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Multiple Late Holocene surges of a High-Arctic tidewater glacier system in Svalbard

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Abstract:

Most large tidewater glaciers in Svalbard are known to have surged at least once in the last few hundred years. However, very little information exists on the frequency, timing or magnitude of surges prior to the Little Ice Age (LIA) maximum in ~1900. We investigate the sediment-landform assemblages produced by multiple advances of the Nathorstbreen glacier system (NGS) in order to reconstruct its Late Holocene surge history. The glacier has recently undergone one of the largest surges ever observed in Svalbard, advancing ~16 km from 2008 to 2016. We present flow velocities and ice-marginal observations (terminus change, proglacial geomorphological processes) from the later stages of this surge. A first detailed assessment of the development of a glaciotectonic mud apron within the fjord during a surge is provided. Geomorphological and sedimentological examination of the terrestrial moraine areas formed prior to the most recent surge reveals that at least two advances were responsible for their formation, based on the identification of a previously unrecognised ice-contact zone recorded by the distribution of sediment facies in coastal exposures. We distinguish between an outer, older advance to the distal part of the moraine system and an inner, younger advance to a position ~2 km upfjord. Radiocarbon dating of shells embedded in glaciotectonic composite ridges formed by the onshore bulldozing of marine mud during the outer (older) of the two advances shows that it occurred at some point during the interval 700-890 cal. yr BP (i.e. ~1160 AD), and not during the LIA as previously assumed. We instead attribute the inner (younger) advance to the LIA at ~1890. By combining these data with previous marine geological investigations in inner and outer Van Keulenfjorden, we demonstrate that NGS has advanced at least four times prior to the recent 2008-2016 surge: twice at ~2.7 kyr BP, at ~1160 AD, and in ~1890. This represents a unique record of the timing and magnitude of Late Holocene tidewater glacier surges in Svalbard.

Keywords: glacier surge; glacial geomorphology; glaciology; Little Ice Age; Holocene; Svalbard

1. Introduction

Marine-terminating or tidewater glaciers in the High-Arctic archipelago of Svalbard have undergone accelerated mass loss in recent decades (Nuth et al., 2007, 2010; Błaszczyk et al., 2009; Carr et al., 2017). Most of these glaciers are known to experience flow instabilities called surges (Sevestre and Benn, 2015), whereby they periodically undergo rapid advances for short periods of between three to ten years, before returning to a multi-decadal quiescent phase characterised by frontal thinning and retreat (Murray et al., 2003; Sund et al., 2009; Sevestre et al., 2018). Tidewater glacier surges result in rapid ice mass loss to the ocean and have a significant impact on the climate, oceanography, sediment budget, and geomorphology of fjord systems (e.g. Elverhøi et al., 1983; Hald et al., 2001; Plassen et al., 2004; Forwick et al., 2010).

The current state of knowledge on surging in Svalbard is largely based on observations from satellite imagery since the 1970s. Glacier surges pre-dating this are usually identified from aerial photographs (1930s onwards) or historical observations/written accounts (since the Little Ice Age (LIA) maximum ~1900) of characteristic surge evidence, such as widespread surface crevassing and/or rapid terminus advances (e.g. Liestøl, 1969; Hagen et al., 1993; Bennett et al., 1999; Ottesen et al., 2008; Flink et al., 2015). Very little is known about surge behaviour prior to the LIA maximum. In terms of general glacier behaviour at this time, some land-terminating glaciers in Svalbard are known to have experienced multiple episodes of ice expansion during the Late Holocene (i.e. since ~4 kyr BP) in response to a decline in summer insolation (Miller et al., 2017). The timings of maximum advances of tidewater glaciers during the Late Holocene display a large amount of variability across Svalbard. In some areas, such as inner Isfjorden, the LIA is thought to represent the Holocene maximum position (e.g. Plassen et al., 2004; Ottesen and Dowdeswell, 2006; Mangerud and Landvik, 2007). Other fjords record much older, more extensive tidewater advances (Hald et al., 2004; Evans and Rea, 2005; Kempf et al., 2013; Flink et al., 2017; Larsen et al., 2018). Many of these tidewater glaciers are inferred or known to be of surge-type, raising the question as to whether previous advances (LIA maximum or earlier) were glaciodynamic surges or were in response to climate forcing (e.g. Farnsworth et al., 2017; Philipps et al., 2017; Streuff et al., 2017a).

The best way to determine possible surging that predates observational records is by investigating sediment-landform assemblages, as surge behaviour is known to produce a diagnostic suite of landforms (Evans and Rea, 1999; Ottesen et al., 2017). Numerous studies have investigated englacial, geomorphological and sedimentological evidence exposed at the receding margins of quiescent phase surge-type glaciers in Svalbard in order to better understand the processes that occur during surges (e.g. Boulton et al., 1996, 1999; Glasser et al., 1998a; Bennett et al., 1999; Christoffersen et al., 2005; Larsen et al., 2006; Ottesen et al., 2008, 2017; Kristensen et al., 2009a,b; Lovell et al., 2015; Sobota et al., 2016; Larsen et al., 2018; Lyså et al., 2018). For tidewater glacier surges, this evidence is typically recorded on the sea floor (e.g. Solheim and Pfirman, 1985; Plassen et al., 2004; Ottesen et al., 2008, 2017; Forwick et al., 2010; Flink et al., 2015, 2017; Streuff et al., 2015, 2017a; Burton et al., 2016; Farnsworth et al., 2017). Field observations of the active phase of glacier surges are rare (e.g. Glasser et al., 1998b; Murray et al., 1998; Kristensen and Benn, 2012), but are crucial for linking surge processes to the geomorphological evidence left behind. This ensures interpretations based on exposed basal ice, englacial debris-rich structures, and/or sediment-landform assemblages (whether in marine or terrestrial positions) are more robust.

In order to contribute towards closing aforementioned gaps, we aim to reconstruct the history of Late Holocene advances in Van Keulenfjorden recorded within marine and terrestrial sediment-landform assemblages. We do this by investigating:

(1) active geomorphological processes at the glacier margin during a recent surge;

(2) the geomorphology of the terrestrial moraine areas in the inner fjord; and

(3) sediment facies exposed within the terrestrial moraine areas.

We combine this information with radiocarbon dating and previous marine geological investigations in order to produce a revised chronology of glacier advances.

2. Nathorstbreen glacier system (NGS) surge history

The Nathorstbreen glacier system (NGS) consists of several major tributary glaciers and currently terminates as a ~5 km-wide tidewater front in Van Keulenfjorden, a ~30 km-long fjord in southern Spitsbergen (77°30.55'N, 15°57.67'E) (Fig. 1). Nathorstbreen is the central and longest flow-unit (~39 km in 2017) in the system and drains from the accumulation area of Ljosfonn at an elevation of up to 700 m a.s.l. Radio echo sounding data from the 1980s indicate that NGS was over 300 m thick along its centre-line and warm based, with a cold surface layer up to 200m thick. The cold layer intersected with the bed in the terminal zone at this time (Dowdeswell et al., 1984). The other major NGS flow-units confluent with Nathorstbreen are Polakkbreen and Zawadzkibreen to the west and Dobrowolskibreen to the east. The system recently experienced the largest surge in Svalbard since the 1930s surges of Bråsvellbreen and Negribreen (Liestøl, 1969; Hagen et al., 1993), advancing >15 km from 2008 onwards and expanding onto the two moraine areas Nordre and Søre Nathorstmorenen at the lateral fjord margins (Fig. 1). Prior to this, the combined front of NGS (including neighbouring Liestølbreen and Doktorbreen) is thought to have advanced to more-extensive downfjord positions than reached in 2016 on at least three separate occasions: once during the Little Ice Age (LIA) in ~1870-80 (Ottesen et al., 2008) and twice at ~2.7 kyr BP (Kempf et al., 2013).

2.1 Recent surge

The recent NGS surge is described in detail in Sund et al. (2014) up until summer 2013, with the key details briefly summarised here. The combined tidewater terminus began to advance from inner Van Keulenfjorden sometime after October 2008 (Sund et al., 2014) (Fig. 1), signalling the onset of the frontal advance phase of the surge (stage 3 in Sund et al., 2009). Prior to this, surface measurements in 2000-01 showed that the upper basins of the four main flow-units active during the surge (Nathorstbreen, Dobrowolskibreen, Polakkbreen and Zawadzkibreen) were recording velocities of up to 1 m d^{-1}, representing an acceleration of the order of 100 times' quiescent phase velocities of 0.01-0.02 m d^{-1} measured in 1992 (Sund et al., 2014). This indicates that the early stages of surge initiation (stage 1 in Sund et al., 2009) had begun in all contributing flow-units up to eight years before the start of the tidewater frontal advance. Between 2003 and 2008, Dobrowolskibreen, Polakkbreen and Zawadzkibreen were all observed to thin in their upper basins and thicken at lower elevations, demonstrating that the downglacier propagation of mass was underway (stage 2 in Sund et al., 2009). The onset of stage 2 in Dobrowolskibreen coincided with the appearance of large transverse crevasses in the upper basin, which by 2006 were present all the way to the terminus of the flow-unit. By 2007, dense crevasse fields were also observed in the upper and middle parts of Zawadzkibreen and had expanded to its entire length by 2008 (Ottesen *et al.*, 2008; Sund et al., 2014). By contrast, surface crevassing of both Nathorstbreen and Polakkbreen was still limited in 2008 and did not become widespread until after the combined tidewater front had begun to advance (Sund et al., 2014).

