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Investigations to constrain retreat of the Greenland Ice Sheet: glacial geomorphology and sampling for cosmogenic exposure dating of the Centrumsø area, Kronprins Christian Land, northeast Greenland

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Abstract: Over the last few decades atmospheric warming across the Arctic has been far more rapid than elsewhere in the world, contributing to an increase in the sea-level contribution from the Greenland Ice Sheet. Given predictions of continuing atmospheric warming during the 21st century and beyond, it is crucial to understand how the ice sheet has responded to past variations in climate. Kronprins Christian Land lies in a climatically sensitive, yet sparsely studied part of northeast Greenland, in an inter-ice-stream region just north of Nioghalvfjerdsbrae. This paper presents the results of preliminary geomorphological mapping from a 2m spatial-resolution digital elevation model of a 5500km^2 region around Centrumsø, as well as a report of sampling for cosmogenic exposure dating, and field observations concerning the extent and nature of palaeo-ice coverage and dynamics. Twenty-one 2kg samples were collected from carefully selected glacial erratics of various lithologies using a hammer and chisel as well as a small angle-grinder. In general, moraine ridges in the study area are relatively small (2 – 5m in height) and lack a prominent peak, reflecting limited sediment availability, and suggesting some post-glacial re-mobilization of sediment or deflation caused by melting of the moraines' ice cores. Striated cobbles and boulder-sized clasts were observed at up to 540m a.s.l., sub-rounded erratics (some of which were sampled) at up to 800m a.s.l. and streamlined bedrock at up to 360m a.s.l., all of which indicate sliding between the ice and the bedrock and temperate basal conditions. In addition, several proglacial spillways were noted, along with numerous terraces, commonly situated between lateral moraines and valley sides, which are probably kame terraces formed by glaciofluvial transport and deposition. The prevalence of these landforms indicates significant glaciofluvial action requiring large volumes of meltwater, suggesting this region experienced high-volume melt in short intensive summers during past ice-recession events.

Keywords: Greenland Ice Sheet; glacial geomorphology; climate change; cosmogenic exposure dating; Kronprins Christian Land; Northeast Greenland National Park

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Background

Climatic fluctuations affect the mass balance of the Greenland Ice Sheet (GrIS), causing it to expand, recede, thicken, thin, speed-up or slowdown in response to changes in surface melting, snowfall, iceberg calving and submarine melting (McMillan *et al*., 2016). Far from its margin at high elevations, where ice is formed by the gradual compression of snow by subsequent accumulation, the ice sheet's topography and flow may respond only over hundreds or thousands of years to changes in climate (Alley *et al*., 2010). At lower elevations, however, where surface meltwater may access the base of the ice and lubricate its flow, and ocean waters melt tidewater glacier termini reducing the stresses that resist ice flow, climate-related variations in ice-sheet mass balance and topography can occur on annual and shorter timescales (Trusel *et al*., 2018). Such changes are important globally because an increase in mass loss from the ice sheet contributes to global sea-level rise (SLR), and total wasting of the GrIS would cause an estimated 7.4m SLR (Bamber *et al*., 2013).

During the past few decades, atmospheric warming across the Arctic has been significantly faster than in the rest of the world (Dai *et al*., 2019). This, along with broadly synchronous ocean warming (Rignot *et al*., 2012), has led to a six-fold increase in mass loss from the GrIS since the 1980s, with an average of 286 ± 20 gigatonnes or Gt/yr (0.8mm/yr SLR) in 2010–2018 (Mouginot *et al*., 2019), and a greatest mass loss recorded to date of >400Gt (1.1mm SLR) in 2012 (van den Broeke *et al*., 2016). Note that the melting of one gigatonne (1×10^9 tonnes) of ice produces almost a cubic kilometre of meltwater. Predictive models suggest that the contribution to sea-level rise from the GrIS will continue to increase over the coming decades (Goelzer *et al*., 2013), but considerable uncertainty remains because there are gaps in the scientific understanding of complex non-linear interactions between the ice sheet, atmosphere and ocean.

Given this uncertainty, in addition to numerical modelling and contemporary process-based research, it is crucial to understand how the ice sheet's previous extent and volume relate to past variations in climate (Vinther *et al*., 2009). Such information can be deduced from various palaeo-climate and palaeo-ice-volume proxies such as: isotope and sediment analysis in ocean-sediment cores (e.g. Andresen *et al*., 2017; Dyke *et al*., 2017); isotope analysis and measurements of gas concentrations in ice cores (e.g. Vinther *et al*., 2009); investigation of glacio-isostatic adjustment and relative sea-level changes from salt marshes and isolation basins (e.g. Lecavalier *et al*., 2014; Strunk *et al*., 2018), and the estimation of former ice extents and volumes from relict landforms (e.g. Chandler *et al*., 2018). Here the latter approach is employed, involving mapping, interpreting and dating glacial landforms including moraines (ridges of sediment deposited by the ice), erratics (boulders of non-local lithology eroded and carried by the ice), glacially-eroded bedrock surfaces and glaciofluvial features. Moraines mark either the most extensive ice extent or a significant pause or re-advance during retreat, the location of erratics relative to their source lithology can be used to determine past ice-flow direction, and the occurrence of streamlined bedrock indicates abrasion caused by ice-sliding.

