Origin, evolution and dynamic context of a Neoglacial lateral-frontal moraine at Austre Lovénbreen, Svalbard

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Abstract

Moraines marking the Neoglacial limits in Svalbard are commonly ice cored. Investigating the nature of this relict ice is important because it can aid our understanding of former glacier dynamics. This paper examines the composition of the lateral-frontal moraine associated with the Neoglacial limit at Austre Lovénbreen and assesses the likely geomorphological evolution. The moraine was investigated using ground-penetrating radar (GPR), with context being provided by structural mapping of the glacier based on an oblique aerial image from 1936 and vertical aerial imagery from 2003. Multiple up-glacier dipping reflectors and syncline structures are found in the GPR surveys. The reflectors are most clearly defined in lateral positions, where the moraine is substantially composed of ice. The frontal area of the moraine is dominantly composed of debris. The core of the lateral part of the moraine is likely to consist of stacked sequences of basal ice that have been deformed by strong longitudinal compression. The long term preservation potential of the ice-dominated lateral moraine is negligible, whereas the preservation of the debris-dominated frontal moraine is high. A glacier surface bulge, identified on the 1936 aerial imagery, provides evidence that Austre Lovénbreen has previously displayed surge activity, although it is highly unlikely to do so in the near future in its current state. This research shows the value of relict buried ice that is preserved in landforms to aiding our understanding of former glacier characteristics.

1. Introduction

The aim of this research is to investigate the origin of buried glacier ice within the lateral-frontal moraine of Austre Lovénbreen, Svalbard (Fig. 1), and to assess the evolution and preservation potential of this landform as the ice core degrades over time. To achieve this aim, a detailed ground-penetrating radar (GPR) survey was used to determine the internal architecture and composition of the moraine and ice core, and set this within the structural and dynamic context of the glacier by undertaking glacier structural mapping from contemporary vertical aerial and historic oblique aerial imagery. The ice core within the moraine preserves potentially valuable palaeoglaciological information from the Neoglacial maximum, which combined with structural mapping, extends recent work in the region that has examined changing glacier characteristics and dynamics (Hambrey et al., 2005). Such work is necessary in order to contextualise glacier change in the Arctic, a region which has experienced exceptional rates of warming in recent decades (IPCC, 2007). In addition, landforms at contemporary glaciers are commonly used as analogues for the interpretation of mid-latitude Pleistocene glacial landforms, so a fuller understanding of the formation and post-formational evolution of moraines in contemporary settings such as this can also aid our understanding of previously glaciated settings.

2. Research context

The lateral and frontal moraines formed at the Neoglacial maximum limits in Svalbard are often considered to be ice-cored (e.g. Glasser and Hambrey, 2003). Lateral moraines have traditionally been considered to have formed by the accumulation of thin layers of coarse angular debris on top of a thick glacier ice accumulation (e.g. Flint, 1971; Embleton and King, 1975; Sugden and John, 1976; Boulton and Eyles, 1979). According to this model, lateral moraines have low preservation potential during deglaciation as the ice would ablate quickly under a thin debris cover. The term has also been used to refer to both moraines that are detached from the glacier and to thin debris covers at the margins of active glacier ice. Where the debris cover in ice-cored lateral moraines is both thin and contains a significant component of fine-grained sediment, the debris cover is prone to reworking and exposure of the relict glacier ice. Where the debris cover allows, an ice-core can form a relatively stable part of the landform. Ice-cored lateral-frontal moraines have been reported from a number of glaciers in Svalbard, including: Scott Turnerbreen (Lønne and Lauritsen, 1996); Kongsvegen (Bennett et al., 2000); Longyearbreen and Larsbreen (Etzelmüller et al., 2000; Lukas et al., 2005); Rieperbreen (Lyså and Lønne, 2001); Platåbreen (Lønne and Lyså, 2005); Platåbreen / Nordenskiöldtoppenbreen (Lukas et al., 2005); Holmströmbreen (Schomaker and Kjær, 2008); and Ragnarbreen (Ewertowski et al., 2012).

The use of the term ice-cored moraine has also caused some debate with Lukas et al. (2007) arguing for a strict application of the term with detachment from the glacier needed to justify its application. A more pragmatic use of the ice-cored moraine term has also been reasoned for (Lønne, 2007; Evans, 2009) with the term not needing to indicate detachment from a glacier.

Evans' (2009) work on *controlled moraine* formation highlights the 'linearity' that is found in landforms associated with incorporated ice. This linearity can, typically, be seen on aerial images (e.g. the western end of the outer moraine in Fig. 2) and serves as a useful and simple diagnostic criterion for the recognition of potential ice-cored character.

Investigation of ice-cored moraines can potentially aid our understanding of former glacier characteristics and any associated climatic significance. The ice core within such moraine complexes may include glacier ice, basal ice, or a combination of both. At modern ice margins, basal ice may record important information about prevailing conditions and the processes operating in the inaccessible subglacial environment further up-glacier (Hubbard and Sharp, 1989; Knight, 1997; Hubbard et al., 2009). Evidence for tectonic deformation of the ice-core sequence (i.e. folds and thrusts) could also indicate a range of dynamic and flow conditions when the ice was part of the parent glacier. For example, englacial thrusts and folds have been inferred to indicate flow compression either as a result of polythermal glacier conditions (e.g. Hambrey et al., 1999), ice flow against a steep reverse bedslope (e.g. Swift et al., 2006), or during glacier surges (e.g. Sharp et al., 1994; Waller et al., 2000). Some of these basal ice characteristics may also be preserved in the moraine sediment as the basal ice melts, offering the potential to reconstruct basal ice characteristics from deglaciated terrain (e.g. Evans, 2009; Knight et al., 2000; Cook et al., 2011).

Recent work by Hambrey et al. (2005) at neighbouring Midtre Lovénbreen highlighted the value of glacier structural mapping in developing an understanding of the changing dynamics of glaciers in the context of climatic warming. The work of Hambrey et al. (2005) remains, however, an isolated example of how analysis of temporally separated aerial and oblique aerial imagery can be used to evaluate glaciological change over time. Our study extends the record of changing glacier dynamics in this region, and thereby contributes to a broader understanding of both glacier and climatic change in the region. In particular, and as highlighted in the study of Midtre Lovénbreen, there is some uncertainty about whether the Lovénbreen glaciers experience surge-type behaviour (Hambrey et al., 2005). Ground-based imagery of these glaciers by Hamberg (1894) from 1892 showed near-vertical ice cliffs at their Neoglacial moraines. This feature was interpreted by Liestøl (1988) to indicate surging. Hagen et al. (1993) also classify Midtre Lovénbreen as a surge-type glacier. Later work by Jiskoot et al. (2000) indicated that these glaciers were not surge-type, whereas Hansen (2003) suggested that Midtre Lovénbreen had surged in the past, but could no longer be classified as a surge-type glacier. On the basis of structural analysis, Hambrey et al. (2005) also concluded that Midtre Lovénbreen was not a surge-type glacier, or at least had not surged for several hundred years. Recognition of surge-type behaviour has important implications for understanding their behaviour in the context of climatic change, since glacier surges may lead to advance even during climatic amelioration. Little is known about whether Austre Lovénbreen has experienced surging behaviour in the past, but our analysis of historical and modern aerial imagery, as well as the structures preserved within the ice-core of the Neoglacial moraine, contributes to our understanding of the dynamics of this glacier.

3. Study area

Austre Lovénbreen (78°53’12’’N 12°08’50’’E) is located near Ny-Ålesund on Brøggerhalyøva on the island of Spitsbergen, part of the Svalbard archipelago, in the Norwegian high-Arctic (Fig. 1). Austre Lovénbreen is a small valley glacier that was around 5 km in length at its Neoglacial maximum, but is currently just less than 4 km in length.

The thermal regime of Austre Lovénbreen in 2010 was polythermal, based on our interpretation of GPR profiles undertaken in 2010 by Saintenoy et al. (2013), albeit with an extensive region of cold-based ice and an exceptionally small region of warm-based ice at the deepest part of the glacier. The longitudinal profile of the Austre Lovénbreen bed, again based on our interpretation of GPR profiles undertaken by Saintenoy et al. (2013), also highlights an overdeepening starting at around 250 m and extending to around 2.7 km up-glacier from the 2010 glacier terminus (Fig. 4 in Saintenoy et al., 2013). At the adjacent polythermal Midtre Lovénbreen, previous research has highlighted up-glacier migration of the boundary between cold- and warm-based ice that was identified from GPR surveys undertaken in 1998 and 2006 (Rippin et al., 2007). Evolution of the thermal regime in response to climatic warming and thinning of the ice is also recognised at other Svalbard glaciers (e.g. Hodgkins et al., 1999).

In common with other glaciers in the area, the glacier terminus of Austre Lovénbreen has receded by around 1 km since the Neoglacial maximum extent at the end of the nineteenth century. The adjacent Midtre and Vestre Lovénbreen were photographed by Hamberg (1894) in 1892 with high, near-vertical ice margins, at what is now probably the outer part of the moraine-mound complex surrounding each glacier. Given that Austre Lovénbreen is comparable to these glaciers in most respects, it seems likely that it exhibited similar features and reached its Neoglacial maximum at around the same time. The photographic evidence of the Lovénbreen glaciers also corresponds with the work by Svendsen and Mangerud (1997) on the response of Linnébreen in central Spitsbergen indicating Neoglacial distal moraine formation during the late nineteenth century. Overridden soil and vegetation, now found beneath the nearby Longyearbreen, indicate that *c*. 1100 years ago the margin of the glacier was at least 2 km upstream of the current margin (Humlum et al., 2005). As this glacier is typical of central Spitsbergen glaciers in terms of topographic setting, aspect and size (Humlum et al., 2005), it seems likely that Austre Lovénbreen has experienced a similar advance and recession to that of Longyearbreen over a timescale of over 1100 years.

The continuing terminus recession of Austre Lovénbreen is associated with the typically negative mass balance of the glacier that is demonstrated by the mass balance record from 1968 to 2009 at the adjacent Midtre Lovénbreen (WGMS, 2011). Friedt et al. (2012) show the Austre Lovénbreen glacier front positions mapped in 1962, 1995 and 2009. Between 1962 and 1995 the glacier receded by ~300 m, and between 1995 and 2009 the glacier receded by ~75 m.

