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Glacial curvilineations found along the southern sector of the Laurentide Ice sheet and a hypothesis of formation involving subglacial slope failure in tunnel valleys and subglacial lakes

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Glacial curvilineations found along the southern sector of the Laurentide Ice sheet and a hypothesis of formation involving subglacial slope failure in tunnel valleys and subglacial lakes

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Abstract

First discovered in Poland, glacial curvilineations (GCLs) are enigmatic landforms comprising parallel sets of sinuous ridges and troughs of metres amplitude and around 150 m wavelength, found within kilometres-wide valleys interpreted as being produced by meltwater flowing subglacially. Their morphological and sedimentary characteristics and association with tunnel valleys has been described for some prominent Polish examples. From these observations the existing hypothesis is that they form as a consequence of erosion by longitudinal vortices that develop in subglacial floods. Here we report, for the first time, GCLs found along the southern sector of the Laurentide Ice Sheet in three northern states of the USA. Using mapping and topographic analysis from high resolution digital elevation models we report observations on their morphological properties and landform associations. We find aspects of their context and morphology difficult to explain using the existing hypothesis. We instead suggest that these glacial curvilineations are produced by subglacial bank and slope failures that locally widen tunnel valleys, or that occur near subglacial lake shorelines. Further investigation is required to test this hypothesis and to ascertain the mechanisms of proposed mass movements, which may have occurred by rotational or translational slope failure or by creep deformation. Our preferred mechanism is that such movements occurred where subglacial water was emplaced over previously perma-frozen ground. Under such circumstances, sediment blocks thawed by the water may then easily glide over a frozen décollement at low slope angles; analogous to subaerial active-layer glides in permafrost environments. Permafrost spring sapping may have provided lines of weakness for slope failure. If the requirement for permafrost is found to hold, then GCLs may become an important indicator of the palaeo-distribution of permafrost.

Key words; glacial curvilineations; tunnel valleys; permafrost; subglacial lakes; slope failure.

Introduction

Glacial Curvilineations (GCLs; Fig. 1) are enigmatic landforms comprising parallel sets of sinuous ridges and troughs typically of metres amplitude and around 100 m in width (Adamczyk *et al.* 2015) and found within tunnel valleys produced by meltwater flowing subglacially. The existence of such landforms has been known for a long time in north-central Poland (Nechay, 1927) but they were mostly thought to be rather strange and sinuous versions of drumlins (Fig. 1 and Wysota, 1994; Głębicki and Marks, 2009; Waga and Fajer, 2016). More recently their appearance on digital elevation models and satellite images (Fig. 1B and Lesemann *et al.,* 2010) has shown them to be more longitudinally continuous and sinuous than is typical for drumlins and their association with valleys has been strengthened. This led Lesemann *et al.* (2010) to regard them as distinctly different from drumlins and therefore to propose a new term; Glacial Curvilineations (GCL). Their association with tunnel valleys led them to suggest formation due to the flow of meltwater at the ice sheet bed.

Figure 1. Polish glacial curvilineations (GCLs). A) Morphological map (by Olszewski, 2001) of some GCLs near Zbójenko in Poland, reproduced from Piotrowski and Wysota (2001). At the time of publication, the repeated parallel and sinuous ridges were interpreted as drumlins. B) A wider view of the landscape, also near Zbójenko, (but exact relationship to those in A not known) showing a parallel series of smooth and slightly sinuous ridges and troughs contouring across a gentle slope (falling to the right) and running parallel to the upper escarpment (left). Topographic profile (along the white line) shows the slope context but is not of high enough resolution to reveal relief of the individual ridges and troughs (metres in amplitude). Obliquely-viewed satellite image draped on a digital elevation model, looking NW and centred on 53° 01' 43'' N; 19° 04' 35'' E, around 5 km NW of Zbójenko, Poland. Topographic and satellite data from Google Earth.