There is evidence of ice cover in Greenland as long ago as 45 million years (Tripati and Darby, 2018), with signs of more consistent glaciation of some kind (mountain glaciers, ice caps and perhaps a larger ice sheet) from at least 14 million years ago. Since that time, the ice sheet has waxed as atmospheric temperatures reduced and waned as they have increased (Alley *et al*., 2010; Bierman *et al*., 2016; Knutz *et al*., 2019). There is evidence that during these warmer periods snowfall increased, but not by enough to compensate for the mass lost by ablation processes. It is possible that for extended periods during the Pleistocene (2,500 – 11.7 thousand years ago or 'ka') the ice sheet's volume reduced by up to 90% relative to its current size, with just a remnant ice sheet remaining in the East Greenland highlands (Schaefer *et al*., 2016). Over the past million years the GrIS has fluctuated in volume around its current state. For example, between about 130–188ka, the ice sheet was more extensive than it is nowadays (Roberts *et al*., 2009), while at the Last Interglacial (Eemian), about 122ka, when July temperatures were at least 5.5 to 8.5°C warmer than now (McFarlin *et al*., 2018), extensive surface melting occurred far from the ice sheet's margin at high elevations (Dahl-Jensen *et al*., 2013), resulting in a contribution to global mean sea-level of 0.5–4.2m relative to the Present (Vasskog *et al*., 2015). Geomorphological mapping and dating of landforms in southeastern Greenland (Roberts *et al*., 2008; Arndt 2018), and sea-floor landforms and acoustic-stratigraphical records in western Greenland (Dowdeswell *et al*., 2014), indicate that at the time of the Last Glacial Maximum (LGM – approximately 22ka) the ice sheet in these regions reached to the continental shelf edge, with striated clasts and other signs of warm-based ice at elevations of up to 740m above sea level (a.s.l.) in the southeast. Geomorphological evidence from northeast Greenland also indicates that ice reached the continental shelf edge (e.g. Arndt *et al*., 2017), but details of the related geochronology are limited or poorly constrained (Larsen *et al*., 2018). It therefore remains possible that the shelf-edge evidence relates to an older advance, with a more modest ice expansion covering only parts of the inner-middle continental shelf during the LGM (Evans *et al*., 2009; Funder and Hansen, 1996; Vasskog *et al*., 2015).

Since the LGM the ice sheet has experienced an overall reduction in volume and extent, albeit at a spatially variable rate and punctuated with relatively brief periods of expansion, for example during the Younger Dryas (a period of widespread cooling, with temporary return to glacial conditions) 12.9–11.7ka (Larsen *et al*., 2016; Vasskog *et al*., 2015). By the end of the mid-Holocene, which was characterized by temperatures ~1°–3°C above the 20th-century average, much of the GrIS had receded beyond its present-day extent, by up to >15km in west Greenland (Young and Briner, 2015), 60km in south Greenland and 20km in north Greenland (Alley *et al*., 2010). Subsequently the ice sheet expanded to reach its maximum Neoglacial extent during the Little Ice Age, 1650 – 1800 CE (Common Era) (Vasskog *et al*., 2015), before receding to its present-day configuration.

This report presents an initial interpretation of the glacial landforms of the Centrumsø area, Kronprins Christian Land (KCL), northeast Greenland, from field and satellite-based mapping, and an account of the sampling of erratics for cosmogenic exposure dating. Mapping and sampling were carried out as part of the Greenland Caves Project 2019 expedition to KCL, in the Northeast Greenland National Park (Moseley, 2020). The overarching aim of the expedition was to augment the existing record of palaeo-climate data from Greenland ice cores (Dahl-Jensen *et al*., 2013) and to extend the record beyond its current limit at 128ka, using calcite flowstone samples collected from solution caves (Moseley *et al*., 2016). Details of preliminary findings included here provide a basis for further investigations that could characterize the fluctuation of the ice sheet, ice caps and glaciers in this remote and sparsely studied area of Greenland, and provide useful corroboration of proxy climate data, including those obtained from cave flowstones.