The moraine complex in front of Austre Lovénbreen consists of well-developed high-relief (*c*. 30–60 m high) lateral moraines, completely detached from the glacier, which continue and merge into the frontal outer moraine complex (*c*. 10 m high) with a distinct difference in morphology to the low-relief (commonly around 5 m high) 'hummocky moraine' areas within the moraine-mound complex (Fig. 2).

The west coast of Spitsbergen experiences a much warmer climate than its 79°N location might imply, with Ny-Ålesund having a mean annual temperature of –6.3 °C from 1961 to 1990 and –5.2 °C from 1981 to 2010 (Førland et al., 2011).

4. Methods

A pulseEKKO Pro ground-penetrating radar (GPR) system was used with a 400 V transmitter and 100 MHz centre frequency antennae to investigate the subsurface characteristics along a series of transects over the outer lateral-frontal moraine complex of Austre Lovénbreen (see Fig. 2B for transect locations). The fieldwork was undertaken during winter conditions in April 2012 to ensure the presence of frozen ground. The moraines were covered with a surface ice layer (where this ice layer was visible, it was typically ~5 cm thick) and overlying snow. Whilst snow depth was spatially variable, based upon 45 measurements taken at fixed interval along the transects, snow depth was generally less than 5 cm, but was exceptionally as deep as 88 cm. Whilst the majority of the outer moraine had limited snow cover, it was not possible to survey complete transects through and beyond the moraine limits. This was because the prevailing wind through Kongsfjorden at the time the research was undertaken had resulted in deep snow and the formation of large cornices on the NW side of the moraines, which combined with the steep slope of the ice-distal outer moraine face, made both topographic and radar surveys impossible to complete on the ice-distal faces. The 100 MHz antennae were used with the standard 1 m separation and a 0.25 m step size along each transect. A 750 ns time window was used, along with 36 stacks and each trace was manually triggered with the transmitter and receiver stationary and positioned along a 100 m tape. A perpendicular broadside antennae configuration was used with each transect transverse to the moraine ridge crest orientation. The GPR control unit was positioned at least 5 m away from the transmitter and receiver to mitigate any potential signal interference. Velocity was calibrated along each transect with common mid-point (CMP) surveys orientated perpendicular to the main transect (and parallel to the moraine crest). Because the field interpretation of the main reflection-mode transects was that of dipping reflectors, reflection surveys were also undertaken along the line of the CMP surveys to ensure that the CMP survey lines were, as far as possible, parallel to the strike and normal to the direction of dip of the reflectors. The separation distance of the antennae that was completed on each CMP survey was dependent upon the substrate conditions, and ranged from 26–40 m separation, with 40 m being the limit of the fibre optic cable length. An automatic level was used to survey height change along each transect so that the topography could be applied to the radar profiles.

Radar profiles were produced using the EKKO_View Deluxe software from Sensors and Software. Dewow, an automatic gain control and topography were applied to each data set during post-processing. A total of 9 reflection-mode main surveys and an additional 17 CMP-mode surveys were obtained around the Austre Lovénbreen lateral-frontal complex.

Structural mapping of the glacier surface was undertaken from two images. The first is a monochrome oblique aerial image from 1936 obtained by Norsk Polarinstitut. The second image is an orthorectified aerial image of the lower ~2 km of the glacier tongue and its proglacial area obtained by the NERC ARSF (Natural Environment Research Council, Airborne Research and Survey Facility) in 2003. The 2003 image was derived from 8 scanned true colour contact prints with a resulting spatial resolution of around 1 m.

5. Results

5.1. CMP surveys

The CMP surveys that cross transects 1–5 show ground velocity characteristics that range from 0.16–0.17 m ns^{-1} (Table 1). CMP surveys that cross transects 6–7 have a velocity of 0.15 m ns^{-1}, whereas CMP surveys that cross transects 8–9 show ground velocity characteristics that range from 0.13–0.14 m ns^{-1} (Table 1). As an example, Fig. 3a shows a CMP survey across transect 2 with an initial air wave of 0.3 m ns^{-1}, a ground wave around 0.22 m ns^{-1} through the snow and a subsurface velocity of 0.17 m ns^{-1}. In contrast, Fig. 3b shows a

CMP survey across transect 9 with an initial air wave and a subsurface velocity of 0.13 m ns^{-1}.

5.2. Internal structure of the moraine

Multiple up-glacier dipping reflectors that intersect both the ice-proximal and ice-distal faces of the moraine are found in all transects (Figs. 4 and 5). These reflectors are common in transect 1, abundant in transects 2–6 and isolated examples occur in transects 7–9 (Figs. 4 and 5 and Table 2). The reflectors often have an asymptotic profile where the dip become progressively shallower at depth; a characteristic that is shown with particular clarity in transect 2 (Figs. 4 and 5). The apparent angle of dip of the reflectors at the intersection of the ground surface ranges from 6–50° (Table 3). The reflector apparent dip angles appear reasonably consistent through transects 2–6, with a dominant 41–50° range. However, transect 1 shows lower apparent dip angles with an 11–20° dominant range. Transects 7 and 9 are distinct from the other profiles with lower dip angles dominantly within the 20–39° range, but also including examples below 10°, and transect 8 has a dominant range of 31–40°. Transect 6 very clearly demonstrates an open syncline structure of reflectors dipping up-glacier in the distal part of the moraine and dipping down-glacier in the proximal part of the moraine (Figs. 4 and 5). This syncline structure is also found in transects 1, 3–4 and 5, but is shown in these examples with less clarity than in transect 6. Transects 7–9 show a number of surface parallel reflectors below the air and surface wave of the GPR profiles (Figs. 4 and 5).

5.3. Hyperbolae from point targets

A hyperbolic curve developed over sequential radar traces is created by a point target. Hyperbolae are rare in transects 2–5, in contrast to transects 1 and 6 that show a greater number of hyperbolae (Table 2). The dipping reflectors in transects 1 and 6 are, to an extent, slightly obscured by these numerous point hyperbolae. The GPR transects did not have a migration process applied because the dipping tails of each hyperbola can be clearly differentiated from the dipping reflectors. Transects 7–9 reveal a markedly different radar facies that are characterised by multiple overlapping hyperbolae and a lack of clearly identifiable reflectors, in contrast to the surveys along transects 1–6.

5.4. Signal attenuation

Transects 1–5 each show clearly identifiable reflector layers down to 15 m depth and in some places down to 20 m depth associated with low signal attenuation (Table 2). Penetration in transect 6 is slightly reduced at 10–15 m depth, but transects 7–9 are markedly different with a lack of clarity below 5 m and an absence of clarity below 10 m depth associated with high signal attenuation (Table 2).

5.5 Glacier structural mapping

An assessment of the structural composition of Austre Lovénbreen in 1936 has been undertaken using oblique aerial imagery (Fig. 6). The lowermost ~1 km of the terminus is mapped in greater detail since it is nearer to the viewer and hence the structures more readily identified. In 1936 the glacier had barely receded from its Neoglacial maximum position, although the flat terminus where the glacier met the moraine indicates that it had experienced thinning at the terminus. This is in contrast to the steep terminal ice cliffs described by Hamberg (1894) when the area was visited in 1892.

A number of structural features are identified (Fig. 6). Primary stratification is produced originally by snow accumulation in horizontal layers and is found: (1) within one flow unit of the glacier that has been deformed into a nested set of arcuate bands; and (2) as bands stretching across much of the frontal margin, although best developed on the true left of the glacier (Fig. 6).

The longitudinal features stretching up-glacier from the ice margin are interpreted as longitudinal foliation. This structure appears around much of the glacier margin, although there are clear concentrations of longitudinal foliation which appear to have released significant quantities of sediment onto the glacier surface.

There are also isolated debris-laden fractures in the upper true left terminus. The precise origin of these features is uncertain, but they could represent debris-filled crevasse traces, debris-rich primary stratification, or englacial thrust faults laden with basal sediment.

One intriguing feature of the 1936 imagery is a bulge in the glacier surface from the true left valley side across around two thirds of the glacier width (indicated by the thick dotted line on Fig. 6). This bulge is best identified by tracing the prominent longitudinal foliation up-glacier and the slope of the true left lateral margin. The origin and significance of this bulge is uncertain, but it would be consistent with a surge wave propagating down-glacier in 1936.

The quality of the 2003 aerial imagery allows a much more detailed structural assessment of Austre Lovénbreen to be mapped (Fig. 7). Three primary flow units are identified, defined by dense areas of longitudinal foliation that can be traced as far up-glacier as the imagery presented permits. These may represent medial moraines produced at the confluence of individual flow units.

Primary stratification is a prominent feature in the 2003 imagery and is seemingly more extensive than is shown in the 1936 image. Much of the primary stratification is folded, indicating lateral compression, and where it can be picked out along the trace of longitudinal foliation, is shown to be tightly folded with the fold limbs extending along the axis of flow. Primary stratification is generally less folded in the true left flow unit.

Longitudinal foliation is a ubiquitous feature around the glacier margin where it releases significant quantities of sediment. Many of the foliae melting out on the glacier surface can be traced linearly into the proglacial zone. Although longitudinal foliation is concentrated along medial moraine features at flow unit boundaries (cf. Hambrey and Glasser, 2003), this structure can be traced up-glacier from almost any point from the ice margin. There are significant concentrations of longitudinal foliation along the lateral margins, and through much of the central flow unit.

Debris-bearing fractures are mapped close to the true right margin. It is unclear what the origin of these features could be, as was the case for the 1936 imagery, and we advance the same hypotheses for their origin. Notably, these features do not appear in the same location as in the 1936 imagery.

The higher resolution 2003 image allows the mapping of more subtle features including crevasses and crevasse traces. Open crevasses are generally rare, and most such features mapped are in fact crevasse traces (Fig. 7). The highest density of crevasse traces can be found along the true left flow unit. Crevasse traces are also found along the true right lateral margin, but the density of crevasse-related features here is much lower. Crevasse traces along the true right are relatively short (~150 m in length) compared with the extensive (up to ~500 m long) arcuate crevasse traces across the centre of the glacier terminus.