On the Dobrzyń Plateaux of Poland (near Zbójenko) Lesemann *et al.,* (2010, 2014) used cliff exposures within GCLs to log and describe their sedimentary properties (e.g. grain size, fabric measurements, lithological composition) and used subsurface geophysics to interpret structures beyond the field exposures. It was found that the landform system is composed of sand, gravel and till whose varied distribution appears to have no relation to the ridges. Furthermore, sedimentary beds within some of the ridges were found to be truncated leading to the conclusion that the sediments were deposited prior to the development of the morphology comprising the GCLs and that these landforms are therefore genetically unrelated to the sediments into which they are cut.

So far, just one (post-drumlin) theory for GCL formation exists; erosion by longitudinal-vortices produced in subglacial meltwater floods emerging from either sub- or supraglacial lakes and directed down tunnel valleys (Fig. 2; Lesemann *et al.,* 2010; 2014). The finding of large (1.5 m) well-rounded boulders at the distal end of some tunnel valleys is interpreted to support such high energy flows.

Figure 2. A mechanism of GCL formation whereby subglacial meltwater drainage events erode into pre-existing sediments (reproduced from Lesemann et al., 2010). In this hypothesis, erosion is concentrated as a consequence of the development of pairs of counter-rotating longitudinal vortices which cut the troughs and leave remnant intervening ridges.

While using newly-available high resolution elevation data to map and analyse tunnel valleys for parts of the formerly glaciated USA (reported in Livingstone and Clark, 2016) we found numerous examples of parallel sets of ridges and troughs that match the descriptions of GCLs reported from Poland. In this paper, we report on these landforms, classifying them as GCLs, providing the first evidence for their existence in North America. Our work is restricted to morphological properties and their landform associations and we describe and illustrate their key properties. We find that some of these new observations are difficult to explain using the existing hypothesis of erosion by longitudinal vortices in subglacial floods. We therefore propose a new hypothesis for creation of these enigmatic landforms; subglacial slope failure of the banks of tunnel valleys.

Dataset and methods

The main data source used was the USA's National Elevation Dataset (NED) (http://nationalmap.gov/elevation.html), which is a seamless digital elevation model (DEM) with a resolution of 1/3 arc seconds (~10 m) across the entire study area, and 1/9 arc seconds (~3 m) in some locations. We investigated a large area (ca. 750,000 km^2) making a complete and thorough search for tunnel valleys and GCLs visible in the DEM within the box defined by 82-102°W; 40-48°N, covering parts of the states of North and South Dakota, Minnesota, Iowa, Wisconsin, Ohio, Indiana, Illinois and Michigan. The DEM was manipulated and displayed in a GIS (ArcGIS 10.1) to render images for visual interpretation of landforms using a variety of processing methods of combined solar-shading and colour-rendition of elevations (e.g. Smith and Clark 2005). Extensive tunnel valley systems were mapped (Livingstone and Clark 2016) and the locations of all features resembling Polish GCLs were identified from their ridge crestlines. To help understand the morphology of GCL terrains and their relation to tunnel valleys numerous topographic profiles were extracted from the DEM.

Observations

Figure 3. A. Distribution of GCL locations. A total of 871 ridge and trough sets were found within 19 different tunnel valleys. Subsequent figures in this paper are marked by black boxes. Southernmost ice extent of Last Glacial Maximum (LGM) is shown by thick blue line. Dashed black line indicates still-stand positions associated with known moraines. B. Known moraines and major ice lobes of the area, redrawn from information in Wright et al. (1973) and Jennings (2006). Darker blue indicates younger moraines.

Numerous features were discovered, which so closely visually resemble glacial curvilineations described in Poland (compare Figures here with Figure 2 in Lesemann *et al*. 2010) that we regard them to be the same landform type. GCLs were found to be common with a total of 871 sets across 19 tunnel valleys. Figure 3 provides an overview of their locations along with the distribution of tunnel valleys where they were identified in South Dakota, Minnesota and Iowa. No GCLs were found outside of tunnel valleys or depressions linked to tunnel valleys. We illustrate some of the GCLs to show their typical scale, form and spatial contexts, and use these observations to build an inventory of morphological characteristics.