Field site

KCL lies between the Nioghalvfjerdsbrae (79 degrees north Glacier) calving front, approximately 50km to the southeast, and Mylius-Erichsen Land to the northwest (Fig.1). Investigations were focussed on the region around Centrumsø (Lat: +80.160°, Long: −22.192°; inside the black rectangle in Fig.1). The surrounding topography is dominated by a 400 – 800m plateau consisting of Ordovician–Silurian limestone and dolostone of the Børglum River, Turesø, Odins Fjord and Samuelsen Høj formations to the west, and conglomerate, sandstone and mudstone of the Neoproterozoic Rivieradal Group to the east (Higgins, 2015; Smith and Rasmussen, 2020). The higher-elevation terrain is cut through by several 2–10km-wide, glacially-eroded valleys, which currently host seasonal proglacial rivers carrying meltwater runoff from the GrIS, whose northeastern margin lies to the southwest of the study area, and from several plateau ice caps of between 40 and 1000km^2.

The part of the GrIS that borders KCL is terrestrially terminating and predominantly cold-based, meaning that the ice is frozen to its substrate (MacGregor *et al*., 2016). Precipitation decreases inland from the sub-humid coastal area with 100–300mm annually, towards the ice-sheet margin with less than 70mm (Weidick, 1995). The snow accumulation rate is correspondingly low and, combined with the cold-based ice and minimal basal ice motion, leads to relatively modest flow velocities of less than 40m/yr (Joughin *et al*., 2018). The Prinsesse Caroline-Mathilde Alper, to the east of the study area, are drained by several marine-terminating glaciers that reach speeds of 500m/yr, as well as slower-flowing yet spectacular piedmont lobes (Weidick, 1995).

Whereas surrounding regions have previously been the focus of palaeoclimatic and palaeoglaciological analyses (e.g. Evans *et al*., 2009; Landvik *et al*., 2001; Larsen *et al*., 2016; Zekollari *et al*., 2017), KCL itself has received relatively little attention – perhaps due to logistical difficulties in reaching its interior. It is thought that the GrIS coalesced with local ice caps and extended across Peary Land at the LGM (Landvik *et al*., 2001), where there is clear evidence of a 5–10km ice-cap outlet glacier advance and subsequent retreat during the Younger Dryas cooling, which is thought to have been more prominent than farther south in Greenland due to the distance from the climate-modulating influence of the Atlantic Meridional Overturning Circulation (Larsen *et al*., 2016). Given the proximity of the cold East Greenland current, which flows southwards from the Arctic Ocean through Fram Strait, it seems likely that the Younger Dryas glacial advance will be similarly prominent in KCL. Radio-carbon dating (Landvik *et al*., 2001) and modelling (Zekollari *et al*., 2017) suggest that the Hans Tausen Iskappe (the largest and highest elevation ice cap in Peary Land) partly deglaciated by the end of the mid-Holocene (approximately 6.5–7.5 ka). This agrees broadly with the reconstructed evolution of Flade Isblink (Hjort, 1997), situated c.375km to the northeast, and therefore suggests that many of the smaller, lower elevation, ice caps in northeast Greenland, including those in KCL, probably

***Figure 1**: Map of northeast Greenland showing key locations and features described in the text and the mapping study area, delineated by the black rectangle. Shaded topographical data are from the ArcticDEM (* pgc.umn.edu/data/arcticdem *). Inset shows the GSHHG outline of Greenland (* www.soest.hawaii.edu/pwessel/gshhg *), and the Greenland Mapping Project ice mask (* nsidc.org/data/measures/gimp *).*

disappeared completely during this period, but re-formed later in the Holocene. Nioghalvfjerdsbrae (the large marine-terminating glacier to the south of KCL) responds to subtle variations in climate – principally atmospheric and ocean temperatures – but remains less sensitive than large tidewater glaciers farther south in Greenland, perhaps due to the buttressing effect of fast sea-ice (Larsen *et al*., 2018). The glacier's calving front extended 250–350km beyond its current position at the LGM, but approximately 70km behind it during the mid-Holocene climatic optimum (Larsen *et al*., 2018), coinciding with reduced to variable regional sea-ice cover (Syring *et al*., 2020). Despite its proximity to areas of contemporary or ancient fast ice-flow, KCL has likely remained an inter-ice-stream area since at least the LGM, indicating high preservation potential for glacial landforms that could reveal extra information about local and regional ice-mass fluctuations (e.g. Klages *et al*., 2016).