The first indications of terminus advance and calving were observed at the front of Dobrowolskibreen in late 2007, followed by the abrupt advance of the combined terminus sometime after October 2008 when velocities increased simultaneously (and by a factor of three compared to 2007 values) within the Nathorstbreen and Zawadzkibreen flow-units (Sund et al., 2009, 2014; Sund and Eiken, 2010). By September 2009, the terminus had advanced ~8 km at the centre-line into the deepest part of the inner fjord (~70 m according to pre-surge bathymetry), representing the largest advance in a single year during the surge (Figs 1 and 2a). The highest recorded velocities throughout the duration of the surge were also during this period, averaging 20 m d^{-1} from March-May 2009 and 25 m d^{-1} from May-September 2009 at the front (Sund et al., 2014). All four contributing flow-units appeared to advance at a similar rate at this time, resulting in the combined front maintaining its overall shape and width and precluding the development of looped moraines. By 2010, the terminus began to spread towards the bay in front of the former tributaries Doktorbreen and Liestølbreen (not active during the surge), with velocities reducing to 12.9 m d^{-1} across the front in the second part of 2010 (Sund et al., 2014). The terminus continued advancing northwards and by August 2011 had advanced onto Nordre Nathorstmorenen, effectively closing off the bay at the front of Doktorbreen and Liestølbreen. From August 2011 until August 2012, the front advanced a further ~1.5 km along the central axis of Van Keulenfjorden, recording average velocities of ~5 m d^{-1} in the period 2011-12 (Sund et al., 2014). By July 2012, when fieldwork for this study was conducted, the front had advanced into a shallow (~20 m deep according to pre-surge bathymetry; Ottesen et al., 2008) and narrow part of the fjord and as a result ceased calving (Figs 1 and 2b). In 2011-12 there was a reduction in both the rate of terminus advance (to ~1 m d^{-1}) and surface velocities, with velocities in winter 2012 (~2 m d^{-1}) about one-third of those in winter 2011 (~6 m d^{-1}; Sund et al., 2014). Between December 2012 and January 2013, frontal velocities remained ~2 m d^{-1} (Schellenberger et al., 2016). The front was still advancing in August 2013 at the end of the period covered by the Sund et al. (2014) observations, and extended ~0.9 km further downfjord compared to the August 2012 position. Between 2008 and 2013, NGS advanced a total of ~15 km (Fig. 1), with an additional ~3 km in length estimated to have been lost through calving in the period 2009-2012 (Sund et al., 2014).

2.2 Little Ice Age maximum surge

There is evidence that NGS surged during the Little Ice Age (LIA) based on historical maps and observations (Dunér and Nordenskiöld, 1865; Hamberg, 1905; Gripp, 1929), and marine geological investigations (Ottesen et al., 2008). Photogrammetric mapping in 1898 by Hamberg (1905) shows a tidewater glacier front with a large calving bay terminating ~3 km upfjord from the northern extents of Nordre and Søre Nathorstmorenen (Fig. 1). An earlier map by Dunér and Nordenskiöld (1865) shows the combined glacier front in 1864 terminating at a position a further ~9 km upfjord from the 1898 terminus. From this, Ottesen et al. (2008) inferred that NGS advanced sometime after 1864, and by 1898 was in the early stages of retreat from the maximum position reached during this advance. The maximum position reached prior to 1898 was suggested to be immediately downfjord of the northern extents of Nordre and Søre Nathorstmorenen (Liestøl, 1973, 1977; Ottesen et al., 2008) (Fig. 1). This implies that between 1864 and 1898 NGS advanced ~12 km, followed by a retreat of ~3 km (Ottesen et al., 2008). Assuming an average retreat rate comparable to the ~160 m a^{-1} that Nathorstbreen underwent in the subsequent quiescent phase between 1898 and 2008 (~18 km in 110 years), this suggests that the maximum position was reached ~15-20 years prior to 1898, in the late 1870s or early 1880s (Liestøl, 1973, 1977; Ottesen et al., 2008).

Several pieces of evidence suggest that the LIA advance was a surge. Firstly, the glacier advanced ~12 km within a period of ~20 years, which is comparable in size and timescale to the recent surge and a number of other observed surges of Svalbard glaciers (Murray et al., 2003). Secondly, Hamberg (1905) mapped looped moraines on the glacier surface in 1898, which are diagnostic of surges (cf. Meier and Post, 1969). Thirdly, swath bathymetry data from inner Van Keulenfjorden presented by Ottesen et al. (2008) revealed a submarine landform assemblage that is consistent with surging. This included: (i) glacial lineations, formed beneath fast-flowing ice (e.g. King et al., 2009); (ii) a large terminal moraine located just beyond the northern extents of Nordre and Søre Nathorstmorenen (Fig. 1), interpreted to be glaciotectonic in origin (Ottesen et al., 2008); (iii) geometrical ridges, interpreted as crevasse squeeze ridges formed by the injection of seafloor sediments into basal crevasses (e.g. Lovell et al., 2015); and (iv) annual retreat moraines, marking minor winter readvances during terminus retreat in the quiescent phase (e.g. Flink et al., 2015). This landform assemblage, or slight variations of it, is found at the marine margins of several other known surge-type glaciers in Svalbard and is suggested to be diagnostic of tidewater glacier surging (Ottesen et al., 2008, 2017; Flink et al., 2015).

2.3 Late Holocene maximum surge-like advances

The large terminal moraine and debris flow lobe mapped by Ottesen et al. (2008), and assumed to be of LIA age, were investigated and reinterpreted by Kempf et al. (2013) based on a combination of swath bathymetry data, high-resolution seismics, and sediment cores. The seismic data showed that the debris lobe actually consisted of two stacked units, which could be correlated to a sediment core (JM07-014) collected from just beyond their distal margins (Fig. 1). The age-depth model developed from the core indicates that both debris flow lobes were deposited during a period of rapid sediment accumulation between 2.61 and 2.79 cal. kyr BP, thus suggesting that these, and the terminal moraine complex, are considerably older than the previously-assumed LIA age (Kempf et al., 2013). The implication is that the LIA surge did not reach the crest of the terminal moraine complex, which was formed by the two ~2.7 kyr BP advances, as it would presumably have reworked the ridge and disturbed the debris flow lobes. This was not apparent from the seismic profiles or the core. Instead, Kempf et al. (2013) suggested that the LIA surge must have terminated to the east of the large moraine. Kempf et al. (2013) concluded that the two advances at ~2.7 kyr BP were surge-like, and estimated a time interval between deposition of the two lobes of ~100-150 years based on the thickness of the acoustically stratified sediments. This is comparable to the modern NGS surge return period of ~130 years.

3. Methods

The glacier margin from 2008-2017 was mapped from ASTER, Landsat (ETM+ and OLI) and Sentinel-2 satellite imagery (acquired from earthexplorer.usgs.gov), apart from the 2009 margin, which was taken from Sund et al. (2014). Flow velocities were derived by feature-tracking on TerraSAR-X (2013-2015) and Sentinel-1 (2015-2017) satellite image pairs. The geomorphology of Nordre and Søre Nathorstmorenen was mapped from uncorrected 1:15,000 scale digital aerial photographs (acquired by the Norwegian Polar Institute (NPI) in summer 2011) and during fieldwork in July 2012 by adhering to the general mapping principles outlined in Chandler et al. (2018). Sediment sections were cleaned before being logged as scaled two-dimensional or vertical logs. Sediment facies were identified based on physical characteristics (e.g. grain size range, sedimentary structures) following Evans and Benn (2004). Samples of 50 sandstone clasts were collected for clast shape and roundness analysis following Benn and Ballantyne (1994). Clast shape data were plotted as ternary diagrams using TriPlot (Graham and Midgley, 2000), clast roundness data were plotted as frequency distributions, and C_{40}, RA and RWR indices were calculated (see Lukas et al., 2013). Bulk sediment samples were oven (diamict) or freeze (mud) dried and dry-sieved to separate the fraction finer than 2 ϕ (250 µm). The finer fraction was treated with hydrogen peroxide and disaggregated with a dispersing agent before being analysed using a Beckman-Coulter Laser Sizer. These were plotted as grain size distributions using GRADISTAT (Blott and Pye, 2001). Paired and individual bivalve shells were radiocarbon dated at the ^{14}CHRONO Centre for Climate, the Environment and Chronology at Queen's University Belfast. The radiocarbon ages were calibrated using OxCal 4.3 (Bronk Ramsey and Lee, 2013; Bronk Ramsey, 2017) and the internationally accepted Marine13 radiocarbon calibration curve (Reimer et al., 2013), using a marine reservoir correction with a ΔR value of 70±30 years (Mangerud et al., 2006; Mangerud and Svendsen, 2018). All radiocarbon ages are reported in the text as calibrated years before present (cal. yr BP or cal. kyr BP). Key ages younger than 1000 cal. yr BP are also presented as years AD for comparison with reported historical and modern dates. Bayesian modelling within OxCal 4.3 was used to produce a robust age estimation for the likely timing of an identified glacial advance by constructing a simple '*Phase*' model. This included using selected radiocarbon ages of bivalve shells, which are assumed to be slightly older than (or maximum-limiting) the advance, and using the '*Boundary End'* age function within the model.