Figure 4. Within a prominent widening in a tunnel valley of two anabranches (water flow to the southeast) are numerous GCLs that parallel and mimic the shape of the tunnel valley edge. Topographic profiles (see method for source data and note high vertical exaggeration - x725) indicate the relief across the valley, with individual GCLs (arrowed) typically 1 to 10 m in amplitude. The town of Pinewood, Beltrami County in Minnesota is located near the image centre. See Figure 5 for an oblique view of this landscape.

Figure 5. Obliquely-viewed satellite image draped on a DEM looking NW across the Pinewood GCLs of Figure 4 and centred on 47° 36' N; 95° 06' W. Image is 4.25 km in width. Overall this is a low relief landscape with the tunnel valley around 20 m deep and with individual GCLs (some arrowed) of around 2 metres in amplitude. Topographic and satellite data from Google Earth.

The Pinewood GCLs in Minnesota (Figs. 4 and 5) occur in a prominent widening of the tunnel valley and do not exist immediately up or downstream. Perhaps GCLs are more likely to form in wider valleys or their processes of formation actually contribute to the widening. The GCLs display the usual parallelism with the tunnel valley edge as reported in Polish examples (Lesemann *et al.,* 2010; 2014) and we note here that they often have cuspate forms and defects that mimic the tunnel valley edge, but which degrade with distance (Fig. 4). The ridges (see topographic profiles) mostly seem to decline in elevation away from tunnel valley edges although this is not always so. They are never higher than the local edge of the tunnel valley. GCL trough-ridge sets extend for 0.5 to 4 km in length and there are examples of discontinuous troughs with sudden terminations (Fig. 4). Secondary valley incision that seems to have truncated some GCLs (near downstream end of the tunnel valley in Fig. 4) indicates that there has been more than one phase of overall land-forming and valley cutting.

Figure 6. Two widenings in a tunnel valley (flow to the east) displaying GCLs that parallel the valley edge. The westernmost widening is especially bulbous and mirrored on both sides; atypical compared to valley widening in rivers where meander cuts alternate on valley sides. These GCLs are 10 km NW of Austin, south Minnesota, a modern river (Turtle Creek) runs parallel but further south than the tunnel valley. Arrows on the X' to X topographic profile mark the GCL ridge summits.

North-west of Austin, in south Minnesota, GCLs of a few metres in relief occupy two widenings in a tunnel valley (Fig. 6). The tunnel valleys were formed at the eastern limit of the Des Moines Ice Lobe (Wright et al., 1973). The bulbous nature of these widenings locally and abruptly increase the width of the valley from 0.5 to 2 km and back to 0.5 km. This is unusual compared to valleys produced by flowing water which typically do not have such abrupt changes and gradually widen downstream. Again, the ridges mimic the shape of the valley edges. Just to the north of this tunnel valley is a 6 x 3 km depression of 10 m depth (Fig. 7), down-flow from a tunnel valley and with two higher-level outflows that cut through a moraine at its eastern edge. We speculate that this as a shallow subglacial lake or swamp, although, alternatively, it could just be seen as an unusual widening and blockage in a tunnel valley; where to draw the line between these two styles of drainage? As usual the GCLs mimic the edge of the depression (notably the higher southern rim), but unlike earlier examples, the geometry is different regarding likely water flow-paths through the system. In particular, the GCLs do not align with the likely water flow paths out of the eastern outflows, and actually lie orthogonal in some instances. A further key observation is that running exactly parallel to the rim of the depression in the NE (Fig. 7B) is a prominent and sharply inscribed trough (~ 6 m depth) bounded by a ridge. We interpret this as an incipient or fresh GCL, which contrasts with more subdued examples elsewhere. That this type of sharply-defined GCL is so rare suggests there has been post-formation modification of most of the ridges and troughs. Finally, in the centre of the depression (Fig. 7A) GCLs appear to cross-cut each other forming a palimpsest landscape signature indicative of multiple events or phases. Because the ridges in this basin have a fairly consistent orientation (NE-SW) rather than following the curved geometry of the basin rim an alternative interpretation could be that they are Ribbed (Rogen) Moraine formed under ice flowing towards the southeast. Here they are certainly of a similar scale and appearance to ribbed moraine (cf. Dunlop and Clark 2006).

