dissolved in sea water metabolized by those organisms. This marine reservoir effect averages +400 years in the modern global surface ocean (Stuiver and Braziunas, 1993) but it can vary through space as well as over time at a given location, with particularly large offsets (in excess of 1,000 yr) often inferred for the high latitude North Atlantic during deglaciation (Koester et al., 2017; Stern and Lisiecki, 2013; Waelbroeck et al., 2001). Thus, corrections for the reservoir effect affect both the accuracy and precision of radiocarbon age estimates.

Although numerous radiocarbon-based emergence curves have been constructed in formerly glaciated high latitudes (Andrews, 1987; Forman et al., 2004; Lecavalier et al., 2014), there are places and times where current methods do not work or do not work well because radiocarbon-datable material is unavailable. For example, terrestrial organic material often is not present in sparsely vegetated, scoured bedrock terrains such as those found along the coasts of many high-latitude landmasses. High energy, bedrock-dominated coastlines may have never had or may not preserve fine-grained shallow marine deposits in which radiocarbon-datable bivalves are typically found.

Perhaps the most critical limitation of radiocarbon dating for the development of accurate emergence curves occurs immediately after deglaciation, when emergence rates are the most rapid (Clark, 1976). At and just after deglaciation, climate remains cold and the landscape barren, dramatically limiting the amount of terrestrial organic material available for preservation and thus dating (Davis and Davis, 1980).

Assumptions inherent to cosmogenic dating of emergence

Using ^{10}Be to date post-glacial shorelines was first proposed in the 1990s coincident with similar attempts in unglaciated regions including the Negev and Mojave Desert (Matmon et al., 2003; Trull et al., 1995). These initial attempts were stymied by geological complications and measurement imprecision. For example, ^{10}Be exposure ages from cobbles, pebbles, and bedrock surfaces in arctic Canada were judged unreliable, because ^{10}Be ages were much older and had far greater scatter than the ^{14}C dates from detrital organic material collected at the same elevation (Gosse et al., 1998). Only boulders sourced from till and exposed as the shorelines eroded agreed with ^{14}C dates, but analytic uncertainties on the ^{10}Be measurements were large, 25% at 1σ (2.5 ka at 10 ka), limiting the utility of these early data (Briner et al., 2006).

Since Gosse et al. did their work in the 1990s, knowledge of the ^{10}Be system has greatly expanded. ^{10}Be production rates have been determined empirically at many sites around the world (Borchers et al., 2016), including in the Arctic (Briner et al., 2012), more closely tying cosmogenic nuclide ages to other chronometers, especially radiocarbon, although uncertainties at the percent level remain. Advances in sample preparation (Corbett et al., 2016c; Hunt et al., 2008) and AMS technology (Rood et al., 2010) have led to several-fold improvements in measurement precision. Lower procedural blanks and improved AMS efficiency now allow ^{10}Be concentrations of samples from Arctic shorelines near sea level with mid- to late-Holocene ages to be made with percent level analytic uncertainties (Corbett et al., 2016c; Rood et al., 2010). Despite these advances, there remain geologic processes that can affect the accuracy of shoreline dating using ^{10}Be .

Shoreline ages can appear too old if nuclides are inherited from prior periods of exposure. For bedrock outcrops, as well as for cobbles on even the highest beach ridges, this inheritance could be the result of cosmic-ray exposure at or near the surface prior to the latest glaciation and ineffectual glacial erosion (Briner et al., 2016; Briner et al., 2006; Hakansson et al., 2008). In ice marginal zones, exposed for tens of thousands of years during glacial cycles, low but measurable concentrations of ^{10}Be can be produced by muons; because muons are deeply penetrating, measurable concentrations of ^{10}Be can persist despite meters of erosion (Bierman et al., 2016; Briner et al., 2016). Cobbles exposed on higher beach ridges can be

reworked by storms, brought down the beachfront, and then redeposited on lower ridges, giving ages older than the shoreline (Briner et al., 2006). Although rapid post-glacial emergence minimizes the cosmic-ray dosing of outcrops below the water surface before emergence, at slower emergence rates, cosmogenic nuclides would be formed by neutrons and muons penetrating shallow water before the outcrops rose above mean high water, biasing ages upward (Stone et al., 1995).

Shielding of outcrops and beach deposits from cosmic rays after emergence will result in exposure ages that are too young, as will erosion of rock surfaces during exposure. Such shielding could come from snow (Schildgen et al., 2002), till, now-eroded beach deposits (Hallet and Putkonen, 1994), and ocean water (Stone et al., 1995).

Study Sites, Previous Studies, and Sample Collection Strategies

In Greenland, numerous emergence curves have been constructed using ^{14}C limiting ages of organic material (Lecavalier et al., 2014), including a growing number of curves based on isolation basin data (Long et al., 2011). Here, we focus on previously determined emergence histories only in and near the field areas we sampled rather than attempting to summarize the entire Greenlandic literature. In both of our field areas, summary papers suggest ~40 m of emergence (Long et al., 2011), a minimum value that does not account for contemporaneous sea-level rise driven by increasing ocean water volume after the LGM (Lambeck et al., 2014).

We specifically selected two field sites with very different geomorphic settings in order to test the ability of ^{10}Be to date emergence, one in southern Greenland (Narsarsuaq/Igaliku) and the other in western Greenland (Kangerlussuaq) [Figure 1]. Both sites are underlain by quartz-rich, gneissic bedrock providing sufficient quartz for the extraction of ^{10}Be . Previous ^{10}Be measurements near both sites and made for the purpose of dating glacial retreat are consistent with erosive, warm-based ice removing most nuclides produced during previous interglacial periods (Nelson et al., 2014; Carlson et al., 2014; Levy et al., 2012).

At Kangerlussuaq, the current winter climate is very dry and monthly snowfall during winter (in water equivalent) is on the order of only a cm or two. Narsarsuaq/Igaliku has a wetter climate, with up to 4 cm water equivalent falling per winter month. At neither site is the current winter snowfall sufficient, even if it did not melt over the 6 winter months, to cause more than percent level differences in annual ^{10}Be production under snow (maximum annual average shielding of 12 g cm^{-2}); there are data suggesting that snowfall may have been higher in the mid-Holocene (Thomas et al., 2016).

Southern Greenland, Narsarsuaq/Igaliku area

In Igaliku/Narsarsuaq (southern Greenland) we collected samples from nine different sites in order to estimate the age of deglaciation and the relative sea-level fall that followed [Figures 2 and 3]. The landscape is dominated by deep fiords incised into the uplands; most bedrock is quartz-bearing although there are outcrops of feldspar-dominated rocks (nepheline syenites) in which quartz is absent. A regional compilation of radiocarbon ages (both above and below the marine limit) suggests deglaciation in our field area at or before 9.7 cal ka BP (Weidick et al., 2004). A basal AMS radiocarbon age on a macrofossil (8920 ± 190 , Poz-31634; cal age, 9540–10430, 2σ range) in a lake core collected from nearby Lake Igaliku (Figure 1C) indicates deglaciation at our primary field site before 10.4 cal ka BP (Massa et al., 2012).

Previously published cosmogenic ^{10}Be deglacial exposure ages in the region are older than most radiocarbon ages of organic material collected above the marine limit. Lowland moraine boulders in Narsarsuaq give four ages of 11.3 ± 0.2 ka (Carlson et al., 2014), older than the deglaciation of the valley upstream from Narsarsuaq (10.5 ± 0.5 ka, $n=10$, bedrock and boulder samples) (Nelson et al., 2014). Qaqortoq, 70 km to the south, was deglaciated between 11.6 and 12.0 ka ($n=10$, Table 1) (Winsor et al., 2015).