4. The surging margin of the Nathorstbreen glacier system (NGS)

During the recent surge, NGS advanced onto the terrestrial lateral moraine areas (Figs 1 and 2), providing a rare opportunity to observe ice-marginal processes during a surge and investigate the geomorphological impact on the fjord and surrounding terrestrial areas.

4.1 Frontal change and flow velocities 2013-2017

The glacier front continued to advance from July 2013 until at least March 2016, showing that the surge was still ongoing, albeit at a much-reduced rate of terminus change than in preceding years (Figs 1 and 3). We measured flow velocities close to the front, recording an overall deceleration from 2 m d^{-1} in early 2013 to ~0.1 m d^{-1} in late 2017, punctuated by dramatic acceleration peaks in the summer months that coincide with precipitation events (Fig. 4). The front advanced ~500 m in the centre of the fjord between July 2013 and July 2014. Flow velocities increased abruptly in summer 2013 from ~2 m d^{-1} in June to ~5 m d^{-1} in July, decreasing to <0.5 m d^{-1} in winter 2013-14 (Fig. 4). Frontal velocity peaked again at 4 m d^{-1} in July 2014, before dropping to <0.5 m d^{-1} from September 2014 through to April 2015. A data gap has resulted in no identifiable velocity peak in summer 2015, but the terminus advanced ~300 m from July 2014 to July 2015 (Figs 3 and 4). The front continued to advance a further ~200 m from July 2015 until March 2016. Velocities reduced from ~1 m d^{-1} in August 2015 to <0.5 m d^{-1} in winter 2015-16 (Fig. 4). A further abrupt velocity increase occurred in summer

2016 from ~0.5 m d^{-1} in May to almost ~2.5 m d^{-1} in July (Fig. 4). Velocities reduced to ~0.5 m d^{-1} in late 2016 and to ~0.1 m d^{-1} in early 2017. As of August 2017, most of the glacier front had receded relative to its 2016 position (Fig. 3), but it still experienced an abrupt summer speed-up in July 2017 to ~1 m d^{-1}. By August 2017, velocities had reduced to ~0.1 m d^{-1}, comparable to pre-advance values in 2007. Together with the frontal recession, this indicates that the active surge phase terminated sometime during winter 2016-17 (Figs 3 and 4). The total advance during the 2008-2016 surge was ~16 km, with ~1 km of the advance occurring in the later stages of the surge from 2013-2016 (Fig. 1).

4.2 Ice margin observations in July 2012

When fieldwork was conducted in July 2012, the central and most-extensive part of the advancing terminus had reached a position approximately level with the distinct curved, spit-like arm of Nordre Nathorstmorenen (Fig. 1). Despite having advanced onto the moraine areas, the ice itself could not be accessed in 2012 due to the complex, fragmented nature of the margin, the extensive areas of mud, and the presence of large (up to 15 m wide) and turbulent meltwater channels along the full lengths of both lateral terrestrial margins (Figs 5, 6a and 6b). Chaotic crevassing was observed across the ~10 km of the margin that was explored, including the ~5 km of the front terminating in the fjord. Based on satellite images and aerial photographs throughout the duration of the surge and observations from a helicopter flight over the glacier in March 2011, this extended along the entire length of the terrestrial margin. The chaotic crevassing was evident as large (ranging from ~5-30 m high), heavily-fractured blocks with multiple distinct, typically sharp, pinnacles (Figs 6a and 6c). The orientation of the blocks and pinnacles varied, ranging from vertical and near-vertical, those tilted at up to ~45° (in all directions), through to those that had clearly toppled over and/or broken off. The latter were typically debris-covered and formed dense groups stranded within the areas of mud and shallow fjord waters at the margin. Due to this, there was no clearly-defined ice cliff (as found at calving margins). Instead, the margin was heavily fragmented and stepped in height in most places, increasing from ~2-5 m amongst the jumble of toppled and broken-off debris-covered blocks up to ~20-30 m-high clean-ice pinnacles, often over a distance of tens of metres. Refrozen breccias of smaller ice fragments and blocks were commonly observed within crevasses and between large blocks, and some vertical and near-vertical crevasses contained muddy debris extending up to tens of metres above the fjord level (Fig. 6b). Areas of debris-rich ice were observed all along SW margin (Fig. 6b). Where the front terminated directly on the moraine area, the moraine surface mostly appeared undisturbed, aside from at least one location at the SW margin where part of the moraine had been excavated in front of the margin.

4.3 Mud apron

4.3.1 Description - A large area of seafloor mud located above the waterline first appeared within the fjord across most of the tidewater front in summer 2012 (Figs 3 and 6), hereafter referred to using the non-genetic term mud apron (Kristensen et al., 2009a). By mid-July 2012, the mud apron extended up to 500 m in length from the NE margin and had begun to encroach onto the spit-like arm of Nordre Nathorstmorenen (Figs 6c and 6d). The mud apron covered ~2 km^2 across the entire front at this time, and also extended upglacier at the SW lateral margin, forming a ~10-20 m-wide border adjacent to the channel (e.g. Fig. 6b). Beyond the mud apron in the centre of the fjord, the water was extremely turbid and <1 m deep ~1 km downfjord from the glacier front (position marked by X in Fig. 3). The pre-surge water depth in this part of the fjord was ~20 m (Fig. 1). The shallow water depth was also apparent from the large number of icebergs stranded in turbid water in front of the margin, in addition to those surrounded by the mud apron itself. Stranded icebergs were found all across the central part of the front and towards the area where the SW lateral channel emerged into the fjord (Fig. 6e). The glacier was clearly no longer calving into deep water across the entire front in July 2012, and the only floating ice found in inner Van Keulenfjorden were tiny berglets transported into the fjord along the lateral channels. The mud apron persisted in the fjord at the advancing margin from July 2012 to March 2016, by which time it almost entirely covered the spit-like arm of Nordre Nathorstmorenen (Fig. 3). Throughout this period, the mud apron was present at both the SW and NE margins, and continued to be most extensive at the latter, but was not visible above the waterline in the central part of the front. By August 2017, the margin had started to recede, exposing parts of the mud apron that had been beneath the glacier in previous years (Fig. 3). The surface of the mud apron was examined where it encroached onto the spit-like arm of Nordre Nathorstmorenen (Figs 6c, 6d and 6f). It was characterised by flat areas of highly saturated, slurry-like mud with frequent surface pools (Figs 6d and 6f) and running water. Flow structures and small (~1 m high and several metres long) transverse ridges were also visible. The sediment sampled from the mud apron (see Fig. 5 for sample locations) was a clayey silt, with peaks in the medium and coarse-grain silt ranges (Fig. 7) and very few larger clasts. A small lobe of the mud apron located on the moraine surface in summer 2012 was observed to have advanced by tens of centimetres from one day to the next relative to marker cairns, confirming that it was actively flowing in front of the advancing ice margin.

4.3.2 Interpretation: glaciotectonic remobilisation of fjord-floor sediments - The position, morphology, and sedimentary characteristics of the mud apron are consistent with a continuously-failing mobile moraine formed through the bulldozing of fjord-floor sediments in front of the advancing glacier (Fig. 8). The lack of clasts within the mud apron indicate it has a marine rather than a subglacial origin (e.g. Boulton et al., 1996; Kristensen et al., 2009a; King et al., 2016). The formation of the mud apron is best explained by the tectonic thickening of fjord-floor sediments in response to glacial push. The observed low gradient of both the subaerial and submarine parts of the mud apron are consistent with the oversteepening and failure of fjord-floor sediments with low shear strength (Kristensen et al., 2009a). The transverse ridges within the mud apron, which are typically aligned parallel to the ice margin, are interpreted as minor compressional ridges formed as a result of glacial push (Boulton et al., 1996; Kristensen et al., 2009a). The presence of flow structures on the mud apron surface and the measured apron advance of tens of centimetres a day indicate that it was actively flowing, supporting the interpretation of a continuously-elevating and -failing sediment mass.