Figure 7. A) Ridge-trough systems in a depression that we interpret as GCLs that formed in a small subglacial lake or swamp, fed from the west by a tunnel valley and with at least two overflows to the east. Note that these GCLs do not align with the

likely water flow-paths; they are not orientated towards the outflows and can even be observed at right angles in places. B) In the NE a sharply inscribed trough is found, which we find instructive. It exactly parallels the main break of slope. We interpret it as the opened crack behind a bank or slope failure at the edge of the lake. This incipient or fresh GCL contrasts with the more subdued GCLs elsewhere. The depression and GCLs are 14 km NNW of Austin, southern Minnesota, and formed at the eastern margin of the Des Moines Ice Lobe.

Figure 8. Three sets of GCLs located in tunnel valleys eroded into the higher ground which is part of the Ithasca Moraine complex near Park Rapids, Minnesota. The eastern and central GCLs occupy prominent widenings of tunnel valleys downstream of the moraine complex and leading to outwash fans marking the ice margin position at this time. The westernmost GCLs exist in the main axis of the moraine complex and upstream of an apparent blockage in the tunnel valley that continues further south. In this interpretation a subglacial lake likely existed here in which the GCLs developed.

In contrast to GCLs reported in Poland, which were found to lie upstream of topographic barriers (Lesemann, *et al.,* 2010), we report some, near Park Rapids, Minnesota that have no such downstream barriers and lead to outwash fans at the former ice margin (Fig. 8).

Taking the observations that we have presented along with the Polish examples (from Lesemann, *et al.,* 2010; 2014), we assemble a list of the morphological properties and contexts of GCLs thus far discovered;

1. Occur near southern margins of palaeo ice sheets in low-relief landscapes.
2. Occur in single thread tunnel valleys or in anabranched tunnel valley systems, sometimes upstream of topographic barriers such as moraine complexes. They have not been found outside of depressions acting as conduits or stores of subglacial meltwater.
3. GCLs reported here occur in tunnel valleys with low along-stream slope gradients (typically 0.06º to 0.34º) and either rising or falling. This is similar to those reported in Poland, where GCLs occur in tunnel valleys that rise up ~110 m over a distance of 20 km (0.31º; Lesemann *et al.*, 2014).
4. Occur at prominent widenings (> doublings) of tunnel valleys and sometimes in bulbous incisions into the valley sides.
5. The GCL ridge crests are either at or below the level of the surrounding topography and mostly decline in elevation towards valley bottoms.
6. GCLs occur in sets, are sinuous and lie parallel to their neighbouring ridges.
7. GCLs closely parallel the edge of the tunnel valley or depression, sometimes with abrupt (~90° over 100 m) changes in direction

8. Where tunnel valley rims have cusps or defects in their planform shape, these are often mirrored in adjacent GCLs and this mimicry can sometimes be seen to degrade with distance towards the central axis of the valley.
9. GCLs mostly align with the broad water flow-paths expected down tunnel valleys but this is not always the case (e.g. Fig. 7).
10. GCLs reported here have a median wavelength of 150 m (min. = 41 m, max. = 627 m) and a median height of 4 m (min. = 1 m, max. = 26 m). The majority (90%) of the GCLs have a wavelength of 70-325 m and are 1-16 m high which is within the range of those reported from Poland (Lesemann *et al.,* 2010).
11. GCL ridges and troughs are roughly symmetrical.
12. GCL lengths are mostly of the order of a km, but segments can sometimes be linked over a 10 km distance.
13. GCLs have been observed where two sets appear to cross-cut each other (e.g. Fig. 7).