At four sites near where we collected samples (Table 1), emergence curves have been constructed using radiocarbon dating of organic material both from shorelines and from isolation basins (Lecavalier et al., 2014). At Paamiut, 300 km northwest of where we sampled, there was 50 m of emergence between 10.9 and 9.5 cal ka BP (Woodroffe et al., 2014). At Qaqortoq, 70 km south of where we sampled, isolation basins indicate deglaciation at 11 cal ka BP and more than 30 m of emergence before current sea level was reached about 8.8 cal ka BP (Sparrenbom et al., 2006b). Isolation basin sampling at Nanortalik suggests deglaciation and emergence from 12.6-11.2 cal ka BP, (Sparrenbom et al., 2006a); whereas, at Tasiusaq emergence ages are much younger, 9.3-8.8 cal ka BP (Randsalu, 2008). The first two sites have cosmogenic deglacial exposure ages that agree broadly with the basal radiocarbon age of the highest isolation basin (Table 1). At Paamiut, the cosmogenic and ^{14}C age estimates for deglaciation overlap; at Qaqortoq, the cosmogenic age estimate (depending on the metric used to establish the deglacial age) is 600 to 1000 years older than the central tendency of the ^{14}C deglacial age estimate. We have not been able to find published cosmogenic data from Tasiusaq or Nanortalik.

In Igaliku, where we collected most of our samples, the highest post glacial sea level, the marine limit, is clearly defined by flat-topped, gravelly relict beach ridges surrounding the harbor area at the head of the fiord. Above the marine limit, there are glacially molded outcrops and erratic boulders. Below the marine limit, there are extensive outcrops of hard, minimally weathered rock. In coves, active, contemporary gravel beach ridges are common and extend several meters above modern high water levels. Tidal range in the area is only several meters.

We collected samples both to date deglaciation and define the emergence history. To date deglaciation at Igaliku, we sampled (June 2011) an erratic boulder (GLX28A) and the glacially sculpted bedrock surface (GLX28B) on which the boulder sat, just above a beach ridge (GLX29) that defines the local postglacial marine limit. Below another beach ridge (GLX27B), we sampled four outcrops (GLX30-33) at different elevations above contemporary sea level [Figures 2 and 3] to date emergence. We also sampled a third gravel beach ridge (GLX38) that defines the postglacial marine limit near Narsarsuaq about 30 km away. At each beach ridge, we collected numerous 5-10 cm long cobbles and extracted quartz independently from each cobble. From outcrops, we collected thin surface samples (cm-scale) using a hammer and chisel. In September 2012, we measured sample site locations precisely, including elevation, using both optical total station surveying tied to Danish benchmarks and Trimble PROXH GPS surveying using extended collection times and post processing (Table 2).

Because inundation of outcrops during storms is only a small percentage of total exposure time, storm waves and high tides have an insignificant effect on the ages we calculate both for the marine limit and for progressively lower outcrops exposed as relative sea level fell. The paucity of till in much of Greenland, the openwork nature of the beach deposits, and the

flat upper surface of the beach ridges we sampled argue against significant surface cover that is now eroded.

Western Greenland, Kangerlussuaq area

In western Greenland, for both inner and outer Kangerlussuaq Fjord, emergence curves based on radiocarbon dating of sediment were constructed first in the 1970s (Ten Brink, 1974) and updated recently (Storms et al., 2012). There are additional data near the mouth of the fiord collected from isolation basins (Bennike et al., 2011; Long et al., 2009; Long et al., 2011). The isolation basin data provide a coherent view of emergence history with emergence prevailing from deglaciation until the late Holocene (3 cal ka BP) when submergence began in response to neoglacial ice advance (Figure 4).

However, a compilation (Long et al., 2009) of previously published radiocarbon ages for emergence in the Sisimiut area (western Greenland ~160 km from our sample site at Kangerlussuaq and close to the mouth of the fiord) illustrates the uncertainty of radiocarbon-based emergence curves. In the Sisimiut data set, there is a 20% range in calibrated ages for samples collected at the same elevation (~100 m, the marine limit), as well as 8-10 cal ka BP ages in deposits sampled at many elevations between present day sea level and the marine limit (Figure 4). These calibrated radiocarbon ages, along with ages published later (Bennike et al., 2011), are systematically less than most ^{10}Be exposure ages in the area which have been interpreted as indicating deglaciation at about 14.5 ka (Winsor et al., 2015) although the radiocarbon ages that define rapid early emergence match well with the youngest ^{10}Be exposure age considered an outlier by Winsor et al. Such an offset between the methods could indicate that the ^{10}Be ages are systematically too old (due to the presence of inherited nuclides, (Briner et al., 2016),) or that ^{14}C ages are too young (due to delayed accumulation of organic material after deglaciation and/or emergence (Davis and Davis, 1980)). Offsets between organic radiocarbon ages of deglaciation and those estimated by cosmogenic nuclides such as ^{10}Be have been noted before and can exceed 1000 years (Larsen et al., 2014).

At Kangerlussuaq, during July 2008, we collected seven samples to determine the Watson River's incision history, which we believe reflects isostatic uplift as ice retreated inland during the middle Holocene [Figure 5] The town of Kangerlussuaq is located on a flat-topped, valley-filling landform composed of bedded sand and gravel termed the Keglen Delta, deposited between 6.5 and 7.1 cal ka BP (based on ^{14}C dating, (Storms et al., 2012)). Erosion of this thick blanket of unconsolidated sediment by the Watson River has exposed a bedrock ridge normal to river flow [Figures 5 and 6]. This bedrock was glacially rounded and polished by ice flow before deglaciation, the timing of which was ^{10}Be exposure dated (Levy et al., 2012) at $> 6.8 \pm 0.3$ ka ($n=10$, age of Ørkendalen moraines upstream). At the top of the ridge, deep glacial grooves are preserved and there is no evidence for fluvial erosion. Lower on the ridge, closer in elevation to the river, evidence for glaciation has been overprinted by fluvial processes, specifically, the bedrock has been eroded and fluted by sediment-laden river water.

Downstream from the ridge and immediately adjacent to the estuary is a bare bedrock strath terrace, a several-hundred-meter long, smooth, flat, bedrock surface shaped by fluvial erosion. The present-day channel of the Watson River is incised into this surface and except for summer floods, the strath terrace is high and dry above the channel and thus currently inactive and relict. The terrace bedrock surface is heavily fluted and potholed indicating it was sculpted

by flowing water and sediment rather than by ice [Figure 5C]; that sediment now blankets the fiord bottom downstream. Strath terraces such as this are thought to form when river grade (slope) is stable and lateral planation rather than incision dominates; thus, they indicate relative stability of base level and here a slowing or cessation of uplift and incision.

We collected four samples from hard, polished bedrock surfaces at different elevations along the bedrock ridge and three samples from the strath terrace parallel to the Watson River channel [Figures 5 and 6]; all of these samples once lay below a thick blanket (meters to 10s of meters) of Keglen Delta sediment and so were shielded from cosmic radiation until incision and removal of the material by the downcutting Watson River sequentially exposed the sampling sites. This incision was in response to uplift-induced, relative base-level lowering in the nearby fjord (Storms et al., 2012) not to changes in eustatic sea level which was relatively stable by the mid-Holocene. Such uplift would have been the result of the Greenland Ice Sheet retreating inboard of its current position after 6.8 ka during the mid-Holocene thermal optimum (Levy et al., 2012).

We used a Trimble PROXH GPS in 2011 with extended collection times and post processing to establish precise elevation control and sample location (< 1 m uncertainty, Table 3). Our expectation in sampling was that samples lower on the ridge were exposed later than those higher on the ridge and that the age of the strath terrace would reflect a time when base-level became stable because isostatic uplift slowed or ceased.