6. Discussion

6.1. Moraine composition

The CMP surveys revealed radar velocities through the moraine of between 0.13 and 0.17 m ns^{-1}, indicating that its composition is varied. High velocities (at, or close to the 0.17 m ns^{-1} velocity through glacier ice; Murray and Booth, 2010; Saintenoy et al., 2013), combined with low signal attenuation and associated deep penetration, are characteristic of a large ice component (Table 4). Lower velocities and relatively higher signal attenuation are indicative of a significant sediment component. Schwamborn et al. (2008) determined the radar velocity through unsorted 'outwash [and] morainic deposits' in the proglacial area of the adjacent Midtre Lovénbreen to be 0.127 m ns^{-1}. The sequence at Midtre Lovénbreen, which appears to be mostly clast-rich intermediate diamicton (Fig. 8 in Schwamborn et al., 2008), was just under 3 m thick with a mean ice content of around 10% (gravimetric ice content expressed as water equivalent, as determined from a 6 cm diameter permafrost core) and is a common facies in the proglacial setting of Midtre Lovénbreen (Midgley et al., 2007). Although frozen ground conditions prevented us from directly determining the nature of the sediments within the Austre Lovénbreen lateral moraine, previous work has found clast-rich diamicton to be abundant within this moraine-mound complex (Graham, 2002). Given the consistent geology underlying the two glaciers and the proximity of the sites, it is likely that velocities of around 0.13 m ns^{-1} are indicative of frozen diamicton with around 10% interstitial ice at Austre Lovénbreen. Based upon the known radar velocity through both glacier ice (0.17 m ns^{-1}) consisting of ~100% ice and a known velocity for a proglacial debris facies with ~10% interstitial ice component (0.127 m ns^{-1}), a linear interpolation between these two end members can be used to estimate likely velocities for a range of debris-ice mixes (Table 5).

The observed radar velocities of 0.16 to 0.17 m ns^{-1} across transects 1 to 5 are characteristic of a dominant ice component within the outer moraine complex with up to 20% sediment. Radar velocities along transects 6 and 7 still indicate a significant ice component, but with up to 40% sediment. Radar velocities along transects 8 and 9 are indicative of a relatively low ice component, with sediment contributing between 60% and 80% of the moraine volume.

6.2. Identification of debris within the substrate

Four distinct zones (A–D) of the lateral-frontal outer moraine complex at Austre Lovénbreen are recognised (Fig. 2) on the basis of both the ice-debris mix and the structural characteristics.

Zone A, whilst having a dominant ice component, does exhibit hyperbolae, which are likely to indicate the presence of isolated coarse-grained clastic material within the ice (Fig. 4). This is in contrast to zone B, which also has a dominant ice component, but appears to lack the isolated coarse-grained component that would cause hyperbolae in the radar profiles (Fig. 4). The measured velocity in zone C of transect 6 is the same as that of transect 7, but a high coarse-grained debris load is inferred for transect 7 that inhibits the identification of any structural features (Fig. 4). This is in contrast to the fine-grained debris load found in transect 6, which results in identification of the clear structural characteristics. Zone D has a dominant coarse-grained debris component shown by the ubiquitous overlapping hyperbolae (Fig. 4).

6.3. Structural glaciology and dynamics of Austre Lovénbreen

The structural mapping of Austre Lovénbreen provides important context that aids the understanding of the conditions under which the lateral-frontal moraine formed. A number of features indicate that the glacier is now far less dynamic than it would have been during its Neoglacial maximum extent. Most notably, there were few actively forming crevasses in 2003 (Fig. 7), indicating that the glacier is now flowing very slowly. The 1936 imagery (Fig. 6) is not of sufficient resolution to identify crevasses, but there is evidence that Austre Lovénbreen had a surface bulge. Further analysis is required in order to determine whether this was a surge-related expression, but the dense population of fractures (interpreted here mostly as crevasse traces) along the true left side of the glacier, close to the ice margin, indicates that this flow unit was more dynamic in the past.

If there had been a surge around 1936, it will not have contributed ice to the ice-core within the lateral-frontal moraines that are under investigation here. It is possible, however, that a surge may have allowed pushing of the glacier against the lateral-frontal moraine and thereby allowed some deformation of the ice-core. Another possibility is that the glacier surged during its Neoglacial advance and that the ice preserved in the lateral-frontal moraine is derived from such a surge. Hansen (2003) suggested that neighbouring Midtre Lovénbreen had once been a surge-type glacier, but could no longer be considered to be so. We suggest, albeit tentatively, that Austre Lovénbreen may once have been a surge-type glacier, but there is no indication that it has surged since ~1936, nor is there any indication that it will surge again in the near future.

6.4. Origin of ice incorporated within the lateral-frontal moraine

The structural maps of Austre Lovénbreen provide important context that aid understanding of the origin of the ice now found within the lateral-frontal moraine. The GPR surveys demonstrate that the ice within the moraine contains a combination of ice and debris arranged in layers, some of which have experienced folding.

The up-glacier dipping reflectors with minor folding (Fig. 5) are consistent with the structural characteristics of layered primary stratification, as seen in the 1936 oblique aerial image (Fig. 6). Hambrey et al. (2005), for example, showed in a longitudinal GPR profile (i.e. orientated parallel with ice flow) that primary stratification at neighbouring Midtre Lovénbreen dipped up-glacier, and had experienced minor folding. However, primary stratification is not likely to contain the significant quantities of debris revealed by the GPR survey. The layering of primary stratification instead usually results from differences in crystallography and bubble content.

Debris-bearing structures exist in the terminus of Austre Lovénbreen that are transverse to flow (Figs. 6 and 7). These structures could represent isolated englacial thrusts. It would, however, also be hard to envisage that these isolated features could explain the dense layering shown in the GPR surveys of the moraine. It could be argued, however, that our mapping, without any ground-truthing of the structures, may have under-represented the number of debris-bearing fractures, including thrusts. In particular, there are numerous arcuate fractures that extend across much of the lower part of the terminus, some of which may include thrusts. Indeed, Hambrey et al. (2005) interpreted similar arcuate fractures at Midtre Lovénbreen as englacial thrust planes. Nonetheless, it is hard to envisage that all of the reflectors in the GPR profiles represent englacial thrusts. Other studies have identified debris-rich englacial thrusts with GPR at a number of other glaciers in the region, including Scott Turnerbeen (Sletten et al., 2001), Bakaninbreen (Murray et al., 1997) and nearby Kongsvegen (Murray and Booth, 2010). Radar images of dipping reflectors from Austre Lovénbreen appear distinct from englacial thrust reflectors reported at Kongsvegen by Murray and Booth (2010) which, at Kongsvegen, appear to be isolated, discrete and thicker features than are found at Austre Lovénbreen.

A further possibility is that the dipping structures within the moraine represent layering within buried basal ice. Debris-laden basal ice commonly has a layered appearance derived either from freeze-on of packages of water and sediment to the glacier base, or from regelation, and may have a sediment content from 0 to ~90% (e.g. Hubbard and Sharp, 1989; Knight, 1997; Hubbard et al., 2009). Further, the folding in the layers is also consistent with reports of tectonic deformation within basal ice layers (e.g. Waller et al., 2000), perhaps in this case caused by compression against the adverse bed slope, or the cold-based margin, or possibly during a surge event. Several processes could contribute to basal ice formation at Austre Lovénbreen including regelation as the glacier slides over bedrock in the temperate zone up-glacier from the terminus (e.g. Hubbard and Sharp, 1993), and seasonal freeze-on of meltwater and sediment at the glacier terminus (e.g. Weertman, 1961). Additionally, analysis of the GPR profile of Saintenoy et al. (2013) demonstrates that the adverse bed slope of the basin beneath Austre Lovénbreen is ~1.6 times steeper than the ice surface slope. Hence, the bed slope meets the threshold necessary to permit the operation of glaciohydraulic supercooling and associated freeze-on of water and sediment (e.g. Lawson et al., 1998; Cook et al., 2010). There are no reports, however, of any field evidence diagnostic of the operation of supercooling (cf. Evenson et al., 1999; Cook et al., 2006). Regelation is unlikely to produce the thick sequences of ice and sediment shown in the GPR profiles, as basal ice thicknesses associated with regelation are generally less than ~1m due to ice melting from the base during glacier sliding (e.g. Hubbard and Sharp, 1989; Knight, 1997). Basal ice could be formed by freeze-on, either seasonally or possibly through supercooling. Our favoured hypothesis is that post-formational flow-related deformation in the form of strong longitudinal compression has led to the stacking of the debris-rich layers (e.g. Waller et al., 2000). Strong longitudinal compression could be caused by either: (1) the subglacial overdeepening (based on our interpretation of the GPR profiles undertaken by Saintenoy et al., 2013); (2) the glacier margin during the Neoglacial maximum; or (3) associated with a surge.

The buried basal ice could be composed of a range of descriptively different facies, possibly with different origins. However, at the resolution of the radar imagery the most appropriate classification is banded basal ice (i.e. layering on the scale of centimetres to decimetres), according to the classification scheme of Hubbard et al. (2009). Care must be taken with the interpretation of the reflector angle of dip as the survey lines may not run parallel to the direction of dip of the reflectors in each case. What is recorded, therefore, is an apparent dip, rather than an actual dip. Further work involving three-dimensional GPR profiling of the reflectors could resolve this issue.

6.5. Landform stability and preservation potential

Despite its high ice content, the moraine within zones A–C appears relatively stable. Examination of aerial imagery reveals an absence of slope failure and back wasting features (Fig. 2) that are characteristic of moraines with high rates of ablation of incorporated buried ice (e.g. Bennett et al., 2000). It is, however, likely that surface lowering is occurring, as repeat lidar surveys of the north east side of the outer complex at the adjacent Midtre Lovénbreen has shown surface lowering of 0.65 m a^{-1} (±0.2 m) (Irvine-Fynn et al., 2011). Schomaker and Kjær (2008) also recognised similar downwasting rates of 0.9 m a^{-1} from 1983 to 2004 at Holmströmbreen in central Spitsbergen. Given the mean summer temperature of 3.8 °C recorded during the 1981-2010 period at nearby Ny-Ålesund (Førland et al., 2011), it is likely that the buried ice at Austre Lovénbreen experiences some ablation during the summer months. So zones A–C of the outer moraine complex are downwasting, rather than backwasting. The dampening effect on ablation of the thin protective surface debris layer will depend upon: (1) the thickness of the debris layer; (2) the thermal conductivity of the debris type; and (3) the water content of the surface debris layer (Schomacker, 2008). Other potential factors that result in a difference between the stability of the surface debris layer of the ice-cored lateral moraines at Austre Lovénbreen and nearby Kongsvegen (outlined by Bennett et al., 2000) include a potentially thicker surface debris layer and/or coarser surface debris that promote drainage. A freely drained surface debris layer would be less prone to slope failure and exposure of the underlying ice, but would have a higher thermal conductivity, so could act to either promote or inhibit the ablation of the buried ice. Rates of dead-ice ablation can be similar in both the cold arid Svalbard climate and the mild humid climate of Iceland (Schomaker and Kjær, 2008). This outer moraine complex at Austre Lovénbreen is located away from the proglacial fluvial discharge routes of both Austre and Midtre Lovénbreen: this is likely to be the key issue facilitating the lack of backwasting and apparent stability of the landform.