Modelling of the GrIS during the Last Interglacial, when annual atmospheric temperatures are thought to have been similar to those predicted for the end of the 21st century, indicates that the northeast sector is most vulnerable to atmospheric warming, because even a modest increase in melt removes many years of accumulation (Born and Nisancioglu, 2012). Furthermore, unlike for more southerly parts of the ice sheet, increased temperatures do not bring an associated increase in accumulation (Born and Nisancioglu, 2012), and high basal sliding rates inland of Nioghalvfjerdsbrae (due to elevated geothermal heat flux) mean that bed topography is readily transferred to the ice surface, providing depressions to host surface lakes as surface ablation increases, further hastening mass loss (Igneczi *et al*., 2016). It is clear, therefore, that a better understanding of how glaciers, ice caps and the ice sheet in northeast Greenland have responded to past climatic changes is crucial to prediction of their future behaviour.

Data collection

Geomorphological mapping

Mapping of glacial geomorphology is a well-established technique for delineating the extent and volume of former ice masses and determining the direction and mechanism of ice flow (Wagner, 2017; Chandler *et al*., 2018). Mapping can be undertaken in the field, but due to time and logistical constraints, this is often limited to relatively small areas. Over the past few decades, broad-scale satellite-derived datasets including optical imagery and products such as gridded Digital Elevation Models (DEMs) have enabled large scale mapping by hand digitizing landforms into Geographical Information Systems (GIS). Prior to the field expedition, prospective mapping of landforms associated with former ice margins was undertaken using the 2m-resolution ArcticDEM (pgc.umn.edu/data/arcticdem), derived from stereo photogrammetry of high-resolution optical satellite images (Noh and Howat, 2015), to help target suitable locations for cosmogenic exposure sampling and more detailed field mapping (Chandler *et al*., 2018). A 'hillshaded' version of the DEM was used with artificial illumination from several directions and elevations to highlight relief with different aspects and avoid azimuth bias (Smith and Clark, 2005).

Sampling for cosmogenic exposure dating

Bombardment of exposed rock surfaces by cosmic rays causes spallation reactions, creating isotopes, which accumulate in the surface of the rock (Darvill *et al*., 2013). Quantifying the relative amount of these isotopes can be used to establish how long a rock's surface has been exposed to the atmosphere. Sufficient glacial erosion can remove the surface layer where the isotopes accumulate, effectively re-setting the rock's exposure clock to the time when the ice eroded it (Balco, 2019). This method of dating glacier behaviour, termed '*cosmogenic isotope exposure dating*' has been used successfully across the globe to date the extent and thickness of former ice sheets and glaciers, including extensively in Greenland (e.g. Roberts *et al*., 2013). Beryllium-10 (^{10}Be) is the most common cosmogenic nuclide used in glacial geomorphology for dating glacial fluctuations over Quaternary timescales (approximately the last 1.8 million years) and is produced by nucleonic spallation in quartz (Balco, 2019).

Twenty-one 2kg samples were collected from carefully selected glacial erratics of various lithologies (see Table 1, Fig.2 and Fig.3 for locations) using a hammer and chisel as well as a small angle-grinder. Sampling was limited to erratics because the vast majority of exposed bedrock was quartz-free limestone and dolostone (Higgins, 2015). Erratics were selected based on their size, rounding (evidence of subglacial transport), prominence relative to their surroundings (to minimise the shielding effect of snow cover), and an assessment of their long-term stability (relatively flat ground, far from steep slopes, minimal evidence of periglacial activity and post-depositional erosion) (Darvill *et al*., 2013). Sampling was carried out during several helicopter trips as well as sorties on foot from the campsites in a tributary valley of Grottedal, and on the western flank of Skallingen (Fig.2). Use of a helicopter was also required to enable sampling of sites beyond large glacial meltwater rivers that were impossible to cross on foot. At each site, the elevation angle of the surrounding horizon at regular azimuth increments was also recorded to estimate topographic shielding from cosmic rays (Darvill *et al*., 2013). Results from these samples will form the basis of a later paper, so this report simply describes their location, lithology and geomorphological context and presents additional evidence of former ice cover. Unfortunately, no samples suitable for optically stimulated luminescence dating could be identified.