Analytical Methods

Samples were processed at the University of Vermont using standard methods (Corbett et al., 2016c). All samples were ground and the 250-850 um fraction retained. We ground each cobble in its entirety because cobbles were irregularly shaped and we do not know their stirring history. After quartz was separated and purified, beryllium was isolated in batches of 12 samples (GLX, 7 batches, 8 blanks; KLR, 1 batch, 8 associated blanks, Table 4). Samples were measured using AMS at Lawrence Livermore National Laboratory (Rood et al., 2013; Rood et al., 2010). A blank correction, based on the average measured $^{10}\text{Be}/^9\text{Be}$ ratio of all blanks (and the standard deviation) measured with each group of samples, was applied and errors propagated in quadrature. Analyses were normalized to the 07KNSTD standard series (Nishiizumi et al., 2007). We made three replicate analyses (for samples GLX29C, 29E, and 30) using separate quartz aliquots (Table 4). Considering only internal errors (AMS counting statistics), two replicates give similar concentrations at 1σ ; the other replicate agrees at 2σ . We use the average value for each replicated sample in our data analysis. One sample, GLX27B8, provided a small amount (5 g) of impure quartz (> 1000 ppm ^{27}Al). It had a ^{10}Be concentration 2X the other samples from site GLX27B perhaps because of the inclusion of other mineral phases high in ^{10}Be or because of inheritance. It was removed from further calculations as an outlier.

We calculated exposure ages and external uncertainties (considering scaling and production rate in addition to analytical precision) using the CRONUS calculator (Balco and Stone, 2008) (main calculator version 2.1, wrapper script 2.2, constants 2.2.1, muons 1.1) using the Arctic production rate (Young et al., 2013), Lal/Stone scaling, and a time-invariant cosmogenic production rate. For the CRONUS calculator, we assumed a thickness of 2.5 cm (average intermediate cobble axis, 5 cm) which is appropriate if the cobbles were stirred over time (which we expect due to frost heaving and bioturbation).

Our measurements of ^{10}Be are precise (median 1σ precision $<3\%$), which allows us to define closely (within 200-300 years, internal error) the relative timing of beach gravel deposition and exposure of outcrops as they emerged from beneath water in the Narsarsuaq/Igaliku area and from beneath sediment in Kangerlussuaq. External errors, considering the imprecision in nuclide production rate calibration and appropriate for comparing cosmogenic ages with radiocarbon ages, are larger by a factor of about 2, averaging ~ 500 years. We did not make a correction for elevation change due to isostatic uplift after exposure because the resulting changes in production rates are much smaller than the errors (both random and systematic) in our reported ages. All uncertainties in ^{10}Be concentrations are reported as 1 standard deviation of the analytic uncertainty only. For ages, we report both internal uncertainties (analytic) and external (considering production rate uncertainty). For ages of cobble beaches, we report the mean and one standard error considering the number of clasts analyzed and included in the mean.

Results and Interpretation

Southern Greenland

The Narsarsuaq/Igaliku record, from southern Greenland, spans 1900 years after deglaciation at ~ 11.4 ka (the average of boulder/bedrock pair exposure ages, GLX28A and B) and until the exposure of the lowest sample (GLX33) near present day high water at 9.5 ka. The three beach ridges, which represent the local marine limit (Table 2), have statistically indistinguishable ages (mean $\pm 1\text{SE}$, standard error) considering the age of numerous cobbles collected and analyzed from each beach ridge (11.5 ± 0.1 ka, $n=9$, GLX27B, 36 m asl; 11.6 ± 0.5 ka, $n=6$, GLX38, 42 m asl; and 11.5 ± 0.4 ka, $n=6$, GLX29, 45 m asl) despite being separated by over 30 km (Figure 7; Table 4). The range of beach ridge ages for the marine limit (11.5 to 11.6 ka) overlaps the deglaciation age defined by the mean of the age of the dated bedrock/erratic boulder pair (11.4 ± 0.3 ka (1 SD); GLX28A and B, 45 m asl) above the local marine limit as defined by those same beach deposits. The beaches were deposited immediately after deglaciation.

The samples we collected and dated reflect 45 m of relative sea-level fall [Figures 3 and 7] similar in timing and magnitude to other South Greenland emergence curves (Bennike et al., 2002; Sparrenbom et al., 2013; Sparrenbom et al., 2006b) and the ~ 50 m emergence inferred previously for the Narsarsuaq/Igaliku area (Long et al., 2011; Weidick et al., 2004). The exposure ages of four outcrops (from just below the elevation of the gravel beach to just above the present day high waterline) are in stratigraphic order (GLX-30, 35 m asl, 11.5 ka; GLX-31, 19 m asl, 11.2 ka; GLX-32, 10 m asl, 10.2 ka; GLX-33, 1.5 m asl, 9.5 ka) from which we conclude that relative sea level fell rapidly in the early Holocene, reaching its current level by 9.5 ka, similar to the ~ 8.8 cal ka BP inferred from local (Sparrenbom et al., 2006b) and regional (Woodroffe et al., 2014) isolation basin studies.

The high spatial and temporal resolution of the ^{10}Be record demonstrates that initial sea-level fall was extremely fast, about 25 m in at most a few hundred years, similar to the rapid, immediately post-glacial emergence inferred with fewer data (from bivalves in sediment) in western Greenland (Ten Brink, 1974) and in southern Greenland (Woodroffe et al., 2014) using isolation basins. Local sea level, immediately adjacent to a large (Washburn, 1962) and shrinking ice sheet, can fall with exceptional rapidity as the local gravitational field changes

substantially when the ice sheet ablates and when the underlying rock responds elastically (Clark, 1976; Ten Brink, 1974).

This rapid emergence means that the time any sample site spent under shallow water prior to subaerial exposure was minimal and thus had little if any influence on calculated exposure ages. The Narsarsuaq/Igaliku data provide strong evidence that rapid melting of the ice sheet in part drove initial emergence through changes in the local gravitational field (Clark, 1976), and the timing is consistent with large volumes of ice loss driven by abrupt warming immediately following the Younger Dryas; such rapid ice loss may have influenced later patterns of ice loss (Gomez et al., 2010). Applying a global eustatic correction due to melting ice sheets (Lambeck et al., 2014) of 15 m ka^{-1} suggests total uplift and gravity driven sea-level fall during the 1900-year emergence period recorded by ^{10}Be of $\sim 75 \text{ m}$. Glaciologic modelling of uplift in the region (Qaqortoq) matches poorly our data and those of others (Woodroffe et al., 2014); observed uplift [Figure 7] is much more rapid than modeled uplift (Lecavalier et al., 2014).

The new cosmogenic ages for deglaciation agree with others in the region (when all ages are calculated the same way using the same production rate and are thus directly comparable). For example, our cosmogenic estimate of deglaciation ($11.4 \pm 0.3 \text{ ka}$; $n=2$, GLX28A, B) near sea level at Igaliku is indistinguishable from the estimate 30 km north in Narsarsuaq ($11.3 \pm 0.2 \text{ ka}$; $n=4$) made on the basis of lowland morainal ^{10}Be exposure ages (Carlson et al., 2014). Igaliku deglaciation likely postdates ice leaving Qaqortoq 70 km southeast (Winsor et al., 2015) between $\sim 12 \text{ ka}$ ($n=10$, Table 1) but predates deglaciation (Nelson et al., 2014) of the valley upstream from Narsarsuaq ($10.5 \pm 0.5 \text{ ka}$, $n=10$).