The moraine within zone D contains a relatively small amount of ice and the porosity of the debris is, therefore, important to understand how the incorporated ice influences its morphology. Whilst Kilfeather and van der Meer (2008) note that 'till porosity has largely been ignored', a range of likely porosity values can be assessed (Table 6). The Austre Lovénbreen outer moraine is likely to have a porosity value of between 0.15 and 0.30, based upon comparison to other similar sedimentary and morphological settings. The outer moraine within zone D at Austre Lovénbreen is, therefore, likely to experience little modification associated with the removal of 20–40% interstitial ice. High preservation potential of the outer moraine morphology in zone D is, therefore, likely to occur even following the complete ablation of the incorporated ice.

7. Conclusions

1. Buried ice forms the dominant component of the Austre Lovénbreen outer moraine in the upper lateral zone, whereas sediment forms the dominant component of the frontal zone.

2. Many examples of ice forming unstable components of landforms have been recognised and are associated with sediment reworking, but this example at Austre Lovénbreen illustrates that ice can, so far, form a relatively stable component of landforms without sediment reworking, although landform degradation will still occur.
3. The rate of surface lowering associated with ablation of buried ice is likely to have increased associated with the local change from a summer temperature of 3.4 °C (1961–1990) to 3.8 °C (1981–2010). This ablation rate is likely to increase further if local air temperature also increases.
4. Because of the ice-debris mix within the outer moraine, following complete climatic amelioration, the preservation potential of any geomorphological feature associated with the upper lateral moraine (zones A–B) is negligible. The preservation potential of the frontal moraine, however, is high, with little change predicted in the contemporary geomorphology resulting from the complete meltout of the interstitial ice component that is currently preserved by the low temperature and lack of ice exposure by surface sediment reworking.
5. The ice within the lateral-frontal moraine is likely to be composed of basal ice derived from freeze-on of ice and sediment to the glacier bed. Post-formational deformation, in the form of strong longitudinal compression, has subsequently led to a stacking and thickening of the sequence.
6. The glacier surface bulge identified on the 1936 aerial imagery provides evidence that Austre Lovénbreen has previously displayed surge activity,

although given the current state of the thermal regime and recent mass balance it is highly unlikely to do so in the near future.

7. This research shows the value of relict buried ice that is preserved in landforms to aiding our understanding of former glacier characteristics.
8. Further research on the stable isotope composition, sedimentology of included debris, and crystallography of the buried ice at Austre Lovénbreen will aid our understanding of both its origin and its value as an archive of palaeoglaciological information from the Neoglacial.

Acknowledgements

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Table 1 Common mid-point (CMP) survey velocities obtained for each ground-penetrating radar (GPR) transect at Austre Lovénbreen (multiple values indicate velocities obtained from different CMP surveys undertaken along each transect).

Transect	CMP velocity (m ns^{-1})
1	0.17
2	0.16 & 0.17
3	0.16
4	0.17
5	0.17, 0.16, 0.16, 0.17 & 0.17
6	0.15 & 0.15
7	0.15
8	0.14
9	0.14, 0.14 & 0.13

Table 2 Summary table of radar facies in the Austre Lovénbreen outer lateral-frontal moraine.

Transect	Relative velocity	Signal attenuation	Dipping reflectors	Syncline structure	Surface parallel reflectors	Hyperbolae	Debris component	Ice component	Zone
1	high	low	common	vague	absent	common	limited	dominant	A
2	high	low	abundant	not found	absent	scarce	limited	dominant	B
3	high	low	abundant	vague	absent	scarce	limited	dominant	B
4	high	low	abundant	vague	absent	scarce	limited	dominant	B
5	high	low	abundant	vague	absent	scarce	limited	dominant	B
6	moderate	moderate	abundant	clear	absent	moderate	ice-debris mix	ice-debris mix	C
7	moderate	high	scarce	absent	present	ubiquitous	ice-debris mix	ice-debris mix	C
8	low	high	scarce	absent	present	ubiquitous	dominant	limited	D
9	low	high	scarce	absent	present	ubiquitous	dominant	limited	D

Table 3 Relative abundance of reflector apparent angle of dip at the moraine surface.

Transect	Apparent angle of dip				
	10°	11-20°	21-30°	31-40°	41-50°
1		•••••	•		
2					••••••
3			•	•	• •••
4				•	• ••••
5				•	• ••••
6			•	••	•••
7	•	••	•••		
8			•	••••	•
9	•	•	•••	•	

Table 4 Common radar velocities (as cited by Schwamborn et al., 2008; Murray and Booth 2010; Reynolds, 2011).

Material	Radar velocity (m ns^{-1})
air	0.3
snow	0.194-0.252
glacier ice	0.168-0.172
permafrost consisting of clast-rich intermediate diamicton with 10% interstitial ice	0.127
water (fresh)	0.033

Table 5 Known radar velocities and interpreted velocities of ice-debris mixes.

Radar velocity (m ns^{-1})	substrate ice component	substrate debris component	interpreted substrate ice component	interpreted substrate debris component
0.17 [a]	100%	0%		
0.16			80%	20%
0.15			60%	40%
0.14			40%	60%
0.13			20%	80%
0.127 [b]	10%	90%		

[a] commonly accepted value for glacier ice (e.g. Saintenoy et al., 2013)

[b] velocity value for diamicton with 10% interstitial ice found by Schwamborn et al. (2008) at the adjacent Midtre Lovénbreen

Table 6 Example porosities associated with a range of glacial sediments and landforms.

Debris / landform type	Porosity	Source
Pleistocene till samples	0.01-0.19	Kilfeather and van der Meer, 2008
lateral moraine	0.10-0.15	Parriaux and Nicoud, 1990
value used to model terminal moraine failure and associated glacial lake outburst flood	0.15	Worni et al., 2012
frontal moraine	0.15-0.25	Parriaux and Nicoud, 1990
supraglacial till	0.20-0.40	Parriaux and Nicoud, 1990
B0dalen valley diamictons	0.25-0.40	Burki et al., 2010
recently deposited till from debris-rich basal ice	0.26-0.39	Ronnert and Mickelson, 1992
recently deposited diamicton at Matanuska glacier	0.30-0.50	Lawson, 1979

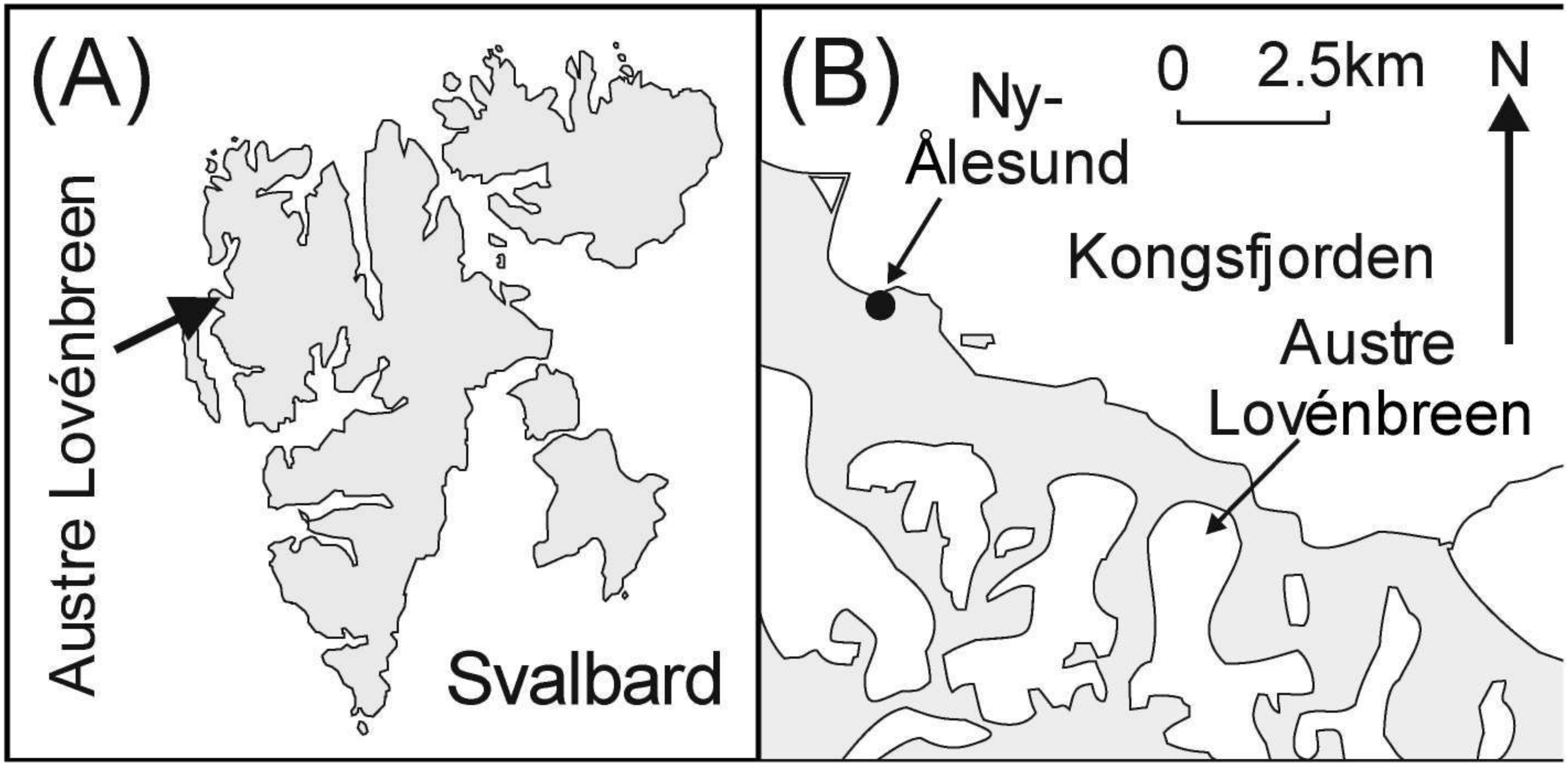

Figure 1 Location of: (A) Austre Lovénbreen on Svalbard in the Norwegian high-Arctic; (B) Austre Lovénbreen on Brøggerhalvøya near Ny-Ålesund.