5. Geomorphology of Nordre and Søre Nathorstmorenen

Nordre and Søre Nathorstmorenen extend for ~15 km along both sides of inner Van Keulenfjorden and cover a total area of ~40 km^2 (Figs 1 and 5). The moraine areas consist of hummocky terrain with multiple ponds and sediment flows, networks of geometrical ridges, and multi-crested composite ridge systems.

5.1 Hummocky terrain

5.1.1 Description - The terrain across both Nordre and Søre Nathorstmorenen is characterised by hummocks and ridges interspersed with ponds, depressions and sediment flows, with a typical elevation range of ~5-10 m (Figs 9a, 9b and 10a). Most of the topography consists of irregular hummocks and ridges, which in places are interspersed with organised networks of sharp-crested geometrical ridges (see *Section 5.2*). The ponds are widely distributed across both moraine areas. At Nordre Nathorstmorenen, the densest grouping and largest ponds are located in a broad corridor towards the distal margins of the hummocky terrain, whereas closer to the active margin they tend to be smaller and more widely spaced (Fig. 5). The densest groupings of ponds at Søre Nathorstmorenen are located at Søre Leirodden and at the fjord edge between the two large outwash corridors that dissect the moraine area (Fig. 5). Sediment flows (Fig. 5), exposed ice cores (Fig. 10b) and tension cracks within ridges, hummocks and the general moraine surface (Fig. 10c) are found across both moraine areas. The dominant sediment facies within the hummocky terrain are two diamicts with a wide range in grain sizes from mud to large boulders, described in *Section 6*.

5.1.2 Interpretation: Ice-cored terrain formed by subaerial stagnation during quiescence – The hummocky terrain records subaerial stagnation and de-icing of the glacier in a terrestrial position. The melting of ice cores and degradation of the terrain surface through thermo-erosional processes (cf. Etzelmüller et al., 1996) is evident across Nordre and Søre Nathorstmorenen in the form of tension cracks and numerous sediment flows, indicative of internal instabilities and sediment remobilisation (Lawson, 1982; Lukas et al., 2005). Complete or partial melting of buried ice has also resulted in the widespread kettle topography of ponds and drained depressions (akin to thermo-karst; Healy, 1975).

5.2 Geometrical ridge networks

5.2.1 Description - Dense groups or networks of predominantly sharp-crested ridges within Nordre and Søre Nathorstmorenen are mapped as geometrical ridges (Figs 5, 9c, 9d and 10d). These ridges were previously identified and described by Gripp (1929) as '*Lehmmauern*' ('loam walls'; van der Meer, 2004). Individual ridges are typically 2-8 m high, 1-3 m wide and ~50-100 m long. Ridge orientations are predominantly offset by 45º from, or sub-parallel to, the central axis of the fjord (Fig. 5). The ridges display a variety of morphologies, ranging from rounded elongate hummocks to free-standing vertical pinnacles or towers (Figs 10d-f). Sharp-crested ridges and pinnacles are primarily located close to the active margin, such as in the area around the spit-like arm of Nordre Nathorstmorenen (Figs 9c and 9d). The ridges become more rounded in a downfjord direction towards Nordre and Søre Leirodden and towards the lateral margins of the moraine areas, as also noted by Gripp (1929). As a result, geometrical ridges are harder to distinguish from the general hummocky terrain in these areas. The ridges are predominantly composed of diamict, described in *Section 6*.

5.2.2 Interpretation: crevasse-squeeze ridges – The geometrical ridge networks are interpreted as crevasse-squeeze ridges, commonly observed at the submarine and terrestrial margins of surge-type glaciers (e.g. Sharp, 1985; Boulton et al., 1996; Evans and Rea, 1999; Ottesen and Dowdeswell, 2006; Ottesen et al., 2008, 2017; Lovell et al., 2015; Farnsworth et al., 2016; Ingólfsson et al. 2016). Crevasse-squeeze ridges are formed by the injection of deformable basal debris into vertical and near-vertical crevasses, as observed at the active ice margin (Fig. 6b). The ridges are then exposed and preserved at the margin as the glacier stagnates during quiescence. This mechanism is most consistent with the formation of the sharp-crested ridges and free-standing pinnacles observed in the moraine areas, and agrees with the interpretation of Gripp (1929) for the same features.

5.3 Composite ridge systems

5.3.1 Description - Extensive areas of undulating topography with multiple linear ridge crests are found at the distal margins of Nordre Nathorstmorenen, forming a sharp boundary with the hummocky ice-cored terrain. These areas are identified as composite ridge systems based on the following key geomorphological characteristics (cf. Lovell and Boston, 2017): their comparatively smooth surface texture compared with the hummocky ice-cored terrain, the orientation of ridge crests (which can be both perpendicular to and parallel with the fjord axis, depending on whether the ridges are in a frontal or lateral position), and the deep channels that are cut into them (Figs 5, 9a, 9b, 10g and 10h). The Nordre Nathorstmorenen composite ridge systems are divided into the Nordre Leirodden and North-East (NE) systems (Figs 5, 9a and

9b). The Nordre Leirodden composite ridge system, which was briefly described by Gripp (1929; in van der Meer, 2004: pp. 54-57), covers an area of ~2 km^2 and extends upglacier for ~6 km from Nordre Leirodden at the NW margin of the moraine area (Fig. 5). The surface of this part of the composite ridge systems reaches heights of up to 10 m above fjord/outwash plain level and is dissected by several deep inactive channels (Fig. 9a). Low-amplitude ridge crests are aligned sub-perpendicularly to the fjord axis close to Nordre Leirodden, and sub-parallel to the fjord axis in a lateral position (Fig. 5). These ridge crests are very subdued and reach typical heights of <0.5 m, and as a result are often difficult to identify in the field (Fig. 10g) but stand out on aerial photographs. The surface of the Nordre Leirodden composite ridge system is composed predominantly of sand and gravel, with shells and shell fragments visible in places. The NE composite ridge system is separated from the Nordre Leirodden system by a large, inactive outwash corridor that joins the lateral outwash at the distal margins of the moraine system (Fig. 5). The NE ridge system is also characterised by an undulating smooth topography, dissected by multiple outwash corridors and reaching a height of ~5-10 m (Figs. 9b and 10h). The NE system extends along the lateral margins for ~6 km and reaches a maximum width of ~1.5 km, in total covering ~5 km^2. Ridge crests and linear depressions are typically aligned sub-perpendicularly to the fjord axis (Figs 5 and 9b). The biggest distinction between the NE and Nordre Leirodden composite ridge systems is that the surface of the NE system is composed of mud, with little to no sand and gravel (and no larger clasts) (Fig. 10h). The mud is shell-rich with abundant shell fragments and complete paired bivalve shells embedded in the surface.

5.3.2 Interpretation: glaciotectonic moraines formed in a proglacial position – The Nordre Nathorstmorenen composite ridge systems are interpreted as glaciotectonic proglacial moraines formed by glacier advance into foreland sediments (cf. Croot, 1988; Boulton et al., 1999; Benediktsson et al., 2010; Lovell and Boston, 2017). The majority of the ridge crests, certainly within the Nordre Leirodden ridges, are oriented parallel to the inferred ice-contact face (boundary with the hummocky ice-cored terrain). This is consistent with ridge crests formed perpendicular to the inferred direction of ice push (e.g. Hart and Watts, 1997; Boulton et al., 1999; Lovell and Boston, 2017) as the glacier spread laterally towards the margins. The smooth surface texture of the Nordre Nathorstmorenen composite ridge systems reflects their surface sediment composition of sorted sand and gravel (Nordre Leirodden ridges) and mud (NE ridges). Information on the internal structure of the Nordre Leirodden ridge system can be found in *Section 6.3*.

6. Sedimentology of Nordre and Søre Nathorstmorenen

The sedimentary composition of the moraine areas was investigated within a series of sections, mostly located at the fjord edge (Fig. 5). Five main sediment facies and facies associations (FA) were identified: (1) shell-rich diamict (diamict 1); (2) shell-poor diamict (diamict 2); (3) deformed fines (mud), sand and gravel (FA1) (4) undeformed fines (mud) and sand (FA2); and (5) massive sand with contorted lenses (FA3). Information on grain size distributions, clast shape, and clast roundness can be found in Fig. 7. Calibrated radiocarbon ages of shells are reported here in relation to the sediment facies they were sampled from, and are discussed further in *Section 7.2.3*.