However, the new ^{10}Be ages are older than most deglacial and emergence ages determined from radiocarbon analysis of organic material in nearby lake cores. For example, our ^{10}Be deglaciation estimate of $11.4 \pm 0.3 \text{ ka}$ is about 1.7 ka older than a previous (9.7 cal ka BP) regional estimate of deglaciation (Weidick et al., 2004) and 1.4 ka older than the central tendency of the basal lake sediment macrofossil radiocarbon age (9.5–10.4 cal ka BP, 2SD) of a core collected from nearby (Figure 1C) Lake Igaliku (Massa et al., 2012). The emergence of the Lake Igaliku basin (stated elevation 15 m, from low resolution topographic map (Massa et al., 2012)) at 9.5 cal ka BP is similarly young in comparison to the ^{10}Be -determined emergence curve we generate (Figure 7). In contrast, our new Igaliku record of emergence is similar in timing and emergence magnitude (Figure 7) to that generated 70 km south in Qaqortoq (Sparrenbom et al., 2006b). They differ in that the new Igaliku record has tighter elevation control, data from the initial 15 m of emergence, and no inconsistent data (such as Nu1, Q4 and K1 rep, Figure 7B).

There are three possible explanations for what appears to be offset between organic radiocarbon ages and cosmogenic exposure ages at some sites, including Igaliku: (i) The ^{10}Be production rate in use is too low causing exposure ages to be too old; (ii) All samples contain ^{10}Be inherited from prior exposure but ^{10}Be production rate calibration samples do not; (iii) The radiocarbon ages to which we and others compare our ^{10}Be ages are too young (Larsen et al., 2014). Below, we explore each of these explanations.

We consider it improbable that all cosmogenic samples we report here as well as those analyzed in the area by others (Carlson et al., 2014; Nelson et al., 2014; Winsor et al., 2015) are systematically too old because the production rate used for calculation is too low. We reject

production rate inaccuracies (which would need to be ~10%) as explanation for the ^{10}Be /organic radiocarbon dating mismatch because the ^{10}Be production rate we and others use to interpret our Greenland data is locally calibrated. The ^{10}Be production rate was determined over a similar timescale and at a similarly high latitude and low-elevation (Briner et al., 2012) as these samples. Furthermore, because both samples for dating (Carlson et al., 2014; Nelson et al., 2014; Winsor et al., 2015) and production rate samples were collected at high latitudes (Briner et al., 2012), varying magnetic field strength over time cannot influence production rates.

Although nuclides can be inherited from previous periods of exposure at and near Earth's surface, as shown for samples in southern Norway (Briner et al., 2016) and in northern Greenland (Corbett et al., 2013), we consider such inheritance an unlikely explanation for the offset between radiocarbon and ^{10}Be age estimates for several reasons. Most importantly, inheritance has been found in many cosmogenic studies in glaciated terrains but it has never been uniform; boulders and outcrops carry different concentrations of inherited nuclides reflecting different prior exposure and erosion histories (Corbett et al., 2016a). In Igaliku, the similarity in ages between multiple beach cobbles and between bedrock and boulder ages in this and other nearby glacial dating campaigns (Carlson et al., 2014; Nelson et al., 2014; Winsor et al., 2015) would require extremely uniform inheritance, with a variance between dozens of samples of only a few hundred years of exposure equivalent; we consider that unlikely.

Furthermore, cobbles collected directly from the Greenland Ice Sheet along its western margin have a median ^{10}Be concentration of only about 1000 atoms g^{-1} , the equivalent of at most several hundred years of surface exposure (Corbett et al., 2016b) far less than reported for the inheritance in Norwegian samples (Briner et al., 2016). Such low inheritance is likely both the result of shorter interglacial exposure around Greenland than in southern Norway and the persistence of the Greenland Ice Sheet over millions of years (Bierman et al., 2016). Since the ages we calculate from cobbles on beach deposits and those we calculate from bedrock and an overlying erratic boulder agree at 1 SD, we infer that none of these samples likely carries more than a few hundred years of surface equivalent muon-produced ^{10}Be . This is a small portion (<20%) of the concentration of ^{10}Be needed to reconcile the radiocarbon and ^{10}Be age estimates for deglaciation and emergence.

We suspect that the offset in southern Greenland between some radiocarbon-based chronologies and cosmogenic ages (Carlson et al., 2014; Nelson et al., 2014; Winsor et al., 2015), including those reported here, mostly reflects a young bias in radiocarbon ages at deglaciation and during early emergence. Considering the evidence presented above, we suspect that many radiocarbon ages are too young because they reflect a lag time after deglaciation, before sufficient organic material accumulated for dating (Davis and Davis, 1980). Such ages, whether derived from samples collected from lake sediment cores or from marine sediment, therefore represent minimum limits on deglaciation and emergence. The challenge of finding deglacially contemporaneous organic material is especially acute in ice marginal areas in the Arctic during the Pleistocene where climate remained cold after deglaciation. During the Holocene, once climate was warmer and vegetation had become re-established, the offset between ^{10}Be and radiocarbon ages should be and is usually less or non-existent (Briner et al., 2010).

Western Greenland

The relative sea-level record at Kangerlussuaq, western Greenland, which is otherwise well constrained (Storms et al., 2012; Ten Brink, 1974) by radiocarbon dating of marine mollusks in sediment (Ten Brink, 1974), has a gap in the middle Holocene when ice retreated beyond the current margin. Our new ^{10}Be data span 3.2 ka and 18.5 m of emergence in the later Holocene and fill this gap [Figure 8 and Table 4]. In Kangerlussuaq, the ^{10}Be exposure ages are younger than in the Narsarsuaq/Igaliku area because glacial retreat occurred later (^{10}Be age, Ørkendalen moraines (Levy et al., 2012), 6.8 ± 0.3 ka and ^{14}C on bivalves in Keglen Delta pro-glacial sediment downstream, $6.5 - 7.1$ cal ka BP (Storms et al., 2012)).

The oldest (6.6 ka, KLR04) and highest (35 m asl) of our Kangerlussuaq exposure ages indicates that incision of the Keglen Delta and exposure of bedrock in the Watson River valley began just after the Greenland Ice Sheet retreated from the Ørkendalen moraines at 6.8 ka (Table 4). Exposure ages lower on the bedrock ridge are in stratigraphic order, with a total of 18.5 m of incision beginning at 6.6 ka and ending at 3.3 ka when the Watson River stopped incising. Downstream, the river cut a broad strath terrace at ~ 4.8 ka (KLR-5,6,7). The terrace reflects decreasing incision rates as a result of increasing base level stability; such stability allowed the river to bevel the channel bed and create the strath terrace. The end of incision and emergence reflects Neoglacial ice readvance and consequent subsidence, which our data suggest started around 3.3 ka, similar to the ~ 4 cal ka BP age suggested by others for the region on the basis of calibrated radiocarbon ages (Tatenhove and Meer, 1996; Wahr et al., 2001; Weidick, 1993; Weidick et al., 1990).

Because our bedrock samples at Kangerlussuaq were exposed by erosion of the overlying sand and gravel as the Watson River incised, inferring changes over time in local relative sea-level elevation from sample elevation requires making assumptions about the relationship between the sample sites upstream of the fiord and local, relative sea level in the fiord. To do this, we presume that the Watson River has maintained a similar grade (water surface and channel bottom slope) over time, and subtract the elevation offset between the ~ 4.8 ka strath terrace (18 m asl) and the 4.5 cal ka BP age of the 2 m asl sea level of Ten Brink (Ten Brink, 1974) from all our data. It is important to consider that our inferences about the timing of uplift, incision, and the end of emergence are independent of the assumptions about river grade and effective sample elevation.