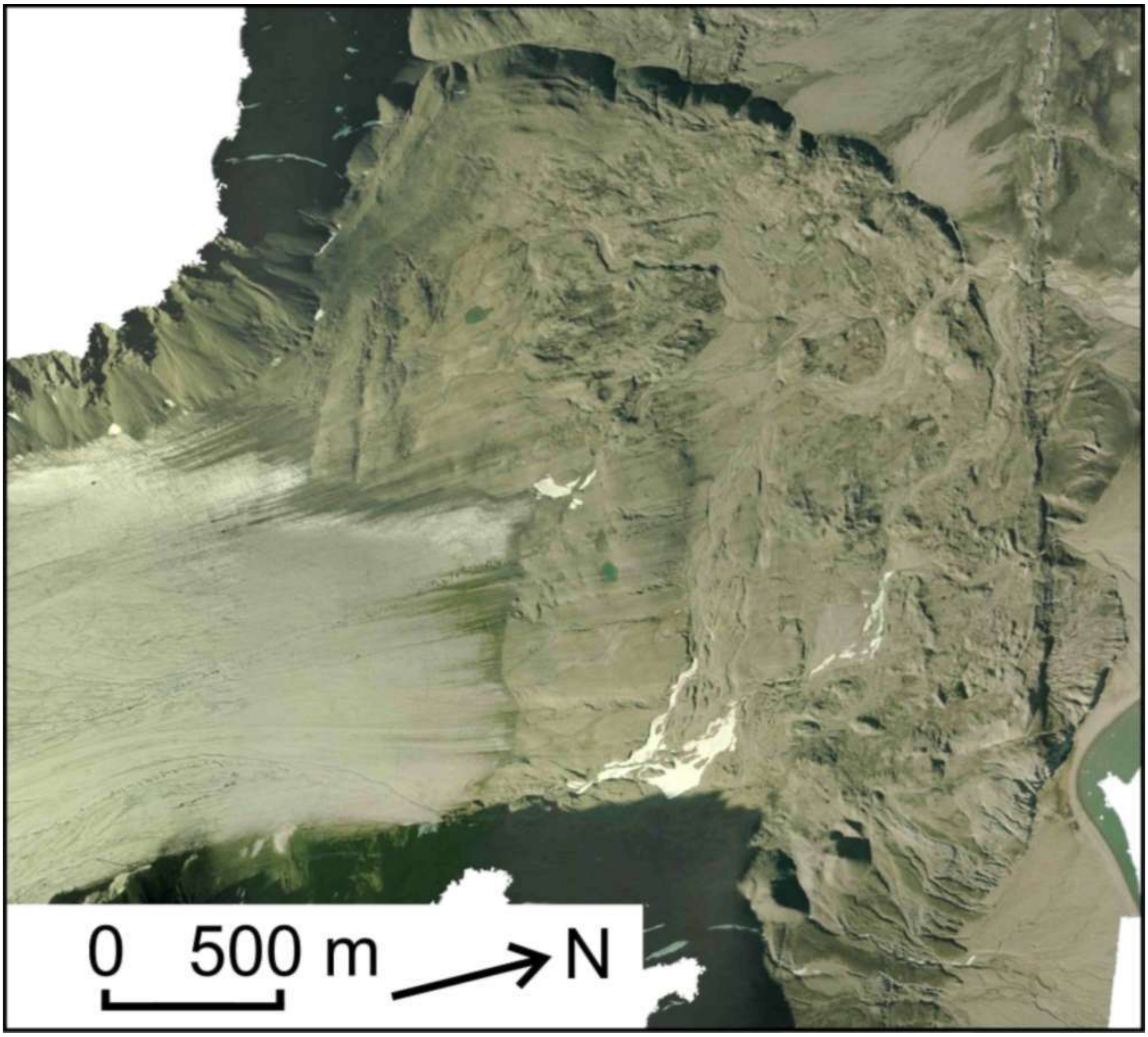

Figure 2 (A) Aerial image of the terminus of Austre Lovénbreen (summer 2003) and the proglacial area; (B) outline of the Neoglacial lateral-frontal moraine and the location of the GPR transects. Aerial image data from the UK Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) are provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

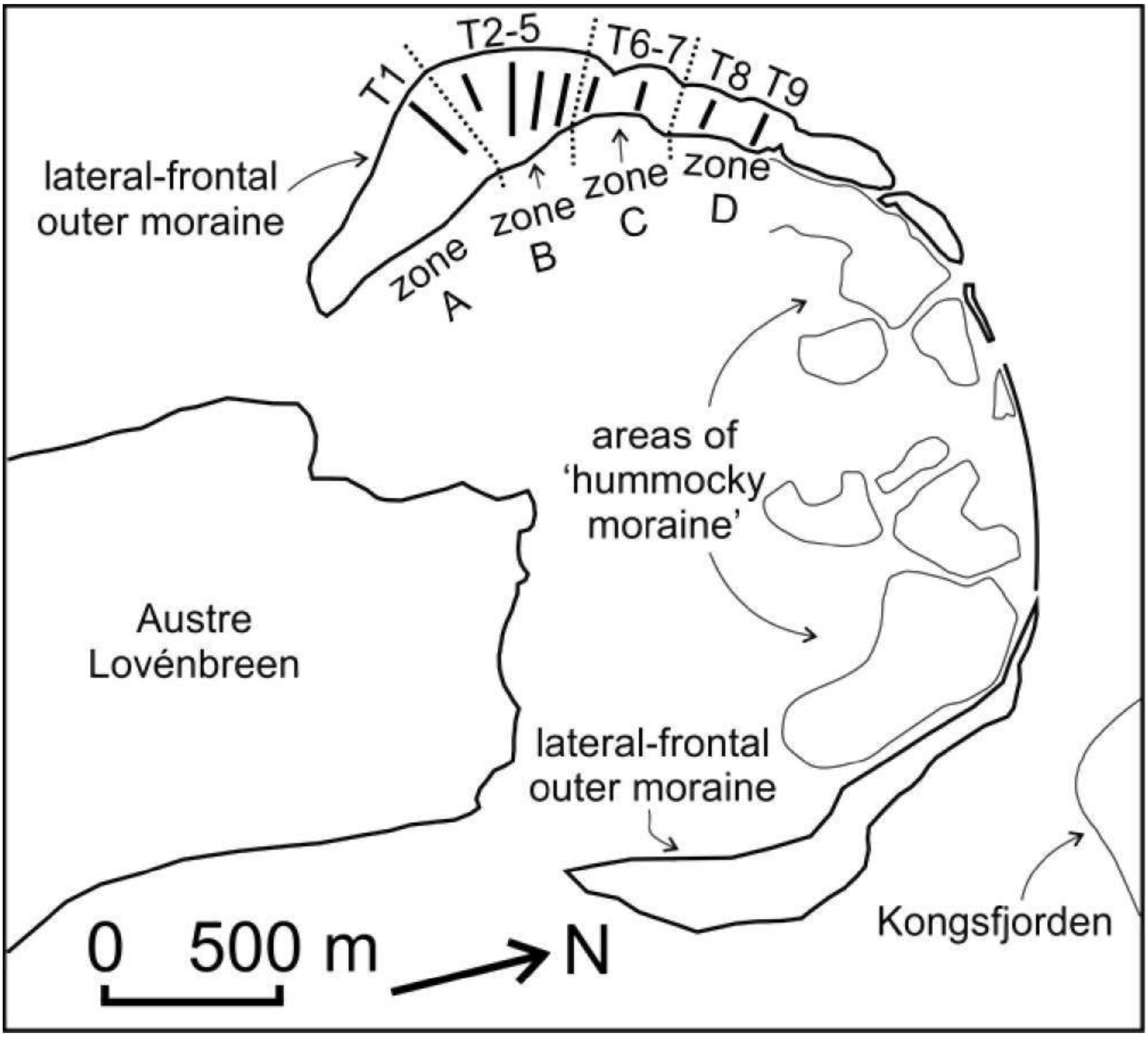

Figure 2 (A) Aerial image of the terminus of Austre Lovénbreen (summer 2003) and the proglacial area; (B) outline of the Neoglacial lateral-frontal moraine and the location of the GPR transects. Aerial image data from the UK Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) are provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).

(A) 0

100

S, 200

A I 300

400

i i i i i i i

velocity (m ns1)

(B) 0

100

S, 200

A I 300

400

"i i i r i i

velocity (m ns1)

Figure 3 (A) Example common mid-point (CMP) survey across transect 2; (B) CMP survey across transect 9.