6.1 Diamict 1

6.1.1 Description - Diamict 1 is the lowermost of two diamicts identified (Figs 11a and 12). Diamict 1 is shell-rich, silty to fine-sandy, well-consolidated, matrix-supported, and contains occasional boulders reaching maximum a-axis lengths of 1 m. Clasts within diamict 1 are predominantly sub-angular and sub-rounded (Fig. 7), with striae common. This diamict is typically structureless, but does contain thin clay stringers towards the distal parts of the moraine areas, in particular close to the sharp boundary with the composite ridge systems (composed of fine material) in Nordre Nathorstmorenen (e.g. section NNM01; Fig. 12a). Diamict 1 was found both within geometrical ridges and coastal sections cut into the hummocky terrain, but is restricted to the distal parts (downfjord ~1.5-2 km) of both moraine areas. Within Nordre Nathorstmorenen, diamict 1 was not identified upfjord from section NNM04, and diamict 1 was the only diamict identified in the downfjord (distal) ~1.5 km of Søre Nathorstmorenen. Shells in diamict 1 were sampled for dating from Søre Nathorstmorenen: two single *Hiatella arctica* shells from a coastal section returned ages of 5720-5870 and 10380-10660 cal. yr BP, and one pair of bivalve shells embedded in the moraine surface at Søre Leirodden (Fig. 11f) returned ages of 1200-1290 and 1170-1260 cal. yr BP (Table 1).

6.1.2 Interpretation: lower till - Based on its fine-grained matrix, presence of multiple shells, and predominantly sub-angular to sub-rounded and striated clasts, diamict 1 is interpreted as a till derived from marine sediment (cf. Boulton et al., 1996; Ó Cofaigh and Evans, 2001). Clay lenses within the diamict at section NNM01 (Fig. 12a) are interpreted as evidence of the incorporation and attenuation of underlying material into the basal zone during glacier overriding (e.g. Kristensen et al., 2009a). Diamict 1 is interpreted to have been transported subglacially during an advance that reached Nordre and Søre Leirodden.

6.2 Diamict 2

6.2.1 Description - Diamict 2 is matrix-supported and overlies diamict 1 at section NNM04 (Figs 11a and 12c), forming a sharp, erosional contact. The two diamicts can be differentiated because diamict 2 is typically friable, poorly-consolidated and shell-poor, containing fewer and more fragmentary shells than diamict 1. Thin, sometimes contorted, layers of sand and occasional clay stringers are also common (e.g. Figs 11b, 12c and 13a). The main difference in grain size distribution of diamicts 1 and 2 is the larger peaks within the coarse silt/fine sand ranges displayed by diamict 2. Clast shape samples taken from sections NNM04 and SNM02 and from within geometrical ridges show predominantly sub-angular to sub-rounded clasts (Fig. 7). Diamict 2 is the only diamict observed close to the active margin and is not found in the distal parts of the moraine areas (e.g. downfjord from NNM04 and SNM01). Within Søre Nathorstmorenen, the lateral transition in surface sediment cover from diamict 2 to diamict 1 is indistinct and, unlike at Nordre Nathorstmorenen, the two diamicts were not observed together in section. Close to the active margin, diamict 2 is massive and sand lenses/clay stringers are rare, but these increase in frequency in a downfjord direction (e.g. Figs 11b, 12c and 13a). A single *Hiatella arctica* shell sampled from diamict 2 at Søre Nathorstmorenen (Fig. 5) returned an age of 7730-7860 cal. yr BP (Table 1).

6.2.2 Interpretation: upper till - Diamict 2 is interpreted as a second till derived from marine sediment, deposited by a separate, less-extensive and more-recent glacier advance than that associated with the deposition of diamict 1. Two main factors indicate that the diamicts relate to separate advances: (1) at section NNM04, diamict 2 directly overlies diamict 1 and there is a sharp, erosional contact between the two (Figs 11a and 12c). This indicates that the glacier overrode and likely eroded diamict 1 following its deposition, emplacing diamict 2 on top. (2) The spatial distribution of diamict 2 is restricted to the zones of sharp-crested geometrical ridges close to the active margin, and it is not found in the distal parts of the moraine areas. This is consistent with its deposition during a second, less-extensive glacier advance than that which reached Nordre and Søre Leirodden and deposited diamict 1. The sand layers and clay stringers within diamict 2 are interpreted as subglacially-reworked FA1 sediments (see *Section 6.3*).

6.3 Deformed fines, sand and gravel facies (FA1)

6.3.1 Description - This sediment facies association is exposed within the hummocky terrain of both moraine areas (e.g. sections NNM01, NNM05, SNM01 and SNM02) and within the Nordre Nathorstmorenen composite ridge systems (e.g. section NNM02) (Figs 12 and 13). It is characterised by poorly-sorted sand with intercalated clay stringers, layers and lenses that have been subject to minor faulting (e.g. NNM01; NNM05), shearing (e.g. SNM01) and/or intense folding (e.g. NNM02; SNM02); faulted fine sand layers within a clay matrix (e.g. NNM01); and clastic dykes and flame structures (e.g. NNM01 and NNM02). FA1 is found in three main settings within the moraine areas, described below.

Firstly, FA1 underlies diamict 1 in both sections NNM01 and NNM05 within Nordre Nathorstmorenen. The lowermost ~1.8 m of NNM01, located within the hummocky terrain close to the boundary with the Nordre Leirodden composite ridge system, consists of FA1. This includes a ~1.2 m section characterised by fine sand with thin clay stringers and shells overlying shale bedrock. The shale is broken up and extremely friable, and angular clasts have been ripped up from it and are present within the lowermost 0.2 m of the fine sand. Thin, sinuous clastic dykes with flame-like structures are evident, trending upwards and towards the true left of the section. A number of small-scale minor reverse faults can be identified, particularly at a height of ~1 m, where the fine sand is laminated and contains small lenses of black shale of a coarse sand grain size (Fig. 12a). The fine sand is overlain by ~0.6 m of massive sand interspersed with discontinuous thin, faulted fine sand lenses.

Secondly, FA1 is also found close to the lateral transition between diamicts 1 and 2, ~1.5-2 km upfjord from the distal margins of the moraine area. Coastal exposures in this part of Søre Nathorstmorenen commonly contain deformed sands with sheared clay lenses (Fig. 11d) overlain by up to 1-2 m of diamict 2. At section SNM01 (Fig. 13a), ~1 m of diamict 2 containing several thin sand layers is overlain by ~0.5 m of FA1 in the form of sheared sand with clay lenses. Approximately 200 m upfjord from this location, section SNM02 (Fig. 13b) shows a ~1 m-wide layer of FA1, consisting of sands and thin clay lenses, forming a downfjord-verging overturned fold around a core of diamict 2. The clay lenses within the sand and the thin sand layers within diamict 2 are aligned parallel to the axial surface of the fold.

The third main location of FA1 is within the Nordre Nathorstmorenen composite ridge systems. The internal composition of the Nordre Leirodden composite ridge system was investigated in coastal exposures and logged in section NNM02 (Figs 11c and 12e). In coastal exposures composed primarily of deformed sand, large-scale anticlinal folding was observed in several places where bedding dipped in opposite directions over distances of tens of metres. Sub-vertical muddy stringers and thrust and reverse faults with small displacements are also common. At section NNM02, located in the wall of a channel cut through the Nordre Leirodden ridges, FA1 is characterised by folded and contorted fine and coarse sand layers forming attenuated synclines, with evidence for clastic dykes and flame structures (Fig. 12e). Asymmetric folds are expressed on the surface of the Nordre Leirodden composite ridge system as linear stripes or low-amplitude muddy ridge crests that stand-out against the general sandy-gravelly surface (Fig. 10g). Several of these fold axes strike ~290º, comparable to fold axes measured in section NNM02 (Fig. 12e). The internal structure of the NE composite ridge system was not investigated, but the surface consisted of mud (massive clayey silt) (Fig. 7a). Four paired shells of *Hiatella arctica* embedded in the NE composite ridge system surface (Fig. 11e) returned ages of 750-870, 830-950, 850-960 and 950-1110 cal. yr BP (Table 1).

6.3.2 Interpretation: glaciotectonised shallow marine and fluvial sediments - The massive and, in places, laminated sands and shell-rich muds that contain evidence for faulting, folding and shearing are interpreted as shallow marine, lacustrine and fluvial sediments that have been glaciotectonically deformed in proglacial (e.g. NNM02 within the Nordre Leirodden composite ridge system) and submarginal/subglacial (e.g. NNM01, NNM05, SNM01 and SNM02) settings. FA1 sediments overlain by diamict 1 towards the distal margin of Nordre Nathorstmorenen (NNM01 and NNM05) are interpreted as glaciotectonised shallow marine/lacustrine sediments due to overriding and deformation as the glacier advanced to Nordre and Søre Leirodden. The clastic dykes, flame structures (interpreted as water-escape features) and reverse faulting within FA1 in section NNM01 are consistent with dewatering and compaction caused by overlying ice (e.g. Phillips et al., 2008). FA1 sediments found in conjunction with diamict 2 at the latter's downfjord limit in Søre Nathorstmorenen (e.g. SNM01 and SNM 02) are similarly interpreted as evidence for the deformation of shallow marine/lacustrine sediments in an ice-marginal position. The location of these sections, ~2 km upfjord from the distal extent of the moraine system at Søre Leirodden indicates that they represent a second former ice-contact zone. This is consistent with a second, less-extensive glacier advance that deposited diamict 2. Deformed FA1 sediments are also found within the glaciotectonic composite ridge systems of Nordre Nathorstmorenen. As the glacier advanced downfjord and into terrestrial positions, it is likely to have encountered shallow marine sediments within the fjord, lacustrine sediments in ponds on the moraine/glacier surface, and outwash sediments. These sediments were then pushed and bulldozed into a series of ridges, with ridge crests typically oriented perpendicular to the direction of ice push. The style of folding and strike of fold axes within NNM02 (Fig. 12e) and exposed on the surface (Fig. 10g), in conjunction with the general alignment of ridge crests on the Nordre Leirodden composite ridge system (Figs 5 and 9a), are consistent with ice push from the south as the glacier advanced into a terrestrial position and towards the lateral margins.