^{10}Be dating of late Holocene bedrock exposure along the Watson River provides new constraints on the timing and magnitude of neoglaciation in western Greenland. Considered along with the dating of the Ørkendalen and Keglen moraines near Kangerlussuaq (Carlson et al., 2014; Levy et al., 2012; Storms et al., 2012; Winsor et al., 2015), the ^{10}Be data suggest that the Greenland Ice Sheet was inland of the Ørkendalen margin to the east of Kangerlussuaq between ~ 6.8 ka and at least 3.3 ka (our youngest age, just above the low flow channel margin). Uplift diminished and the strath terrace was cut by 4.8 ka as ice marginal retreat slowed and river incision slowed or ceased allowing lateral channel migration and bedrock strath planation. The ^{10}Be data and uplift/relative sea-level inferences from them at Kangerlussuaq are consistent with isolation basin data from the Sisimiut area 150 km west (Long et al., 2009). There, relative sea level was +15 m at 5.7 ka (our estimate up fjord at Kangerlussuaq at that time is +16 m) and uplift at Sisimiut ended between 4 and 3 ka similar to our suggestion that uplift slowed by 4.8 ka and ended by 3.3 ka. Overall, ^{10}Be data support the inference (from two

lakes cored near the ice margin) that ice was behind the present-day margin near Kangerlussuaq between 5.8 and 1.8 ka (Young and Briner, 2015).

Discussion

^{10}Be dating of Greenlandic relative sea levels provides precise age/elevation data revealing both tens of meters of emergence in just a few centuries after deglaciation as well as the timing and geomorphic response to neoglaciation in the late Holocene. In Southern Greenland, at Igaliku, cosmogenic dating of deglacial and emergence features shows that deglaciation and thus emergence were especially rapid after 11.4 ka. Systemic differences between cosmogenic and radiocarbon dating of this emergence appear during the first millennia or two after deglaciation when organic material was especially scarce (Davis and Davis, 1980; Weidick et al., 2004) resulting in systematic prior underestimation of initial emergence rates and emergence age at Igaliku and likely elsewhere in southern Greenland. This interval is especially important to capture accurately in order to inform models simulating ice sheet response to past climate forcing. Such bias in dating could make ice sheets and the solid Earth appear to respond with a longer lag and more slowly to climate change than they actually do. At least some models constrained by ^{14}C -based emergence curves appear to underestimate initial emergence rates (Lecavalier et al., 2014; Sinclair et al., 2016), as seen by comparing rapid initial emergence rates from the cosmogenic Narsarsuaq/Igaliku record with simulated emergence curves for many sites around Greenland (Lecavalier et al., 2014).

There are limitations to dating postglacial emergence with cosmogenic isotopes. The method will not provide accurate ages where relative sea level has risen after initially falling because there will be multiple periods of exposure interrupted by shielding under water (Stone et al., 1995). None of the sites we investigated in Greenland have experienced such complex emergence histories (Lecavalier et al., 2014). Accurate exposure dating can be prevented by nuclides inherited from prior periods of cosmic-ray exposure. For example, dating a series of nested cobble beaches is unlikely to produce interpretable data because cobbles with prior exposure histories from higher beach berms are likely to be reworked by storm waves into lower beach berms (Briner et al., 2006; Gosse et al., 1998). In the example presented here, we sampled only the highest cobble beaches assuming that these cobbles were derived directly from glacial till and/or outwash and had no recent history of prior cosmic ray exposure; this assumption is confirmed by their homogenous ages and the minimal offset between the beach ages and an adjacent erratic boulder and glacially scoured bedrock surface immediately above them. In principle, in situ produced ^{14}C , with its short half-life could help address the issue of inheritance. Practically, such analyses are currently difficult to make, imprecise, costly and the production rates of this nuclide over time, space, and depth remain less certain than for ^{10}Be .

The presence of warm-based, erosive ice is critical to the success of the method we propose. In areas where ice was cold-based, erosion will be minimal and nuclides will be inherited from prior periods of exposure (Bierman et al., 1999), which will confound the dating of emergence. Without removal of at least several meters of rock during the most recent glaciation, accurate dating of sea level using ^{10}Be in outcrops would not be possible; even so, in areas where there are long interglacial periods of exposure, low rates of ^{10}Be production by deeply penetrating muons may inflate calculated cosmogenic exposure ages (Briner et al., 2016); although, we do not see that effect in the study areas considered here. We doubt that

inheritance of nuclides from prior periods of exposure will be a significant limitation for application of the method except in areas where cold-based ice dominates, because large volumes of outwash, many deltas, and frequent glacially-streamlined forms suggest that much ice near even high arctic coastlines, at least at in large fjords, was warm-based (Roberts and Long, 2005). The low median ^{10}Be concentration in ice-sourced Greenlandic cobbles (Corbett et al., 2016b) suggests that marine limit beach deposits are likely to be amenable to dating even if lower and younger beach deposits are not (Briner et al., 2006).

Conclusions

Data we present here demonstrate the precision and utility of a widely applicable technique for establishing emergence rates along previously glaciated coastlines. Here, we show that sites can be selected to minimize inheritance of cosmogenic nuclides from prior periods of exposure, measurements can be made reproducibly at several percent precision, and the resulting data used to date directly post-glacial emergence with uncertainties of several hundred years at the end of the Pleistocene. Cosmogenic exposure dating of emergence can be used alone or to fill in elevations at which there are no suitable lakes, a limitation of the isolation basin approach (Long et al., 2008). It will be most useful along rocky coasts where the availability of radiocarbon-datable materials is limited and where there are few reliable geomorphic indications of past sea levels. Such areas include much of the Arctic as well as high latitudes of North America and Europe.

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Figure Captions

Figure 1. Sample locations. A. Index map. B. Narsarsuaq/Igaliku region showing gravel beach berm sample, GLX38, that represents marine limit. C. Expansion of panel B showing samples at Igaliku used to determine deglacial age and emergence history. D. Kangerlussuaq area showing KLR sample locations along the Watson River. E. Kangerlussuaq area and present ice margin with inset showing location of panel D. Dashed white line shows the approximate location of Ørkendalen moraine dated at 6.8 ± 0.3 ka (Levy et al., 2012).

Figure 2. Narsarsuaq/Igaliku sample sites. A. Cobble beach ridge (shoreline), GLX-29, with age of 11.5 ± 0.4 ka (1 SE of cobbles, $n=6$) is marine limit in town of Igaliku. B. Beach berm (GLX-27; 11.5 ± 0.1 ka, 1 SE of cobbles, $n=9$) is marine limit to the north of Igaliku. Inset shows boulder/bedrock pair (GLX-28) above marine limit that dates local deglaciation to 11.4 ± 0.3 ka (1 SD analytic uncertainty). C. Overview looking from near fiord (GLX-31) toward a sampled outcrop (GLX-30) and beach ridge (shoreline) that defines the local marine limit (GLX-29, panel A).

Figure 3. Schematic cross section at Igaliku showing sample sites, ^{10}Be exposure ages, surveyed elevations, and sea level over time. Uncertainties are 1 standard error for cobble beaches and 1 standard deviation, internal error for bedrock out crops and the boulder.

Figure 4. Example of western Greenland emergence information compiled along with ^{10}Be deglacial ages. Plot incorporates calibrated radiocarbon ages of marine organic material related to sea level (black diamonds) as well as isolation basin estimates of past sea levels (open symbols) and cosmogenic ^{10}Be exposure ages for boulders. Data from Long et al. (2009), Bennike et al. (2011), and Winsor et al. (2015).

Figure 5. Kangerlussuaq sample sites. A. Overview showing samples KLR1 to KLR4 along bedrock ridge exposed as terrace sediments (on which buildings sit) were incised by Watson River (shown to right and along front of image). Samples KLR5, 6, and 7 on strath terrace. Field of view about 700 m. B. Glacial groove exposed by removal of terrace sediment at KLR3, field gear for scale. C. Strath terrace with flow features, sample location KLR6, person for scale. D. Oblique view showing vertical transect of sample sites KLR-1 to 4.

Figure 6. Map view (Google Earth) of Kangerlussuaq sample sites showing ^{10}Be ages and inferred history of A. ice retreat, B. channel incision, and C. strath terrace beveling as indicated by three similar exposure ages on the bedrock strath terrace.