A new hypothesis for the formation of glacial curvilineations

Hypothesis development is typically inspired by specific observations that require explanation, and the path taken is often frustratingly sensitive to which observations are seen as primary versus of a tangential nature. Baker and Twidale (1991) discuss this issue and encourage geomorphologists to develop imaginative hypotheses. A key primary observation for us is that GCLs tend to mimic the tunnel valley edge even when it changes direction abruptly (e.g. a 90° kink), and that there are often sharply defined cusps or defects that are repeated (see annotation in Fig. 4 and in Lesemann *et al*., 2010 figure 2 of Polish examples;). These abrupt changes in direction make it problematic for longitudinal vortices to have created GCLs because we presume they would become disrupted at such points (see later). Parallel repetition of cusps and defects however, is common in growth rings such as occur in tree rings or corals viewed in section. This implies incremental production, rather than the necessity of having the GCL-fields simultaneously form in a single or a few flood events. That GCLs have only been found where widening occurs also seems of prime importance; the simplest explanation being that the GCLs are part of the process of widening. Taking our two primary observations along with the presumed context of requiring subglacially-flowing water (GCLs arise in tunnel valleys) we construct a new hypothesis for the formation of GCLs, which we suggest is more plausible than the existing one. We exclude subaerial formation of GCLs because in our survey of the whole area (750,000 km2) we only found GCLs within tunnel valleys, which are widely interpreted to have formed subglacially, as often shown by their uphill-flowing long profiles. If GCLs formed subaerially then we would expect to find them on other slopes in the terrain.

We suggest that GCLs are the record of subglacial slope or bank failures at the edge of tunnel valleys or near subglacial lake shores. In this hypothesis the GCL-troughs are the opened fractures between blocks that have been transported downslope by land-sliding. It is these slope or bank failures which locally widened the tunnel valleys, while the bulbous incisions (e.g. Fig. 7) are the headwall scarps of the mass movements. Figure 9 illustrates likely processes and contexts, either with water in a channel occupying part of a wider tunnel valley (Fig. 9A) or in a depression wholly filled with water (Fig. 9B), such as a subglacial lake or a completely filled tunnel valley (i.e. tunnel channel). A down-cutting subglacial river in a wider valley (Fig. 9A) steepens the valley flanks and in our hypothesis leads to tension cracks incrementally developing, which then act as lines of weakness for downslope movement. Although the tension cracking happened incrementally, in this model, the actual slides could have been incremental and retrogressive or have occurred during a single failure event, or some mix of these. In this model the flow of water is not responsible for forming the GCLs but it is likely to subsequently modify and smooth the ridges. If ice flow adjacent to tunnel valleys was sufficiently directed inwards toward the tunnel valley axis (to replace melting) it might be that ice flow over the valley lip drove or contributed to the tension cracking and block slides, in a mechanism similar to that proposed by Kleman and Hattestrand, (1999) for the formation of ribbed moraine.

Permafrozen conditions are thought to have persisted in-front of and under the toe of ice lobes in Minnesota and surrounding states during deglaciation (Wright, 1973; French & Miller, 2014). If bank failure and downslope movement occurred wholly within a subglacial water body (Fig. 9B) then we suggest that it may have been facilitated by perma-frozen ground acting as glide-planes. Such a situation may occur when an ice margin advances over a permafrozen forefield. For example, in Figures 4, 6 and 8, we observe that GCLs occur in tunnel valleys incised through prominent moraine positions. This may be indicative of tunnel valley and GCL formation during re-advances across frozen ground. Where subglacial water becomes emplaced, say as a subglacial lake, over permafrost, heating of the substrate may permit intact thawed blocks (warmed by subglacial water) to slide over underlying frozen ground; analogous to active layer-detachments and retrogressive-thaw slides (Fig. 9C) (French, 1996).. Alternatively, weaknesses beneath the blocks could have been produced by networks of conduits (soil piping) from permafrost spring sapping. In this idea, groundwater cannot easily percolate downwards once it reaches a frozen permafrost layer so is forced to drain laterally in a series of soil pipes and then causes concentrated erosion (sapping) where it emerges. Given that typical slope angles from the tunnel valley rims to centre-lines are so low (typically 0.5º to 1.5 º) we suspect that permafrost is a required condition, noting that subaerial slope movements in these environments and at such angles are commonly reported (French, 1996). Alternatively, because submarine landslides can occur in glacigenic sediments on slopes of as low as 0.01º to 0.5 º (Hampton *et. al.* 1996) then slides in subglacial water bodies could also occur at these low angles. A further possibility is that the ridges and troughs comprising GCLs are folds from downslope creep deformation, although the sharp trough observed in Figure 7B and that we interpret as an opened tension crack argues against this in that particular case. Subglacial earthquakes from stick-slip movement of the glacier sole might have acted as triggers for landslides.