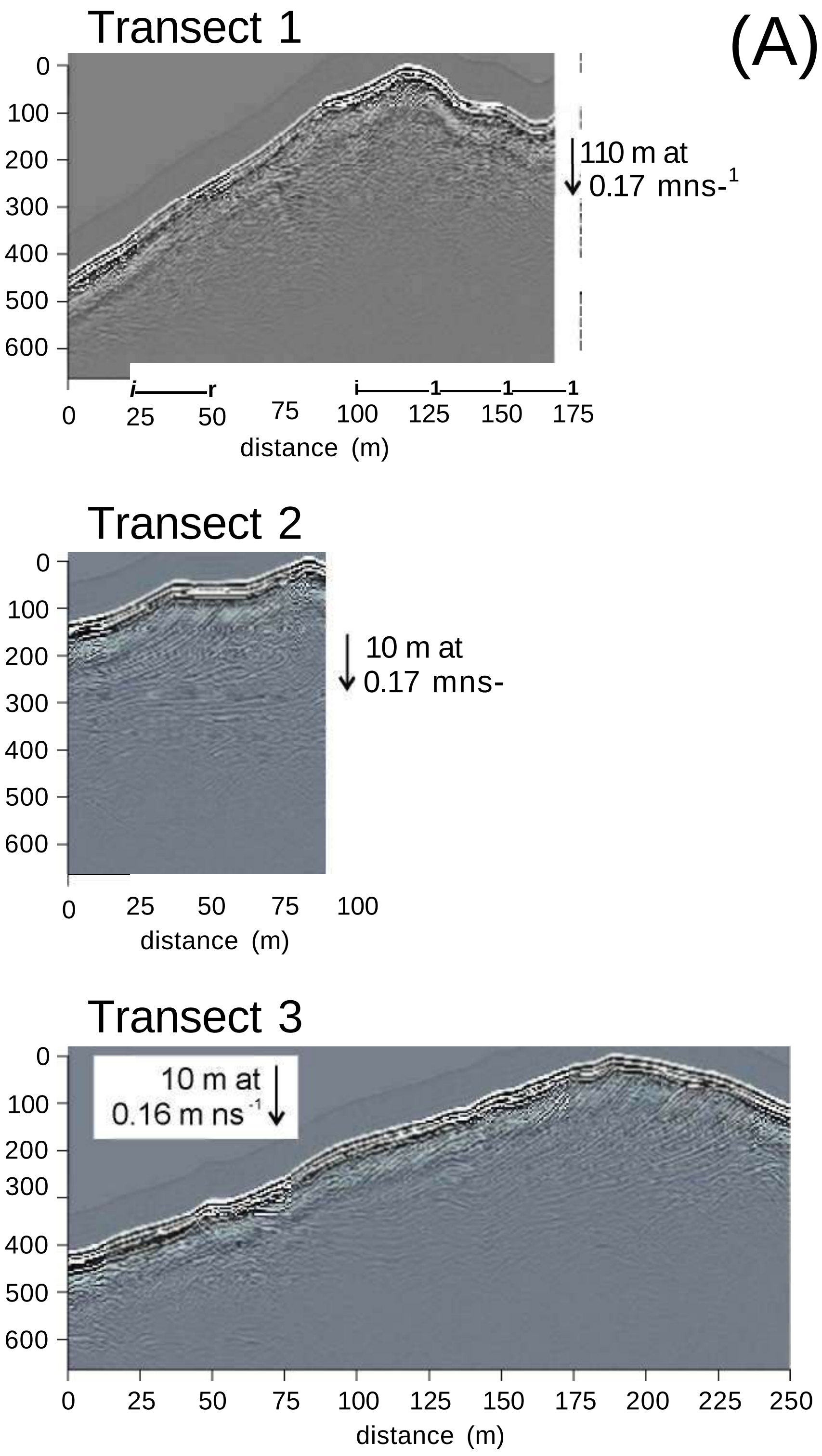

Figure 4 Ground-penetrating radar (GPR) surveys as grey-scale images: (A) transects 1–3; (B) transects 4–6; and (C) transects 7–9.

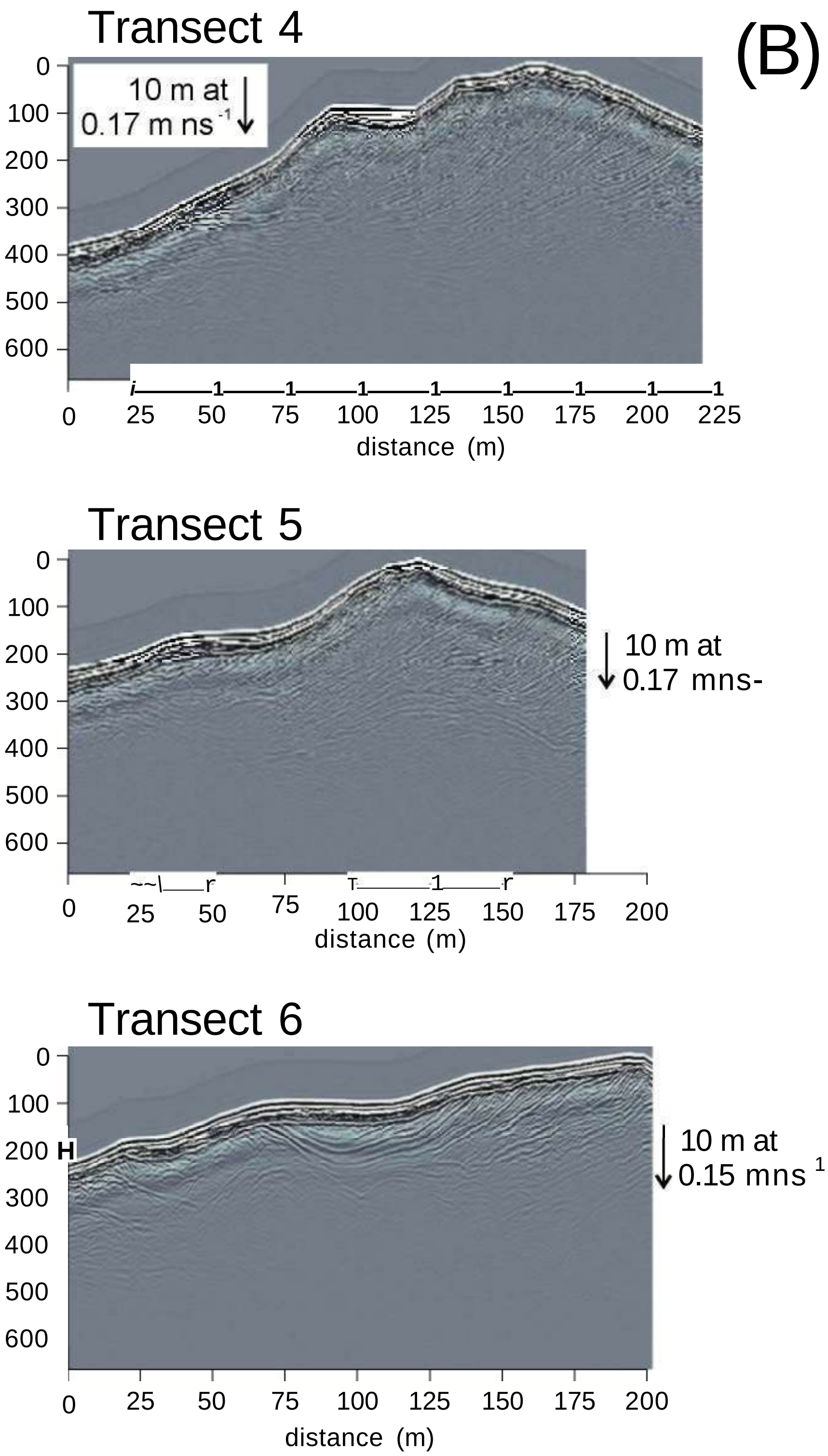

Figure 4 Ground-penetrating radar (GPR) surveys as grey-scale images: (A) transects 1–3; (B) transects 4–6; and (C) transects 7–9.

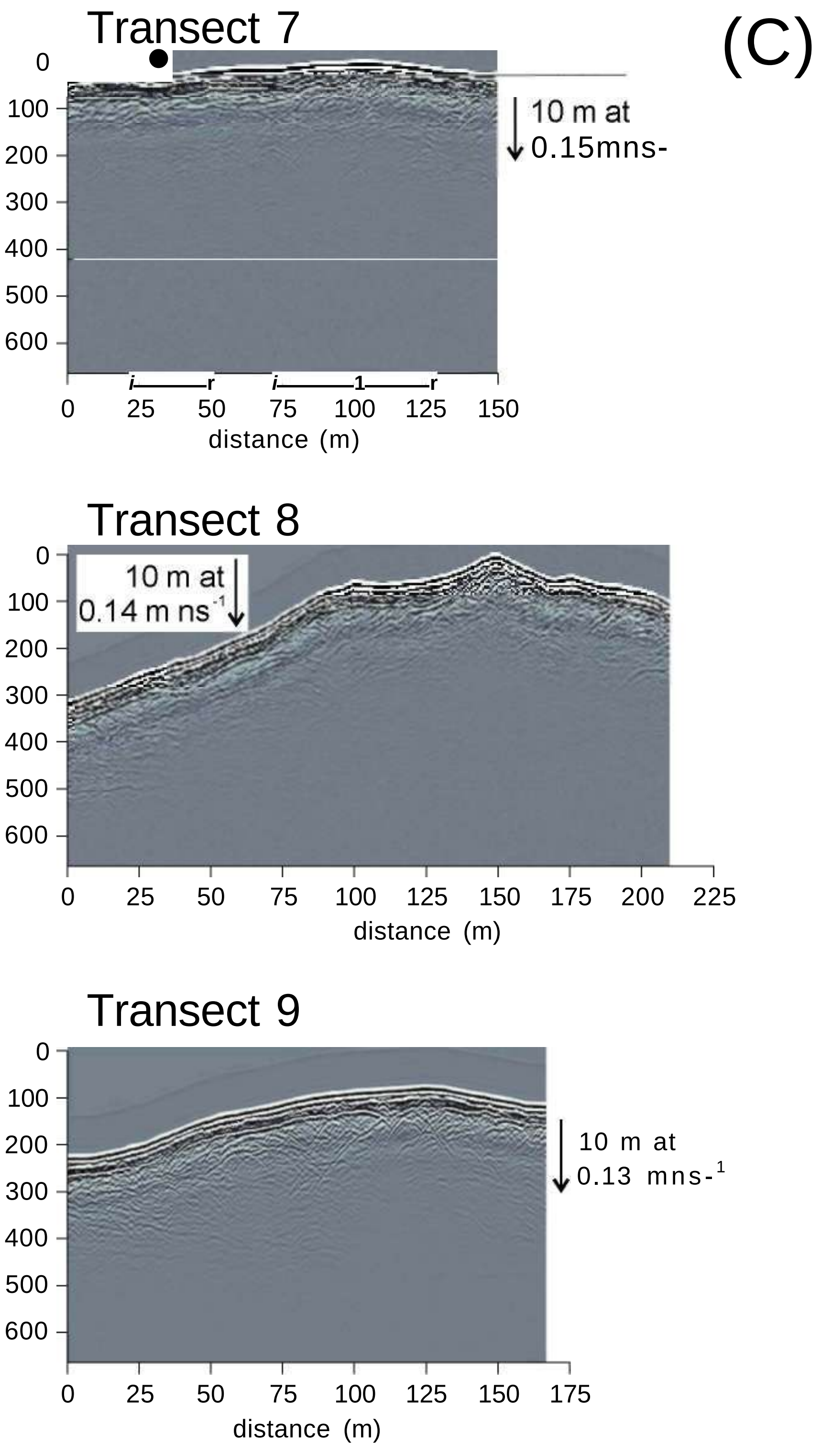

Figure 4 Ground-penetrating radar (GPR) surveys as grey-scale images: (A) transects 1–3; (B) transects 4–6; and (C) transects 7–9.