Figure 7. Emergence curves, southern Greenland. A. Narsarsuaq/Igaliku emergence curve derived from ^{10}Be measurements. (numbers are sample GLX ID) of erratic boulder and glaciated bedrock above marine limit (GLX28), cobble beaches at marine limit (GLX27, 29, 38), and outcrops exposed as relative sea level fell (GLX30,31,32,33). LI emergence is the reported elevation and age of Lake Igaliku emergence (15 m, ~ 9.5 ka) (Massa et al., 2012). LI basal age is reported at ~ 10 ka cal ^{14}C (Massa et al., 2012) and appears to be too young by about 1.5 ka.

Uncertainty of LI and LIE elevation and age is not known but suggested by dashed lines. Elevation uncertainty for ^{10}Be samples smaller than symbol and therefore not shown. Age uncertainty shown at 1 standard error for cobble beaches and internal uncertainty for other samples. B. Qaqortoq area emergence data from Sparrenbom et al. (2006).

Figure 8. Emergence curve for Kangerlussuaq, western Greenland. Includes existing ^{14}C data (Storms et al., 2012; Ten Brink, 1974) calibrated using CALIB and new ^{10}Be exposure ages plotted using relationship between their measured elevation and paleo sea level at 4.5 ka. Kegen delta cal ^{14}C age range (Storms et al., 2012; Ten Brink, 1974) and elevation plotted. Age uncertainties plotted as 1 SD internal error. Elevation uncertainty for ^{10}Be samples smaller than symbol and therefore not shown.

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TABLE 1. South Greenland emergence records and cosmogenic deglacial chronology comparison - Narsarsuaq/Igaliku

Site*	Oldest RSL age range cal ¹⁴ C ka BP (sample ID)	Sea level technique	¹⁰ Be deglacial age^ (ka)	RSL reference	¹⁰ Be reference
13 Paamiut (Paa)	10.8-11.2 (p38)	Isolation Basins, AMS Bulk gyttja	10.5-11.0 (10.8, 11.0, 10.6; n=9)	Woodroffe et al., 2014	Carlson et al., 2014
14 Qaqortoq (Qaq)	10.8-11.2 (Q9)	Isolation Basins, AMS Bulk gyttja and macrofossil	8.8-13.7 (11.6. 11.9. 12.0; n=10)	Sparrenbom et al., 2006	Winsor et al., 2015
15 Tasiusaq (Tas)	8.8-9.3 (T1)	Isolation Basin, AMS macrofossil	no data	Fredh, 2008; Randsalu, 2008	no data
16 Nanortalik (Nan)	11.2–12.6 (N18)	Isolation Basin, AMS macrofossil	no data	Sparrenbom et al., 2006; Bennike et al., 2002	no data

*numbering from Laclivieer et al., 2014

^ range of reported ages with mean, median and error-weighted average in parens including total number of samples excluding samples identified by authors as outliers)

table 2

TABLE 2. Sample site and location data for GLX sample series

Sample	Longitude (W)	Latitude (N)	Sample Type	Sample description	Survey Elevation (m asl)	GPS Elevation (m asl)
GLX27B	45.43144737	60.99601201	beach cobbles	surface clasts from flat surface above gravel pit	36.4	35.4
GLX28A	45.43147594	60.99539243	erratic boulder	erratic boulder on bedrock, some weathering, granite	44.3	43.3
GLX28B	45.43145709	60.99536556	bedrock	bedrock sample, some polish but weathered in places; collected several meters above marine limit.	44.3	44.8
GLX29	45.42778848	60.99062786	beach cobbles	extensive gravel bar partially excavated for gravel	45.5	44.6
GLX30	45.42644157	60.98942906	bedrock	outcrop below steep face, maybe water polish, glacial form	35.6	35.0
GLX31	45.42264026	60.99129051	bedrock	outcrop near red shed and dump, very extensive glacial form, water polish	19.8	19.1
GLX32	45.41969188	60.99198204	bedrock	extensive lichen-covered outcrop, glacial form	10.1	9.1
GLX33	45.42014226	60.99249239	bedrock	under GLX32, platform, ~2m above seaweed line	2.0	0.9
GLX38	45.52266727	61.15369333	beach cobbles	very flat top feature near Qassiarsuq, 100 m long, lagoon behind sampled berm	41.8	ND
			marine limit	near GLX28	42.3	41.6

GPS location from Garmin 12, uncorrected. WGS 84. GPS elevation from Trimble ProXH with external antenna, postprocessed. Survey elevation from total station survey using benchmarks 81821 and 81516.

ND = no data

table 3

TABLE 3. Sample site and location data for KLR samples and terrace

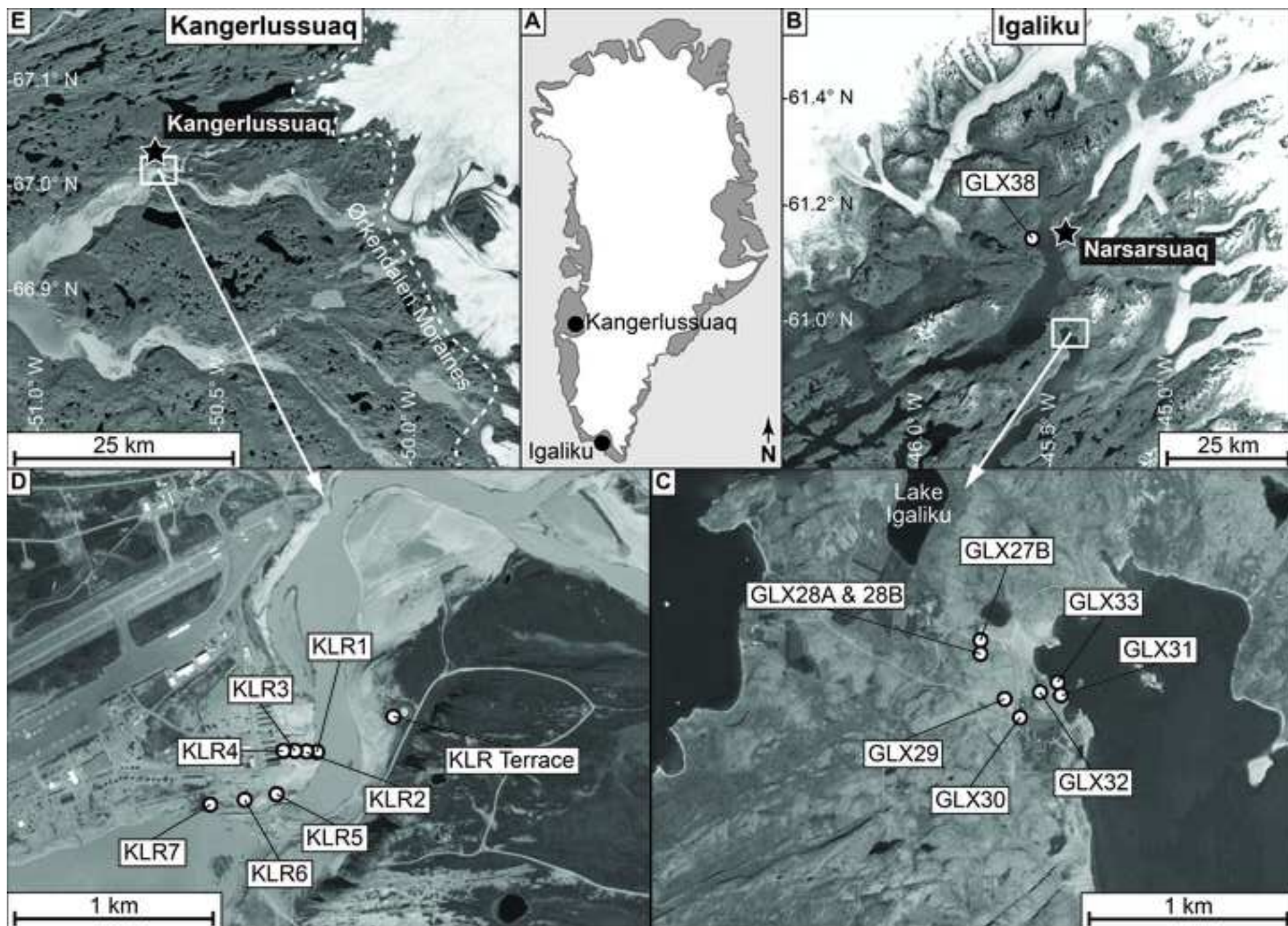
Site	Longitude (W)	Latitude (N)	Elevation (m asl)	Vertical precision (m)	Horizontal precision (m)	Type
KLR1	50.681516076	67.007598756	16.13	0.13	0.08	exposed bedrock ridge
KLR2	50.682357675	67.007584700	21.51	0.34	0.16	exposed bedrock ridge
KLR3	50.683434536	67.007638570	27.93	0.26	0.11	exposed bedrock ridge
KLR4	50.684927877	67.007596514	34.78	0.29	0.12	exposed bedrock ridge
KLRterrace	50.674665505	67.009222327	56.79	0.32	0.20	outwash terrace (gravel)
KLR5	50.685685365	67.005773417	18.59	0.18	0.11	strath terrace bedrock
KLR6	50.689085714	67.005364177	16.39	0.13	0.08	strath terrace bedrock
KLR7	50.692882779	67.005240213	15.04	0.24	0.14	strath terrace bedrock