6.4 Undeformed fines and sand (FA2)

6.4.1 Description - FA2 is characterised by wavy laminated alternating couplets of clay-fine silt grading into coarse silt-fine sand (NNM03; Figs 11g and 12b), ripple-bedded sands (NNM03 and SNM03; Figs 12b and 13c), and massive clay, silt and sand (NNM03, NNM05 and SNM03). This facies association is found at the transition between the zones of diamicts 1 and 2 (i.e. where they are the predominant sediment facies) in both moraine complexes, approximately 1.5 km upfjord from the distal margins. At section NNM03, located immediately upfjord from the observed downfjord limit of diamict 2 within Nordre Nathorstmorenen, FA2 consists of a ~3 m-thick coarsening-upwards sequence of undisturbed wavy-laminated alternating clay-fine silt couplets (~1 cm thick) (Fig. 11g), the uppermost ~1 m of which grades into alternating silt-fine sand couplets (Fig. 12b). This sequence sits on top of bubbly, opaque ice at least 0.2-0.3 m thick, and extends laterally for ~30 m. The laminated clays and silts are overlain by a ~0.5 m-thick coarse sand layer with asymmetric ripples prograding in opposite directions. Undeformed sorted sediments of FA2 are also found in section SNM03 in Søre Nathorstmorenen, in a ~5-10 m-long exposure in a ridge located ~200 m from the fjord edge (Fig. 5). Here, the lowermost 0.5 m of the exposure consists of wavy laminated alternating couplets of fine and medium sand containing asymmetric ripples prograding in opposite directions, interspersed with thin (<3 cm) horizontally-bedded lenses of fine gravel (Fig. 13c).

6.4.2 Interpretation: undeformed shallow lacustrine sediments - FA2 is consistent with sediments of a shallow marine or shallow lacustrine origin. The wavy-laminated couplets resemble tidally-influenced sediments (cf. Stewart, 1991), and the location of NNM03 at the fjord edge suggests that the sediments may have been uplifted following deposition in the fjord. However, the undeformed nature of the sediments and their height above the current fjord level (up to ~3 m at NNM03) suggests that a marine origin is unlikely, as it is difficult to envisage a mechanism by which uplift could have occurred with little or no disturbance of the sediments. This is also the case for FA2 at SNM03, which is located ~300 m from the fjord and therefore would have to have been transported a considerable distance without deformation. The absence of shells within FA2 also suggests a marine origin is unlikely. Based on this, FA2 is most consistent with undeformed shallow lacustrine sediments deposited *in situ* in ponds on the former glacier or moraine surface that have since drained. NNM03 is underlain by glacier ice, indicating deposition in a supraglacial pond before being lowered to the moraine surface. The asymmetric ripples prograding in opposite directions within NNM03 and SNM03 are consistent with delivery of underflows into a pond from changing sediment efflux points.

6.5 Massive sand with contorted lenses (FA3)

6.5.1 Description - FA3 is only observed at section SNM03, where it overlies, and has a sharp contact with, the undeformed laminated sands of FA2. FA3 is characterised by a ~1.7 m-thick layer of massive fine sand containing contorted coarse sand lenses and scattered gravel-sized clasts (Fig. 13c). There is evidence for small rip-up clasts of medium sand within the lowermost ~10-20 cm, sourced from the underlying laminated sands of FA2, and the thin lenses of coarser sand within the otherwise fine sand matrix display a variety of shapes and alignments.

6.5.2 Interpretation: subaerial sediment flow deposit – FA3 is interpreted as a sediment flow subjected to gravitational and water-sorting processes. This origin is consistent with the sharp, erosional lower contact, homogenous nature of the fine sand matrix, the scattered gravel-sized clasts, and the contorted coarse sand inclusions (cf. Lawson, 1982).

7. Discussion

7.1 Formation of mud apron and glaciotectonic surge moraines

The development of a mud apron during the recent surge of NGS provides a link between active phase processes and the formation of surge moraines, both in submarine and terrestrial positions. The emergence of the mud apron above the waterline in summer 2012 coincided with the glacier front reaching a narrow and shallow (~20 m) part of inner Van Keulenfjorden (Fig. 3), as noted by Sund et al. (2014). The extremely shallow water depths (<1 m) in the centre of the fjord in 2012 at ~1 km from the advancing margin demonstrate that a low gradient debris flow lobe extended downfjord from the subaerial part of the mud apron. Based on the pre-surge bathymetry (Fig. 1), the glacier front advanced up a reverse slope for ~10 km from the deepest part of inner Van Keulenfjorden in 2009 to its 2012 position. The soft marine sediments were pushed upslope as the front advanced, incrementally increasing the thickness of the sediment wedge over a distance of ~10 km through tectonic shortening (Fig. 8). By the time the glacier front reached the top of the reverse slope, i.e. at the shallowest part of the fjord, the sediment wedge was thick enough to breach the fjord surface. The advance against a reverse slope also explains why the mud apron is able to attain a significant thickness despite being composed of sediment with a very low shear strength and high porewater pressure, which might be expected to fail continuously (Kristensen et al., 2009a). The gravitational forces acting on the distal slope of the sediment wedge would be less influential than the lateral compression as it advanced upslope, therefore allowing the sediments to thicken. Once the glacier reached the top of the reverse slope and the bed began to slope away downfjord, gravitational processes exerted a larger influence on the sediment wedge and a low-gradient debris flow lobe developed through quasi-continuous slope failure (Kristensen et al., 2009a). It is interesting to note that Hamberg (1905) reported that in 1898 the water near Nordre Leirodden (Fig. 5) contained stranded icebergs and was too shallow for boats due to the large amount of mud deposited by the glacier. These observations are consistent with a mud apron within the fjord associated with the 1898 position of NGS and reflect our own experience of navigating a boat across the mud apron near the ice margin in 2012.

The mud apron that formed during the recent NGS surge is morphologically similar to large submarine terminal moraines and associated debris flow lobes observed on the seafloor in front of a number of tidewater surge-type glaciers (e.g. Solheim and Pfirman, 1985; Plassen et al., 2004; Ottesen et al., 2008, 2017; Kristensen et al., 2009a; Forwick et al., 2010; Flink et al., 2015; Streuff et al., 2015, 2017a; Burton et al., 2016), and we therefore interpret these as having a common genetic origin (cf. Kristensen et al., 2009a). That is not to say that seafloor sediments would have necessarily been pushed above the waterline during the formation of surge terminal moraines in these other examples — this will depend on water depth. Aside from Van Keulenfjorden, to our knowledge the only other report of mud pushed above the waterline at an advancing glacier margin in Svalbard is from the 2002-10 surge of Comfortlessbreen, which advanced ~700 m into the shallow water of Engelskbukta (King et al., 2016; Lønne, 2016). However, such processes have been inferred during past surges of Sefströmbreen (Boulton et al., 1996), Paulabreen (Kristensen et al., 2009a,b) and Osbornebreen (Evans and Rea, 2005; Farnsworth et al., 2017) based on terrestrial geomorphological evidence. Similar to these studies, the terrestrial composite ridge system at the lateral margin of Nordre Nathorstmorenen is also inferred to have formed by a process of glaciotectonic pushing of marine sediments onshore in front of an advancing ice margin. The grain size distribution of the surface of the muddy part of the composite ridge system is very similar to that of the modern mud apron (Fig. 7). Abundant shells on the surface of the ridges, many of which were paired bivalve shells (Fig. 11e), also indicate a marine origin. The internal structure of this part of the composite ridge system is unknown, but we note that the surface morphology is similar to the terrestrial mud aprons/glaciotectonic moraines described by Boulton et al. (1996) and Kristensen et al. (2009a,b).