Results

The preliminary geomorphological mapping revealed many relatively subtle ridges, channels and breaks of slope (Fig.2), which were used to delineate former ice margins. More-prominent moraine ridges were limited to the eastern part of the study area in front of glaciers descending from the Prinsesse Caroline-Mathilde Alper, likely delimiting their Little Ice Age maximum extent. Although this report does not present a systematic classification of landforms from the mapping, moraines, proglacial spillways, ice-marginal meltwater channels, and 'kame' terraces, which form by fluvial deposition between lateral moraines and valley sides (Bennike and Weidick, 2001), were observed in the field. Many of the ice marginal landforms are found within the wide glacially-eroded valleys and these are likely associated with advance of the ice sheet and glaciers spilling down from the larger ice caps, while other less prominent features are restricted to the higher elevation plateaus, and relate to the smaller plateau ice caps, which have only a limited capacity for landscape alteration. Steep-sided, 50–150m-deep, V-shaped valleys that lack a large enough catchment to accumulate sufficient water to form rivers to erode them (especially given the current arid conditions) were also mapped. These are interpreted as proglacial spillways, glaciofluvially eroded valleys that were fed by meltwater flowing off ice masses or ice-marginal lakes. Although it is not possible from this provisional mapping to group landforms into flowsets or to form consistent margins to represent major palaeo-ice-flow configurations, it is nevertheless clear that the landforms of KCL record multiple previous ice extents. These indicate a variety of glacial environments, ranging from smaller plateau ice caps and valley glaciers to larger glaciers emanating from the ice sheet filling the valleys completely. Hence, several of the deeper valleys may offer a detailed chronology of ice mass recession.

Combined with logistical considerations, this initial mapping focused field investigations on four principal areas to sample for cosmogenic isotope dating. Firstly, close to the two campsites, one in a small tributary of Grottedal (Lat: +80.3935°, Long: −21.7814°), and the other on the west side of Skallingen to the south of Centrumsø (Lat: +80.1017°, Long: −22.5236°) (Fig.2). From the Grottedal camp (Camp 1), seven erratics were sampled on foot, five from moraines and two that were resting directly on limestone bedrock (Fig.2A) situated down-valley from the camp towards Vandredalen. These moraines had relief of between 2 and 5m above associated kame terraces (Fig.3A) and were also draped over the strongly bedded Odins Fjord Formation limestones close to the southern side of the valley (Fig.4). In the valley floor there was also a discontinuous ridge that terminated at its eastern end at 300m a.s.l. with a 'tooth' of semi-lithified sediment (Lat: +80.0343°, Long: −21.6179°; Figs 3B and C). This feature was approximately 4m high, 2m wide and 8m long, with its long-axis oriented parallel with the valley, and composed of a matrix-supported, poorly-sorted diamicton, which was interpreted as subglacial till. The till contained numerous angular to sub-rounded non-local clasts, including sandstones of the Palaeoproterozoic Independence Fjord Group, many of which were striated, some on several different orientations.

Sample code	Sample type	Lithology	Geomorphological context	Latitude, Longitude	Altitude (m a.s.l.)
NEGR1_1	rock sample (erratic)	Granite	River/kame terrace	+80.38754, −21.72536	329
NEGR2_1	rock sample (erratic)	Cross-bedded sandstone (Rivieradal Group)	Flat crest of lateral moraine/hill	+80.48515, −21.04627	243
NEGR2_2	rock sample (erratic)	Gneiss	Flat crest of lateral moraine/hill	+80.48374, −21.04884	231
NEGR2_3	rock sample (erratic)	Gneiss	Gently sloping crest of lateral moraine/hill	+80.48804, −21.04028	223
NEGR3_1	rock sample (erratic)	Sandstone (Independence Fjord Group)	Crest of moraine/edge of terrace	+80.37892, −21.66652	317
NEGR3_2	rock sample (erratic)	Granite/gneiss	Moraine/terrace edge orthogonal to main valley	+80.37791, −21.66741	311
NEGR3_3	rock sample (erratic)	Granite/gneiss	On top of (glacially) abraded limestone bedrock	+80.37017, −21.64405	312
NEGR3_4	rock sample (erratic)	Granite/gneiss	On top of (glacially) abraded limestone bedrock	+80.37034, −21.64525	314
NEGR4_1	rock sample (erratic)	Sandstone (Independence Fjord Group)	Crest of lateral moraine/edge of terrace	+80.35440, −21.57773	324
NEGR4_2	rock sample (erratic)	Quartz dolerite	Crest of lateral moraine/edge of terrace	+80.35426, −21.56998	326
NEGR4_3	rock sample (erratic)	Sandstone (Independence Fjord Group)	Crest of lateral moraine/edge of terrace	+80.35677, −21.57936	331
NEGR5_1	rock sample (erratic)	Granite/gneiss	Shallow slope on shoulder of hill	+80.28122, −21.41222	757
NEGR5_2	rock sample (erratic)	Granite/gneiss	Shallow slope on shoulder of hill	+80.28020, −21.41448	775
NEGR5_3	rock sample (erratic)	Granite/gneiss	On top of shallow dipping mudstone bedrock	+80.29427, −21.32021	427
NEGR5_4	rock sample (erratic)	Sandstone (Independence Fjord Group)	Flat crest of moraine ridge	+80.29431, −21.30542	376
NEGR6_1	rock sample (erratic)	Sandstone (Independence Fjord Group)	Steeply-bedded prominent limestone ridge	+80.08662, −22.53498	512
NEGR6_2	rock sample (erratic)	Granite/gneiss	Sediment terrace on limestone bedrock	+80.08758, −22.53432	488
NEGR6_3	rock sample (erratic)	Granite/gneiss	Wide rocky sediment terrace on hill shoulder	+80.08782, −22.53888	488
NEGR6_4	rock sample (erratic)	Sandstone (probably Rivieradal Group)	Wide sediment terrace on shoulder of hill	+80.08828, −22.54251	480
NEGR7_1	rock sample (erratic)	Sandstone (Independence Fjord Group)	Gently-sloping soil-covered terrace	+80.11333, −22.51622	173
NEGR7_2	rock sample (erratic)	Sandstone (Independence Fjord Group)	Gently-sloping rocky terrace with patchy soil cover	+80.11554, −22.48450	159