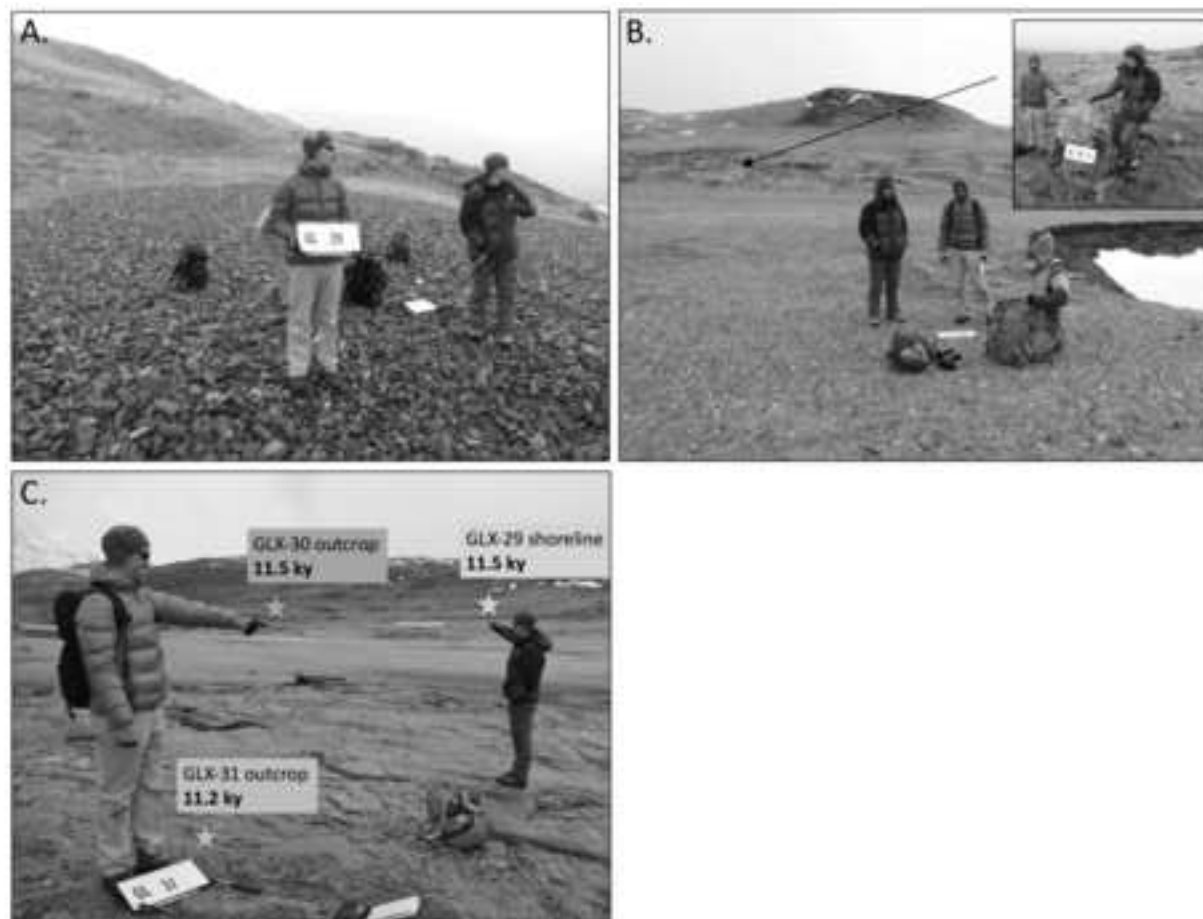
Field data collected using Trimble ProXH unit with external antenna. Post processed against Kellyville basestation using Hstar correction. WGS84.