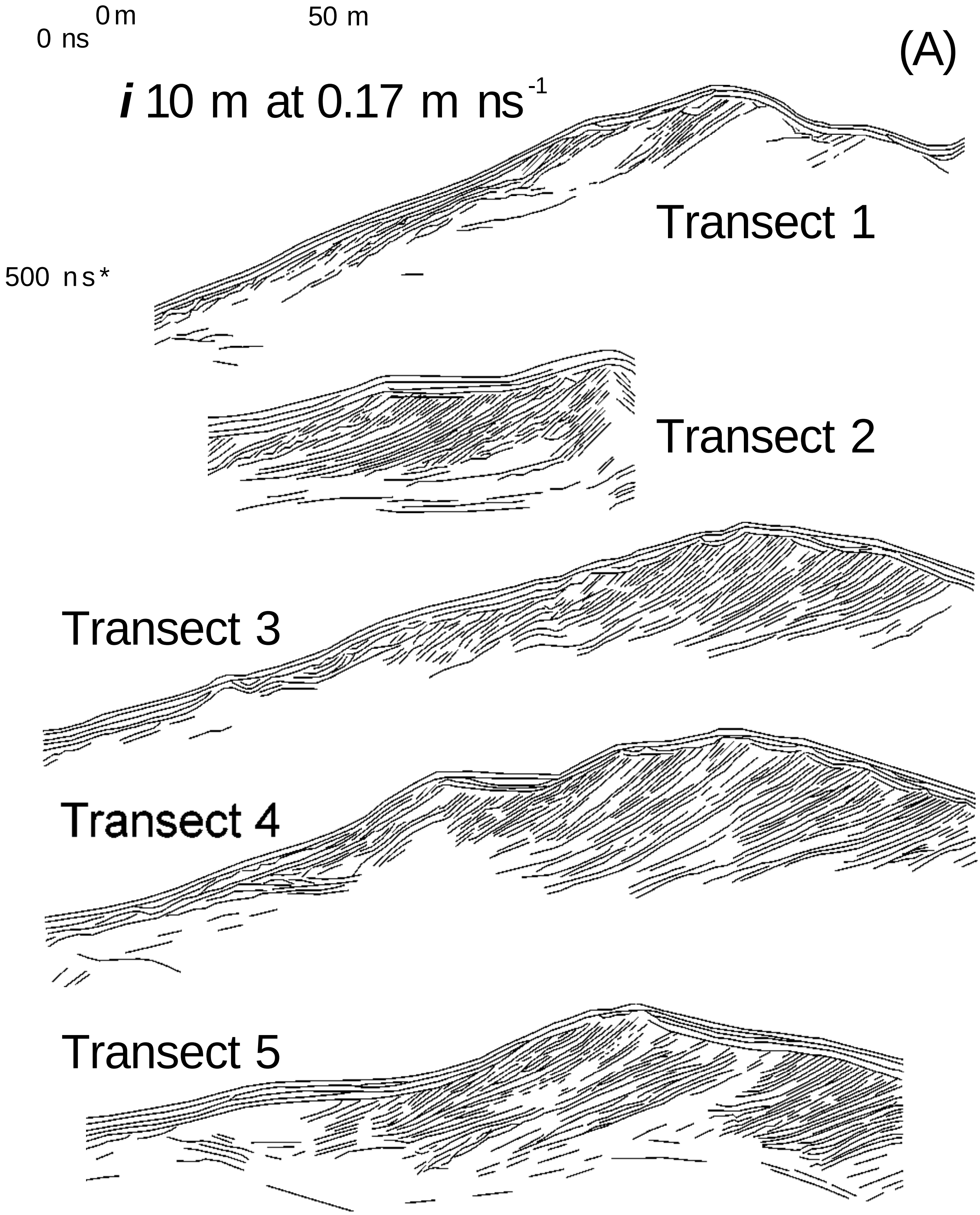

Figure 5 Key reflection characteristics of ground-penetrating radar (GPR) surveys from transects 1–5 (A) and transects 6–9 (B).

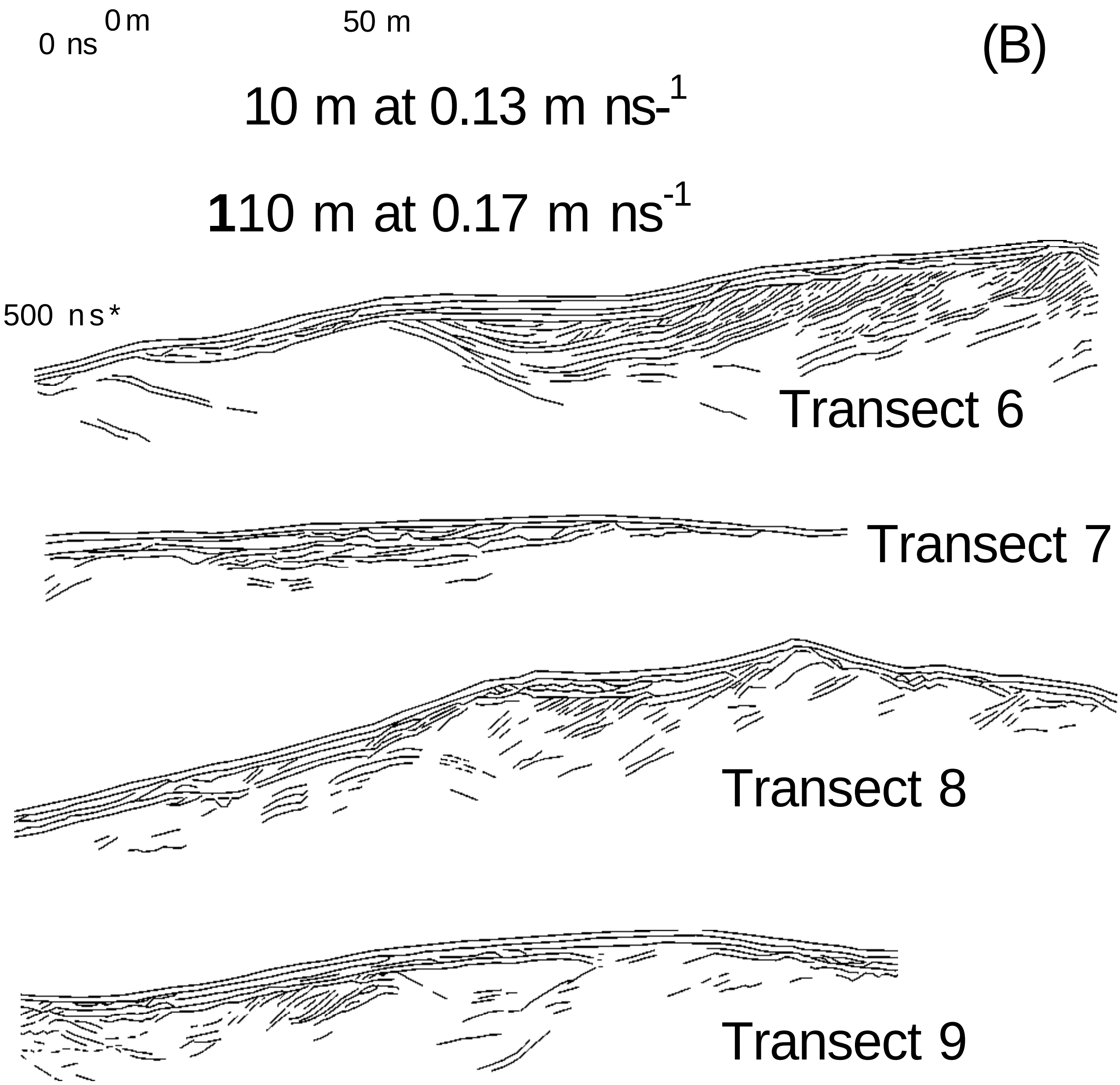

Figure 5 Key reflection characteristics of ground-penetrating radar (GPR) surveys from transects 1–5 (A) and transects 6–9 (B).