Table 1: *Details of samples acquired for cosmogenic exposure dating. See Figure 2 for locations.*

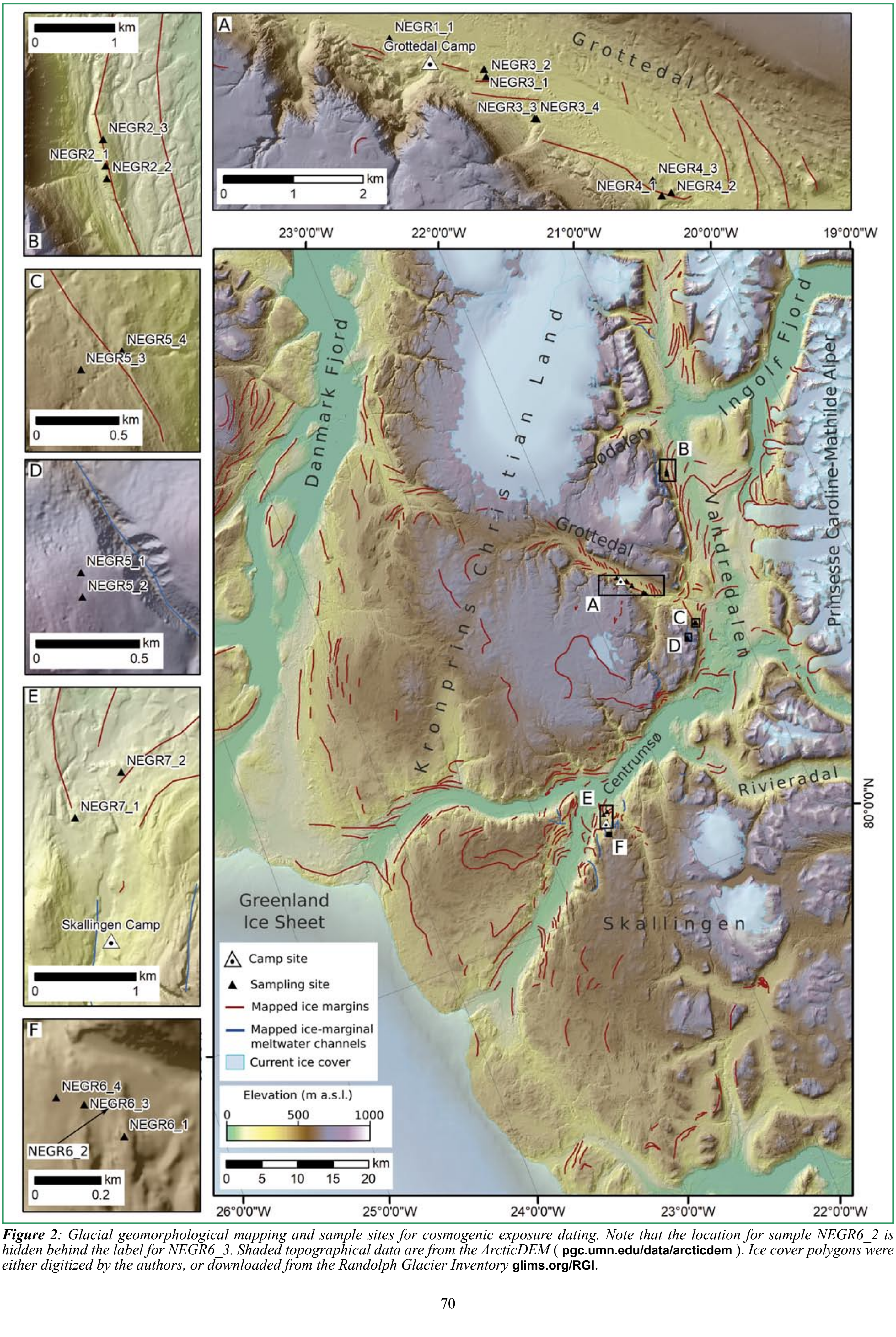

Figure 2*: Glacial geomorphological mapping and sample sites for cosmogenic exposure dating. Note that the location for sample NEGR6_2 is hidden behind the label for NEGR6_3. Shaded topographical data are from the ArcticDEM (* **pgc.umn.edu/data/arcticdem** *). Ice cover polygons were either digitized by the authors, or downloaded from the Randolph Glacier Inventory* **glims.org/RGI**.