TABLE 4. Cosmogenic isotopic data, Greenland emergence

Sample ID	LLNL #	Blank corrected ¹⁰ Be/ ⁹ Be	⁹ Be mass (μg)	qtz mass (g)	¹⁰ Be (atoms/g)	¹⁰ Be exposure age (yr)	Internal unc (yr)	External unc (yr)	Summary statistics
<i>Kangerlussuaq</i>									
KLR1	BE27860	1.12E-14 ± 1.00E-15	244	12.4513	14670 ± 1310	3330	300	320	
KLR2	BE27861	4.69E-14 ± 1.35E-15	244	31.3764	24380 ± 700	5560	160	270	
KLR3	BE27862	3.69E-14 ± 9.42E-16	244	22.7828	26420 ± 670	5930	150	270	
KLR4	BE27863	4.22E-14 ± 1.11E-15	244	23.2267	29680 ± 780	6570	170	310	
KLR5	BE27864	2.68E-14 ± 8.76E-16	244	19.9369	21990 ± 720	4990	160	250	
KLR6	BE27866	1.99E-14 ± 7.35E-16	244	15.1350	21490 ± 790	4890	180	260	
KLR7	BE27867	5.82E-14 ± 1.25E-15	245	46.0452	20730 ± 440	4720	100	210	
<i>Narsarsuaq/Igaliku</i>									
GLX27B1	BE32103	9.13E-14 ± 2.62E-15	247	31.1683	48360 ± 1390	11580	330	550	
GLX27B2	BE32104	9.97E-14 ± 2.07E-15	247	35.6896	46080 ± 960	11030	230	480	
GLX27B3	BE32105	8.67E-14 ± 1.84E-15	246	29.7092	48010 ± 1020	11490	250	500	
GLX27B4	BE32106	5.98E-14 ± 1.36E-15	246	20.7093	47510 ± 1080	11370	260	510	
GLX27B5	BE32107	9.90E-14 ± 1.89E-15	247	32.9375	49510 ± 950	11850	230	510	
GLX27B6	BE32119	7.43E-14 ± 2.02E-15	245	24.8192	49100 ± 1340	11760	320	550	
GLX27B7	BE32108	9.37E-14 ± 1.78E-15	246	32.0016	48220 ± 920	11540	220	490	
GLX27B8	BE32120	3.40E-14 ± 1.07E-15	248	5.3405	105350 ± 3330	outlier, not included			
GLX27B9	BE32109	8.46E-14 ± 2.31E-15	247	30.0789	46320 ± 1270	11090	300	520	
GLX27B10	BE32110	8.65E-14 ± 1.71E-15	247	29.2421	48790 ± 960	11680	230	500	GLX27B (avg, 1SD, 1S 11500 300
GLX28A	BE32133	2.03E-14 ± 7.10E-16	248	6.9139	48680 ± 1700	11550	400	600	GLX28A,B (avg, 1SD)
GLX28B	BE32094	6.69E-14 ± 1.64E-15	247	23.4146	47170 ± 1160	11190	280	510	11400 300
GLX29A	BE32985	4.67E-14 ± 1.19E-15	255	16.3313	48800 ± 1240	11560	300	530	
GLX29B	BE32111	7.44E-14 ± 1.57E-15	247	26.2881	46720 ± 990	11070	230	480	
GLX29C	BE32995	3.07E-14 ± 1.26E-15	257	10.0584	52450 ± 2160	12430	500	700	
GLX29C*	BE32121	3.61E-14 ± 1.20E-15	245	10.0964	58530 ± 1940	13880	460	700	GLX29C (avg, 1SD)
GLX29D	BE32112	9.95E-14 ± 1.97E-15	246	34.8576	46970 ± 930	11130	220	480	13200 1000
GLX29E	BE32996	5.05E-14 ± 1.30E-15	254	17.8945	47860 ± 1230	11340	290	520	GLX29E (avg, 1SD)
GLX29E*	BE32095	4.29E-14 ± 1.18E-15	247	15.1636	46710 ± 1280	11070	310	520	11200 200
GLX29F	BE32096	5.56E-14 ± 1.52E-15	247	19.9901	45890 ± 1250	10870	300	510	GLX29 (avg, 1SD, 1 SE 11500 900
GLX30	BE32997	5.54E-14 ± 1.91E-15	251	19.6529	47200 ± 1630	11310	400	580	GLX30 (avg, 1SD)
GLX30*	BE32097	5.08E-14 ± 1.30E-15	246	17.1781	48580 ± 1250	11640	300	540	11500 200
GLX31	BE32098	5.45E-14 ± 1.35E-15	246	19.4975	45970 ± 1140	11210	280	510	
GLX32	BE32099	5.05E-14 ± 1.24E-15	246	20.1392	41270 ± 1010	10170	250	460	
GLX33	BE32100	4.69E-14 ± 1.25E-15	247	20.2973	38070 ± 1010	9470	250	440	
GLX38A	BE32123	3.84E-14 ± 1.03E-15	246	11.1380	56790 ± 1530	13520	370	630	
GLX38B	BE32124	4.85E-14 ± 1.39E-15	246	14.6789	54270 ± 1560	12910	370	620	
GLX38C	BE32134	1.48E-14 ± 6.49E-16	247	5.2521	46450 ± 2040	11050	490	640	
GLX38D	BE32989	5.13E-14 ± 2.69E-15	256	20.9000	42030 ± 2200	9990	530	650	
GLX38E	BE32990	5.91E-14 ± 1.60E-15	256	21.6473	46690 ± 1270	11100	300	520	
GLX38F	BE32102	5.77E-14 ± 1.33E-15	247	20.2538	47110 ± 1090	11200	260	500	GLX38 (avg, 1SD, 1 SE 11600 1300

* replicate analysis using distinct quartz aliquot; averages and SD shown in italics
all analyses normalized to 07KNSTD standards as per values in Nishiizumi et al. (2007)
GLX measured isotope ratios corrected using multiple full process blanks measured with samples (n=8, 5.6±2.9 x10⁻¹⁶)
KLR measured isotope ratios corrected using multiple full process blanks measured with samples (n=8, 3.5±1.5 x10⁻¹⁶)
1 of 22 cobbles is an outlier (GLX27B8), with an age of 25.31 ky; we omit it from the calculations.





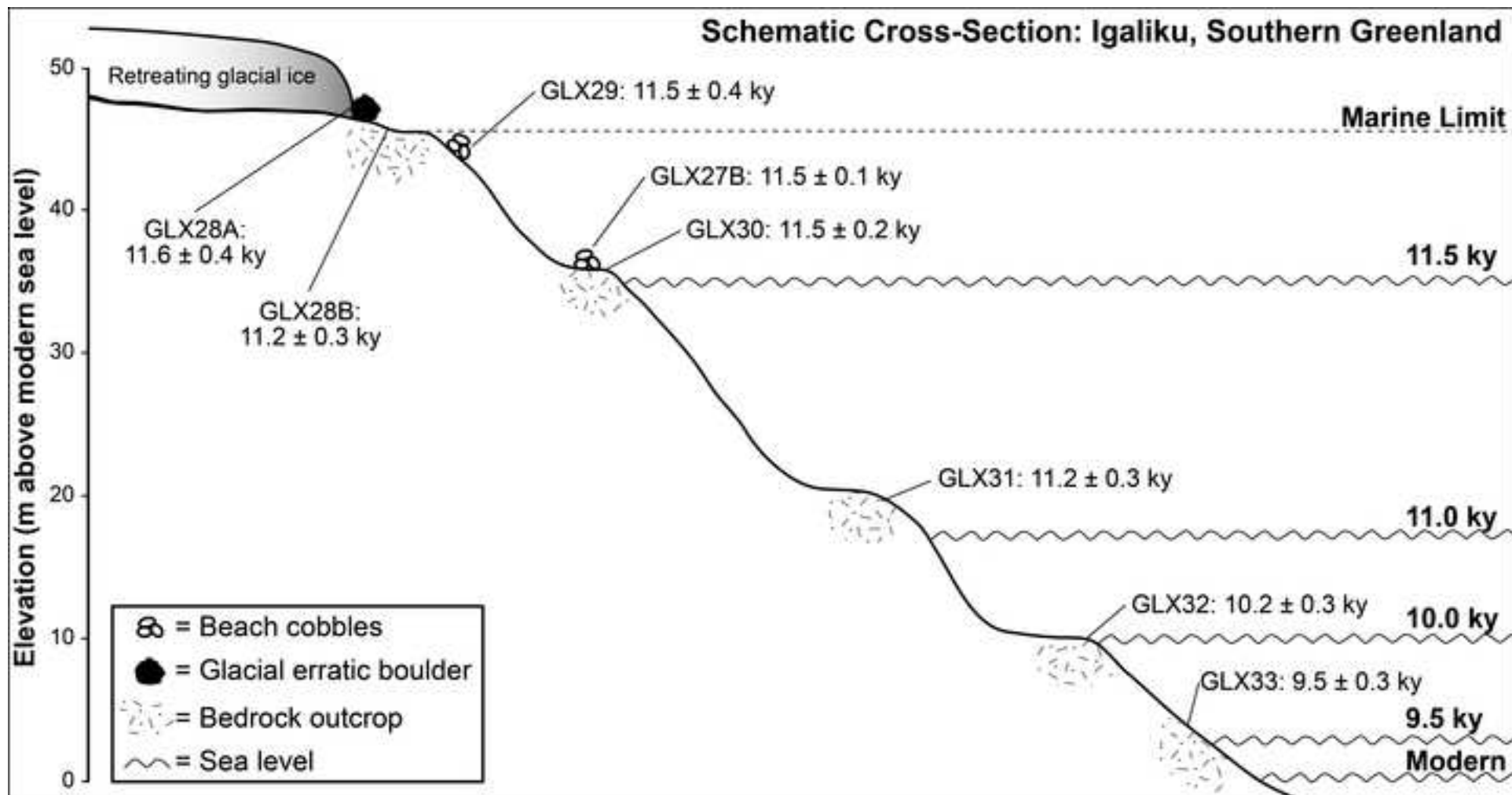


Figure 4