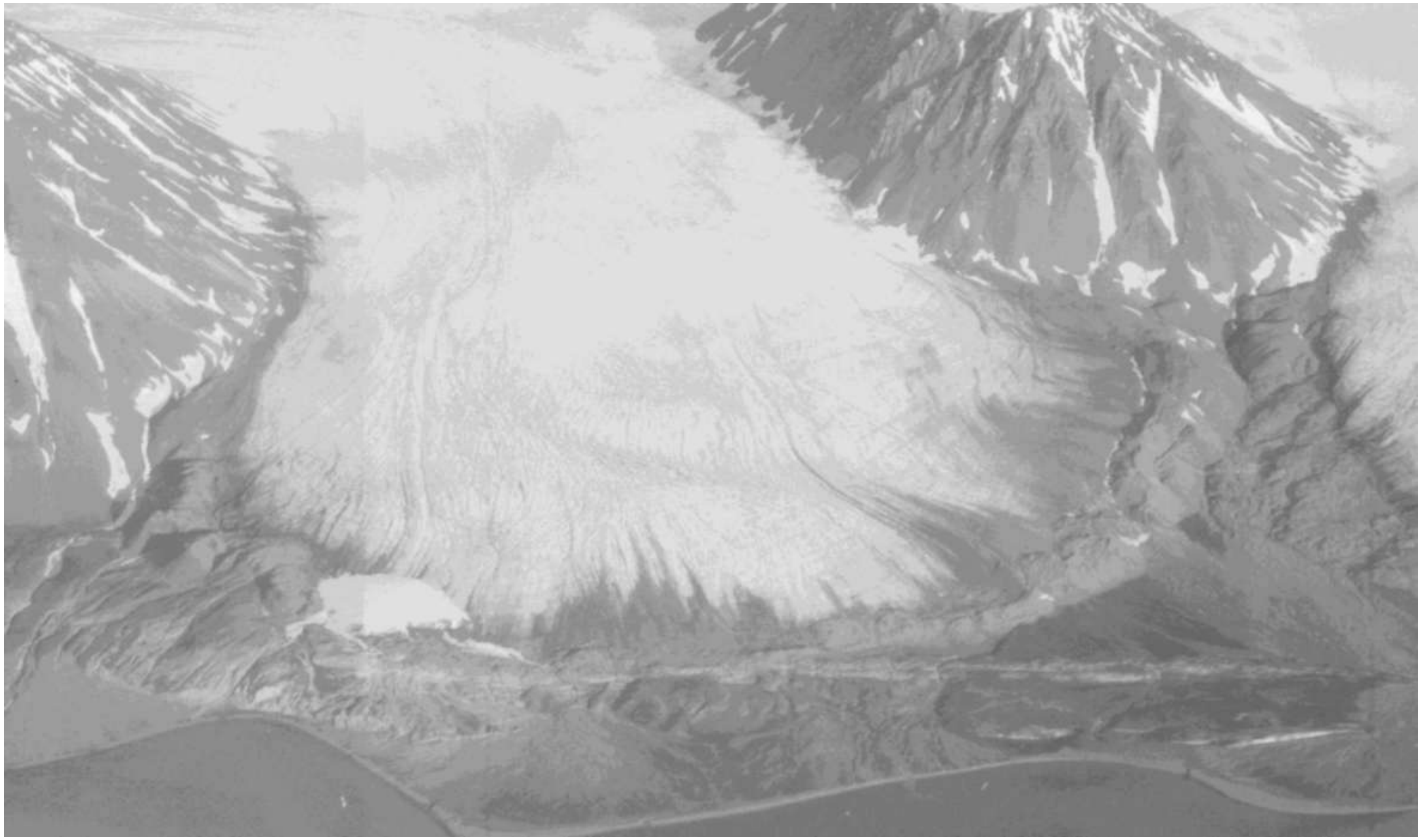

Figure 6 (A) Oblique aerial image of the terminus of Austre Lovénbreen from 1936 imagery (part of aerial photograph S36 1553, published with permission of the Norsk Polarinstitutt); (B) Structural interpretation of Austre Lovénbreen in 1936. The scale varies across the image and associated interpretation, but the widest part of the glacier terminus is around 1.4 km across.

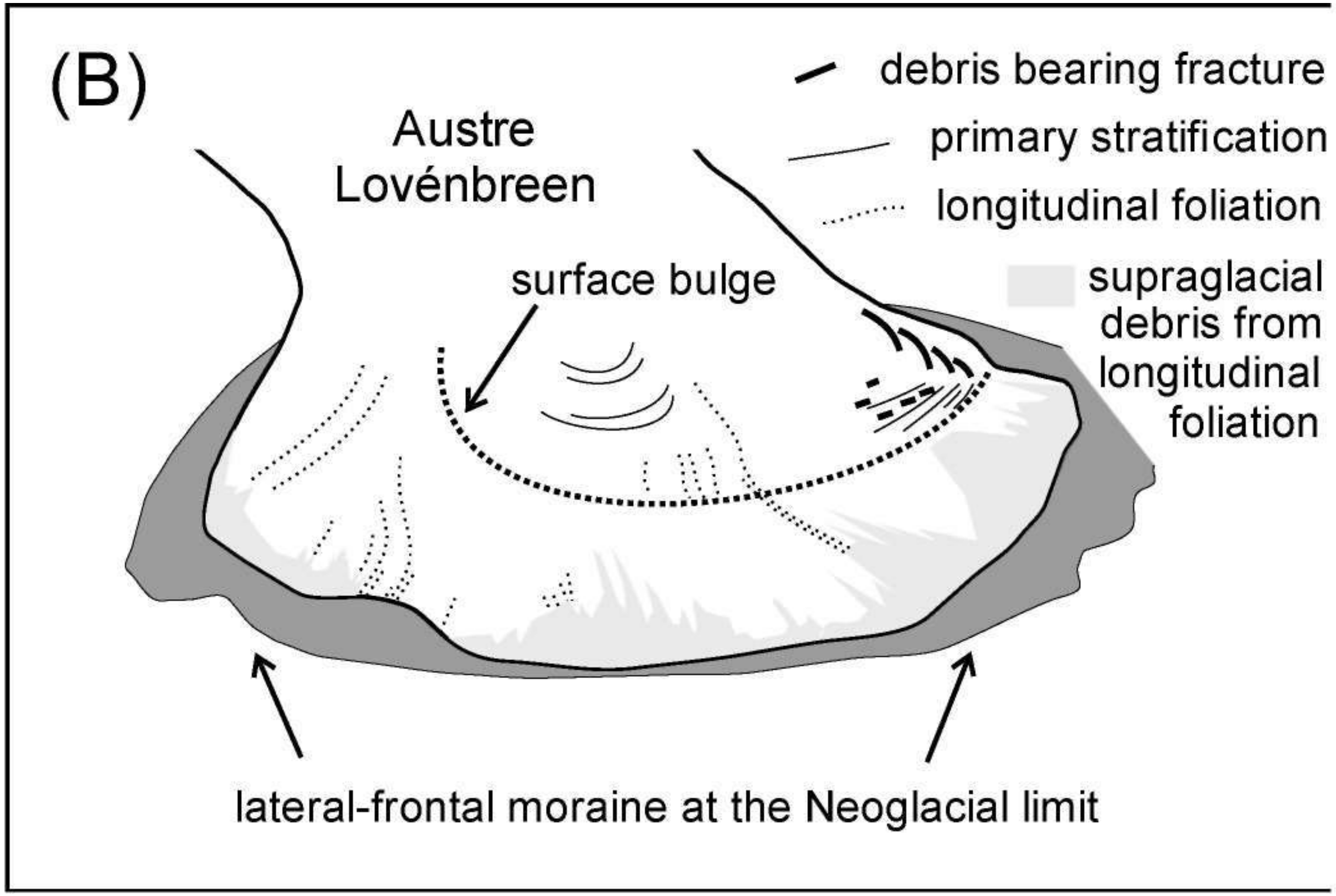

Figure 6 (A) Oblique aerial image of the terminus of Austre Lovénbreen from 1936 imagery (part of aerial photograph S36 1553, published with permission of the Norsk Polarinstitutt); (B) Structural interpretation of Austre Lovénbreen in 1936. The scale varies across the image and associated interpretation, but the widest part of the glacier terminus is around 1.4 km across.

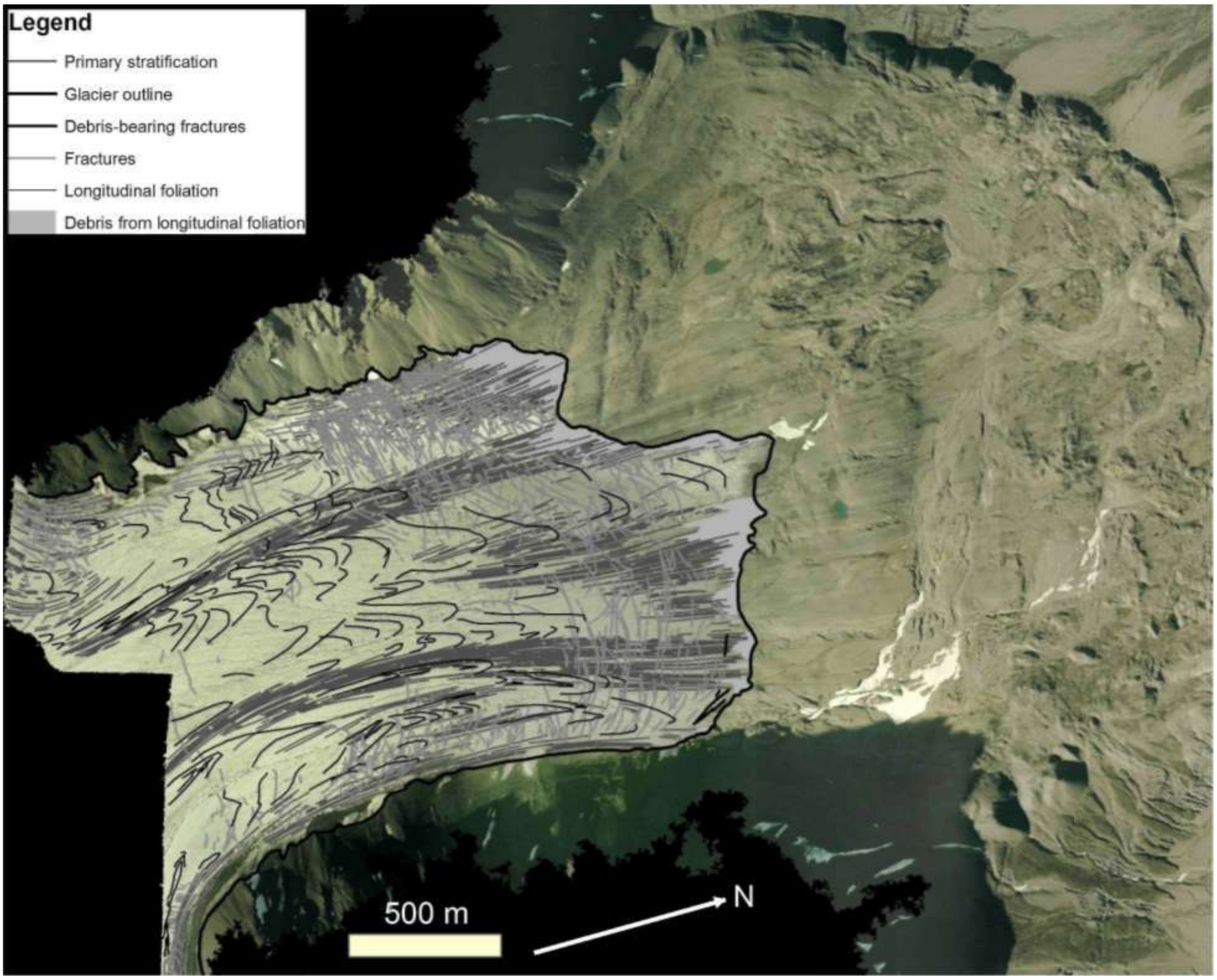

Figure 7 Structural interpretation of Austre Lovénbreen from 2003 imagery. Aerial image data from the UK Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) are provided courtesy of NERC via the NERC Earth Observation Data Centre (NEODC).