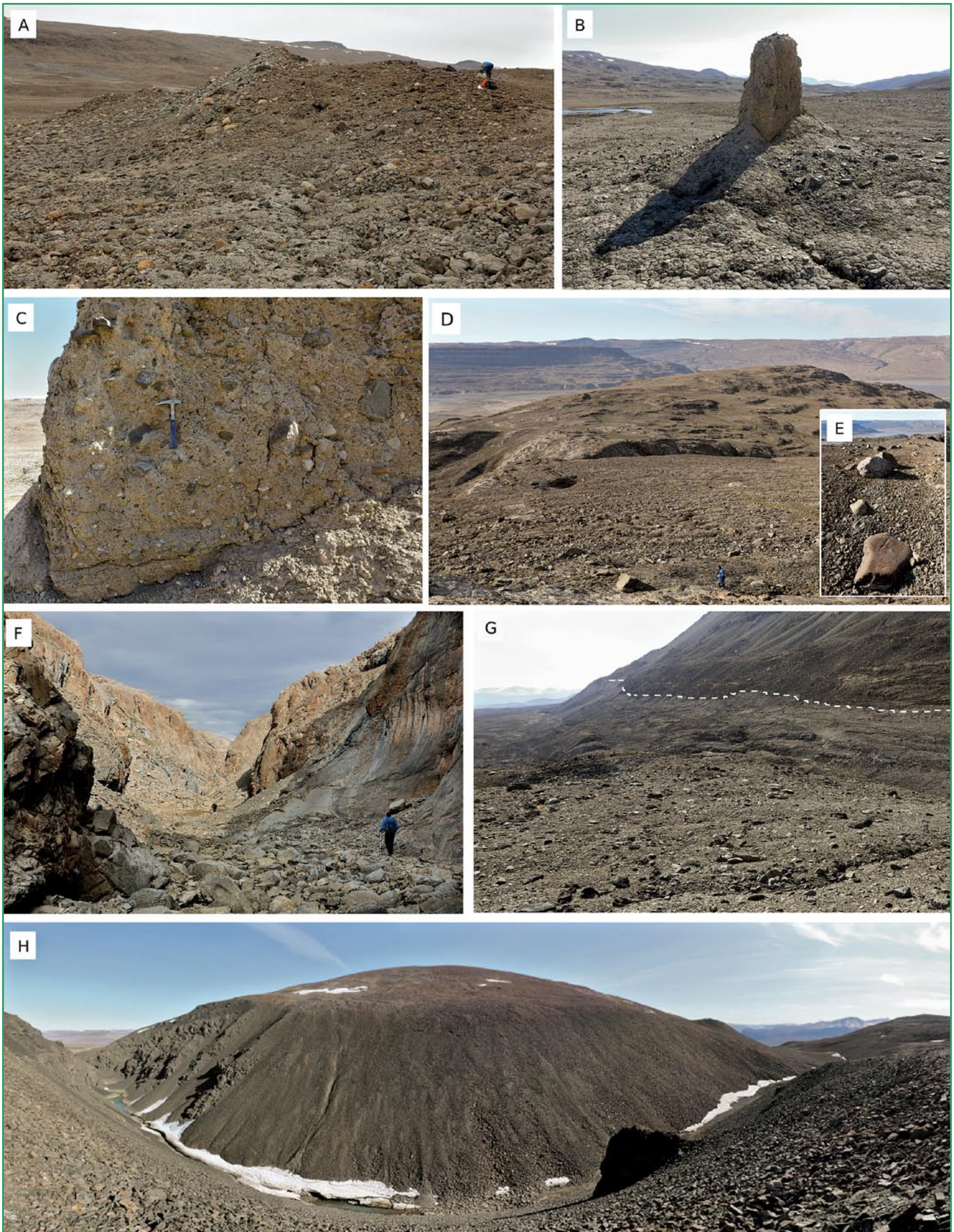

Figure 3: *Photo mosaic of features of interest.*
A: *Moraine superimposed on terrace in Grottedal.* ***B***: *Diamicton 'tooth' in Grottedal looking down-valley.* ***C***: *Close-up of diamicton tooth (note the geological hammer is 33cm long).* ***D***: *Approximately kilometre-scale streamlined bedrock landform west of the Skallingen camp.* ***E***: *Cobble- to boulder-sized striated clasts at 540m elevation above the Skallingen camp.* ***F***: *Evidence of substantial glacio-fluvial erosion in the spillway just south of the Skallingen camp.* ***G***: *Possible trimline in Vandredalen, looking south from close to Sødalen.* ***H***: *Spillway that cuts between Grottedal and Vandredalen. The thalweg undulates between 650 and 690m a.s.l. [All photos: Andrew Sole.]*