There is a significant difference in the thickness of the active mud apron in terrestrial areas, which was <10 cm thick where it had started to encroach onto Nordre Nathorstmorenen (e.g. Fig. 6c), and the ~8-10 m high composite ridge system. Two main processes are likely to explain this difference. Firstly, the sediments within the highly saturated, slurry-like active mud apron have low shear strength, facilitating its continuous failure and the development of the low-gradient debris flow lobe observed in both marine and terrestrial settings. By contrast, large volumes of marine mud pushed further onshore would dewater, increasing the shear strength of the mud. Subjected to continued push by an advancing ice margin, this would allow the marine muds to be pushed into a series of steeper and higher ridges. Drying-out of marine sediments can also result in extra cohesion caused by the crystallisation of salts (cf. Boulton et al., 1996). Secondly, completely or partially frozen marine mud would have higher shear strength than unfrozen mud, which could contribute to the coherence of the sediment mass during proglacial deformation (e.g. Etzelmüller et al., 1996; Etzelmüller and Hagen, 2005). The latter might be expected to form thrust-block moraines as the frozen sediments deformed in a coherent manner, forming a series of thrust slabs (e.g. Evans and England, 1991).

7.2 Late Holocene surge history of NGS

Ottesen et al. (2008) used historical mapping and the submarine geomorphological record to infer that NGS surged to a position downfjord of Nordre and Søre Nathorstmorenen in ~1870 (Ottesen et al., 2008; Fig. 1). This implies that the terrestrial moraine areas formed during the LIA surge. The following sections demonstrate that Nordre and Søre Nathorstmorenen are actually the result of two surges based on (1) the identification of two ice-contact zones recorded by the distribution of sediment facies, facies associations and terrestrial geomorphology; (2) the correlation between the ice-contact zones and submarine geomorphology; and (3) radiocarbon dating of shells emplaced in a terrestrial position by the outer, older surge.

7.2.1 Identification of two ice-contact zones within the terrestrial moraine areas

The sediment exposures record a downfjord transition from predominantly diamict 2 to a zone of FA1 sediments, followed by a zone of predominantly diamict 1 extending to the distal part of the moraine areas. In Nordre Nathorstmorenen only, the diamict 1 zone transitions into the composite ridge systems comprising deformed FA1 sediments. In simple terms, we interpret this as evidence of transitions (ice proximal to distal) from a subglacial zone (diamict 2) to a submarginal/proglacial zone (FA1 in close association with diamict 2), back to a subglacial zone (diamict 1), and finally to a proglacial glaciotectonised zone (FA1) within the composite ridge systems. On this basis, two ice-contact zones can be identified at the subglacial-submarginal/proglacial transitions (Fig. 14), which we attribute to two advances being responsible for forming the terrestrial moraine areas. The second of these advances was less extensive than the first, forming the inner ice-contact zone located ~2 km upfjord from the distal extent of the moraine areas.

The transition from diamict 2 to FA1 deformed shallow marine sediments occurs at approximately the same position within Nordre and Søre Nathorstmorenen (Fig. 14), which delimits the former ice-contact zone (i.e. maximum downfjord position) of the inner advance. This zone also coincides with the downfjord limit of the area of sharp-crested crevasse-squeeze ridges (Figs 5 and 14) — beyond this, the ridges are, in general, more-rounded and typically indistinguishable from the surrounding hummocky terrain of the moraine systems. We suggest this reflects the differences in relative age of the crevasse-squeeze ridges formed by the inner, younger advance and those formed during the outer, older advance to Nordre and Søre Leirodden.

The ice-contact zone of the outer advance is located at the transition from hummocky ice-cored terrain to composite ridge systems within Nordre Nathorstmorenen. This ice-contact zone can be correlated with the downfjord extent of Søre Nathorstmorenen on the south side of the fjord, delimiting the approximate maximum position of the outer advance (Fig. 14). The lateral extents of the outer advance are constrained by the contact with the composite ridge systems (Nordre Nathorstmorenen) and lateral limit of the moraine area (Søre Nathorstmorenen). The lateral margins of the inner advance are harder to determine, as there are no obvious geomorphological features (e.g. lateral meltwater channels or composite ridge systems) that coincide with the ice-contact zones within either moraine system. It is possible that the glacier extended to the lateral margins of both moraine areas. However, it seems likely that the inner advance not only reached a less-extensive downfjord position, but also was laterally less extensive. This is certainly the case for the recent surge, which reached a less-extensive downfjord position and has only impinged on the lateral moraine areas by a few hundred metres (Figs 1-3). In the absence of a clearly demarcated lateral margin for the inner advance, we suggest it may coincide with observed differences in meltwater pond density. In Nordre Nathorstmorenen, there is an identifiable corridor immediately adjacent to the fjord and glacier margin that contains fewer meltwater ponds than the outermost part of the moraine system (Fig. 5). This corridor widens from ~0.2 km at section NNM04 to ~1.5 km adjacent to the 2012 glacier margin (Figs 5 and 14). We propose that the zone of fewer meltwater ponds may represent the footprint of the inner advance. This is based on the logic that the relative abundance of meltwater ponds in the outer, older parts of the moraine system reflect the longer time it has had to de-ice and thus for ponds to develop. Søre Nathorstmorenen contains a similar pattern, with dense areas of meltwater ponds located towards the distal margins, but the lateral contrast is indistinct. We have therefore defined an approximate lateral extent of the inner advance on Søre Nathorstmorenen based on a similar distance of encroachment onto the moraine areas on both sides of the fjord (Fig. 14).

7.2.2 Correlation of inner and outer advances with submarine geomorphology

Based on the terrestrial evidence, it is logical to expect two separate advances to also be recorded in the submarine geomorphology. The large submarine terminal ridge and associated debris flow lobe mapped by Ottesen et al. (2008; Fig. 1), or at least the ice-proximal slope of the ridge (cf. Kempf et al., 2013), correlates reasonably well with the maximum position of the outer advance (i.e. the distal extent of the terrestrial moraine areas). However, Ottesen et al. (2008) did not identify any terminal ridges or debris flow lobes in inner Van Keulenfjorden that correlate to the inner advance. A series of small (average height of ~5 m) ridges aligned broadly perpendicular to the fjord axis were identified and interpreted as annual moraines formed during quiescent phase recession (Ottesen et al., 2008). Two of the largest of these ridges are over 10 m high, ~500 m wide and are located either side of the position of the inner ice-contact zone within the terrestrial moraine areas (labelled R1 and R2 in Fig. 14). The taller of the two ridges (R1) corresponds closely to the position of the glacier front in 1898 mapped by Hamberg (1905), which has the shape of a calving margin. We suggest this ridge is consistent with a recessional moraine formed during quiescence (cf. Flink et al., 2015). Ridge R2 is located ~1 km downfjord from the 1898 margin and immediately downfjord from the approximate maximum position of the inner advance, as recorded within the terrestrial moraine areas. Based on an assumed convex-shaped glacier front consistent with a surging margin (e.g. Figs 1-3), we suggest that R2 is the most likely candidate to record the submarine position of the inner advance maximum position (Fig. 14). Although R2 does not have a debris flow lobe on its distal slope and is not as large as submarine terminal moraines identified at other tidewater glaciers, we note that (i) debris flow lobes are not always found at surge terminal moraines (e.g. Streuff et al., 2017a); and (ii) R2 is comparable in size and morphology to the terminal moraine formed at the 2004 surge maximum position of Tunabreen in Tempelfjorden (cf. Flink et al., 2015). In the latter case, Flink et al. (2015) concluded that where a surge follows soon after a previous surge (e.g. ~40 years at Tunabreen), the glacier will not encounter as thick glaciomarine sediment, and therefore will have less material available to bulldoze into a terminal moraine. In addition, the velocity data from the final stages of the recent NGS surge demonstrate that the glacier front experiences pulses of rapid flow acceleration in the summer months during overall deceleration, probably during enhanced precipitation events as rainfall is routed directly to the bed through the heavily-crevassed terminus (cf. Sevestre et al., 2018) (Fig. 4). It is possible that most of the frontal advance in the later years occurs during these concentrated periods of enhanced frontal velocities. Such a pulsing effect, possibly characterised by parts of the front advancing whilst other areas are almost stationary (Fig. 3), may well have an impact on the size and morphology of any submarine moraines formed at the margin.

7.2.3 Revised chronology of surging

Glacier surges are separated by multi-decadal periods of quiescent phase recession. The two advances recorded within the moraine areas are therefore expected to be of different ages. The oldest radiocarbon ages of 10380-10660, 7730-7860 and 5720-5870 cal. yr BP (Table 1) were from individual shells embedded in diamicts 1 and 2 in coastal sections within Søre Nathorstmorenen. These are considerably older than the two advances dated to between 2610 and 2790 cal. yr BP that formed the large submarine terminal moraine and debris flow lobes in outer Van Keulenfjorden (Kempf et al., 2013; Fig. 1), suggesting that the shells have undergone significant (e.g. multiple cycles of) remobilisation and redeposition (Lyså et al., 2018). The remaining ages were from four sets of paired bivalve shells sampled from the surface of the NE composite ridge system (750-870, 830-950, 850-960 and 950-1110 cal. yr BP; Table 1) and one set of paired bivalve shells embedded in the moraine surface at the distal extent of Søre Nathorstmorenen (1200-1290 and 1170-1260 cal. yr BP; Table 1). The NE composite ridge system is interpreted to have formed by onshore bulldozing of marine mud in a proglacial position during the outer, assumed older, advance. Similarly, the paired bivalve shells embedded in the surface of Søre Nathorstmorenen are within the part of the moraine complex formed by the outer advance (Fig. 14). We use the four, slightly younger ages from the NE composite ridge system to produce a robust modelled age for the outer advance occurring during the period 700-890 cal. yr BP (Fig. 15), or sometime around ~1160 AD.

The inner advance corresponds closely to the 1898 glacier front (Fig. 14). Similar to Ottesen et al. (2008), we interpret the 1898 position as representing the initial stages of frontal recession following a late 19th century surge. However, we have identified that this surge did not extend to the distal part of the moraine system as previously thought, but terminated ~2 km upfjord at our proposed maximum position of the inner advance (Fig. 14). By 1898 the glacier front in the centre of the fjord had calved back ~1-1.5 km from the likely surge maximum position. If we assume a quiescent phase recession rate of ~160 m a^{-1} (as recorded in the period 1898 to 2008), the inner advance likely reached its maximum position ~6-10 years prior to 1898, suggesting the LIA surge occurred ~1890. We therefore determine that NGS has surged at least five times: twice between 2.61 and 2.79 cal. kyr BP (Kempf et al., 2013), at ~1160 AD, in ~1890, and from 2008-2016 AD (Fig 16).

7.3 Timings of Late Holocene tidewater glacier advances in Svalbard

There are very few records of the timings of Late Holocene tidewater glacier advances in Svalbard before the LIA maximum. Indeed, prior to an inferred ~1800 AD surge of

Kongsvegen/Kronebreen in Kongsfjorden (Liestøl, 1988), only six glacier systems have had dated advances since the onset of the neoglacial period at ~4 kyr BP (Hald et al., 2004) (Fig. 16). The oldest dated advances since ~4 kyr BP are the two advances of NGS between 2.61 and 2.79 cal. kyr BP, which were interpreted as surges (Kempf et al., 2013). The Hinlopen-Oslobreen glacier systems in Vaigattbogen also surged sometime prior to 2.6 cal. kyr BP, although this could have occurred at any point since the early Holocene (Flink and Noormets, 2018). In Hornsund, southern Spitsbergen, a tidewater glacier advance to the Treskelen Peninsula was dated to 1.9±0.3 kyr BP using ^{10}Be cosmogenic nuclide dating (Philipps et al., 2017). Philipps et al. (2017) suggested this advance was likely to be in response to regional climate forcing rather than a surge, although they also noted that several of the glaciers feeding into Hornsund are reported to have surged at or since the LIA. Also in southern Spitsbergen, Paulabreen in Van Mijenfjorden surged ~650 yr BP (~1300 AD) (Hald et al., 2001; Larsen et al., 2018). This surge formed the terrestrial glaciotectonic moraine systems of Damesmorenen, Crednermorenen and Torrelmorenen through onshore bulldozing of marine mud (Kristensen et al., 2009a; Larsen et al., 2018; Lyså et al., 2018). Based on the submarine geomorphological record (Ottesen et al., 2008), Paulabreen surged at least twice more between the dated ~1300 AD surge and an inferred surge in ~1898 (Larsen et al., 2018). In northwest Spitsbergen, St. Jonsfjorden and Magdalenefjorden both have tidewater glacier advances dated to before the LIA (Farnsworth et al., 2017; Streuff et al., 2017a). Osbornebreen in St. Jonsfjorden advanced and deposited a moraine dated to ~520±70 cal. yr BP (~1430 AD), which has been interpreted as a surge based on the terrestrial and submarine geomorphological record (Evans and Rea, 2005; Farnsworth et al., 2017). In Magdalenefjorden, Waggonwaybreen advanced at ~300 cal. yr BP (~1650 AD) (Streuff et al., 2017a). The submarine geomorphology was interpreted by Streuff et al. (2017a) to be more consistent with this advance being a response to LIA cooling rather than a surge. Both Paulabreen and NGS are inferred to have surged at the end of the LIA maximum (Ottesen et al., 2008) and have surged in the last 15 years (Kristensen and Benn, 2012; Sund et al., 2014). Osbornebreen also underwent an observed surge in 1986-1988 (Dowdeswell et al., 1991).

The recent expansion in the availability of high-resolution submarine imagery has helped to identify new evidence for dynamic glacier flow in both fjord (Ottesen and Dowdeswell, 2006; Ottesen et al., 2008; Flink et al., 2015, 2017; Streuff et al., 2015, 2017a; Burton et al., 2016; Ewertowski et al., 2016; Farnsworth et al., 2017; Allaart et al., 2018; Ćwiąkała et al., 2018; Larsen et al., 2018) and open-marine settings (Ottesen et al., 2017; Flink and Noormets, 2018). In the majority of these examples, there is clear geomorphological evidence for surging. As more areas are explored, it seems likely that such observations will increase. However, chronological control on the timing of advances is crucial in order to understand tidewater glacier behaviour during the Late Holocene. From the available data, it is clear that there is a great deal of variability across Svalbard. In some areas (e.g. inner Isfjorden, Lomfjorden), the LIA maximum is thought to represent the most-extensive Holocene glacier position (Plassen et al., 2004; Ottesen and Dowdeswell, 2006; Mangerud and Landvik, 2007; Streuff et al., 2017b). By contrast, glaciers in Mohnbukta experienced a surge-type advance prior to 7.7 cal. kyr BP (Flink et al., 2017), and both NGS (Kempf et al., 2013 and this study) and Paulabreen (Larsen et al., 2018; Lyså et al., 2018) surged at least three times prior to the LIA to more advanced positions than their LIA maximums. In terrestrial settings, Farnsworth et al. (2018) established that several land-terminating glaciers in Svalbard re-advanced during the late-glacial to early-Holocene period, reaching positions up to ~8 km beyond their Late Holocene maximum moraines, and Miller et al. (2017) identified several episodes of land-terminating glacier expansion during the Late Holocene. Understanding these variations in the timings of glacier maxima during the Holocene is important in order to understand glacier behaviour over longer timescales, and in particular the interplay between climatic forcing and glaciodynamical (i.e. surging) influences on glacier advances.

9. Conclusions

Investigation of terrestrial and submarine sediment-landform assemblages in Van Keulenfjorden, southern Spitsbergen, reveal a Late Holocene record of multiple advances of the surge-type Nathorstbreen glacier system (NGS).

- NGS advanced ~16 km from 2008 to 2016 during its recent surge. The final years of the surge (2013-2016) were characterised by year-on-year decreases in flow velocities punctuated by occasional, short-lived speed-ups (e.g. fivefold increases) correlated to summer precipitation events. By August 2017, NGS had started to retreat across most of the front, indicating surge termination sometime in winter 2016-2017.
- We present the first detailed observations of the formation of a glaciotectonic mud apron in the fjord during the recent surge. The mud apron emerged above the waterline and began to encroach onto the lateral moraine areas in summer 2012. The mud apron was caused by the bulldozing and thickening of marine sediments into a mobile, continuously failing sediment wedge characterised by a low-gradient flow lobe extending downfjord. These observations provide a modern analogue for the formation of submarine terminal surge moraines and associated debris flow lobes, and terrestrial glaciotectonic moraine systems formed by the onshore movement of marine sediments during glacier surges.
- Investigation of the sediment-landform assemblages within the terrestrial moraine areas reveals that at least two separate phases of glacier advance are recorded. This is based on the identification of an additional, previously unrecognised, ice-contact zone characterised by a transition from subglacial sediments to proglacially/submarginally

deformed sediments. We infer that this records an inner, younger advance that did not extend to the distal parts of the moraine system.

- Radiocarbon dating of shells embedded in the surface of the glaciotectonic composite ridge systems at the distal margins of the terrestrial moraine area indicate that the outer, older advance occurred at ~1160 AD, rather than during the LIA as previously suggested by Ottesen et al. (2008). We instead correlate the inner, younger advance to the LIA and suggest it culminated in ~1890 based on the position of the calving (retreating) glacier terminus mapped by Hamberg (1905) in 1898.
- We demonstrate that NGS has advanced at least five times in the Late Holocene: (1) the recent surge advance of 2008-2016, (2) during the LIA at ~1890, (3) at ~1160 AD, and (4) and (5) twice between 2.61 and 2.79 cal. kyr BP, as previously reported by Kempf et al. (2013).

In addition to the recent 2008-2016 surge, the observed sediment-landform assemblages associated with the four older advances are also consistent with surging. This work contributes to the understanding of High-Arctic tidewater glacier dynamics, and in particular the frequency and magnitude of surge advances, during the Late Holocene. Future work should focus on combined marine and terrestrial investigations at the margins of other tidewater glaciers in order to provide a more complete picture of the regional variability in Holocene glacier advances in Svalbard.

CRediT author statement

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