Figure 4*: An oblique aerial photograph, taken from a helicopter, showing contemporary river and mapped ancient kame terraces and moraines along the southern side of Grottedal, just west of the Grottedal camp. [Photo: Andrew Sole.]*

From the Skallingen camp (Camp 2) a series of 'dip-stick' samples (Davis *et al*., 2017) were collected from erratics spanning from 190m to 540m a.s.l. (Figs 2E and 2F). The aim of this sampling strategy is to quantify the rate of ice thinning, as a complement to samples that provide a lateral recession rate. Large-scale streamlined landforms and smoothed limestone–dolostone bedrock were observed (Lat: +80.1068°, Long: −22.5521°; Fig.3D) at 360m and also striated, cobble–boulder-sized, clasts at elevations >500m (Lat: +80.0859°, Long: −22.5359°; Fig.3E). A traverse of a mapped proglacial spillway just to the south of the Skallingen camp (Lat: +80.0990°, Long: −22.5448°; Fig.3F), revealed evidence of substantial glaciofluvial erosion in the channel, but also truncation and streamlining of the top of the channel rock walls consistent with subglacial abrasion. There are several possible explanations for this. The channel might initially have formed beneath the ice as a Nye channel transporting basal meltwater, and could then also have been utilized as a subaerial meltwater channel as the ice thinned and receded (Jansen *et al*., 2014). Alternatively, the channel might be a far older fluvial feature that was simply modified at its top during later glaciation by basal sliding of overlying ice. Given the prevalence of limestone bedrock in the study area, and the cave systems documented by the Greenland Caves project team (Moseley *et al*., 2020), it is possible that the formation of the proglacial spillways exploited pre-existing cave systems (Woodward and Hughes, 2019).

Additional sampling forays were made by helicopter. From the Grottedal camp a prominent elongated hill separated from the main valley side 10km south of the head of Ingolf Fjord and the entrance to Sødalen (Lat: +80.4862°, Long: −21.0449°, Fig.2B) was targeted, where three erratics were sampled. The preliminary mapping indicated that this site was close to the greatest extent of moraines whose shape, size and locational context suggest that they were formed by expansion of the ice sheet rather than by local ice caps and glaciers. There was evidence of a glacial trimline (likely indicative, in this case, of the elevation of a previous ice surface) at approximately 300m a.s.l. on the west side of the valley adjacent to the sampling sites, whose elevation increased gradually towards the south (Fig.3G). A second set of dip-stick samples were collected from four separate erratics around the confluence of Grottedal and Vandredalen (Figs 2C and 2D) between 400 and 800m a.s.l. The higher elevation samples came from erratics just southwest of a steep-sided, 80m-deep proglacial spillway, which cut between Grottedal and Vandredalen (Fig.3H).

The mapping and field observations of landforms and sediments enable some initial interpretations to be made about the type of past glacial activity in this region of KCL. In general, moraine ridges are relatively small (2 – 5m in height) and lack a prominent peak, broadly reflecting limited sediment availability, and suggesting some post glacial re-mobilization of sediment (e.g. by slumping and periglacial activity) or deflation caused by melting of the moraines' ice cores. These less prominent features are restricted to the higher elevation plateaus, and relate to the smaller plateau ice caps, which have only a limited capacity for landscape alteration. However, observations of striated clasts at >500m a.s.l., sub-rounded erratics at up to 800m a.s.l. (some of which were sampled) and streamlined bedrock at up to 360m a.s.l., all indicate sliding between the ice and the bedrock and temperate basal conditions. Such conditions were likely present only beneath thick ice either during extensive glacial conditions when the ice sheet overran the highlands of KCL and Skallingen, or beneath large valley glaciers emanating from the ice sheet. In addition, commonly situated between moraines and valley sides, there are numerous terraces, which are likely kame terraces formed by glaciofluvial transport and deposition (Bennike and Weidick, 2001), and ice-marginal meltwater channels were observed. The prevalence of these landforms indicates significant glaciofluvial action requiring large volumes of meltwater, suggesting this region experienced high-volume melt in short intensive summers during past ice recession events.

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