Figure 9. Formation of GCLs by subglacial bank and slope failure in tunnel valleys and subglacial lakes. A) Cartoon of a tunnel valley down-cutting into underlying sediments, steepening the adjacent slopes promoting tension cracks from which landslides occur. Slides could happen incrementally or en masse. B) Bank failure within a subglacial water body such as a lake or in a wholly-filled tunnel valley, again occurring incrementally or in a single event. Where subglacial water is emplaced over a permafrozen substrate, heating of the latter may promote zones of weakness or glide-planes from which landslides might develop. C) A possible analogue; widening of a channel by thermokarst slope failure of a permafrost river bank. D) At a much larger scale (image 9 km across), these are submarine landslides in glacigenic sediments on the MacKenzie River delta in NW Canada (modified from Bennett et al. 2004). Note the parallelism between troughs and ridges and replication of cusps and nicks from the headwall scarp.

Discussion

We have not investigated the sedimentary composition of the GCLs reported here and know of no work that directly relates such information to the morphology of the ridges and troughs (but see below). In this paper we merely presume that GCL creation came after deposition of the sediments such that they are unrelated from a process-point of view. This presumption is based on the findings of an intensive investigation of GCL sediment-landform relationships in Poland (Lesemman *et al.*, 2010, 2014), where the ridge-trough morphology was found to be unrelated (came after) to the sediments. Our search of Quaternary and hydrogeologic maps of Minnesota and the County Geological Atlas series of the Minnesota Geological Survey (e.g. Hobbs & Goebel, 1982; Fullerton et al., 2003; Harris, 2007) revealed limited information on GCL sediment-landform relationships. On a Quaternary geology map (Harris, 2007), the GCL ridges in Figure 4 are shown to have a wide variety of surface geological expressions: ranging from unsorted and unbedded sand, silt and clay, commonly with pebbles and interpreted as slope deposits; moderately to poorly sorted sand and gravel interpreted as deposited by meltwater rivers; and unbedded and unsorted sediments with mixes of sand and gravel and glacial sediments interpreted to have been draped over the landscape. These sediments and interpretations are readily associated with deposition in tunnel valleys. If the mapped surface expressions are taken as being representative of their internal composition (aside from the draped units) then in common with the Polish investigations they suggest a variety of depositional contexts unrelated to the morphology of the ridge-troughs. A subset of the GCLs we show in Figure 4 were interpreted from aerial photographs by Harris (2007) as beach ridges or nearshore bars marking the former extent of Glacial Lake Agassiz. Given the close proximity of Glacial Lake Agassiz to this site (tens of kms), we can understand the basis of this interpretation, but regard it to be unlikely for two reasons. The sediments described on the map (Harris, 2007) do not record the typically well-sorted nature of beach ridges. Secondly, the broad distribution of GCLs across our study region and with many far from known glacial lakes (> 100 km) weakens any interpretation that they could all be beach ridges of a subaerial lake. We suggest that future investigations into the composition of these landforms might be able to take this further, or that new fieldwork specifically aimed at GCL landform-sediment relationship would be useful.

Field observations and geophysical investigations could test our hypothesis of slope failure; can distinctive sedimentary units be found straddling a number of ridges but with elevation offsets indicating lateral and downslope movement? Can evidence be found that distinguishes between the types of slope movement we have suggested? Or just from a morphological point of view, does the volume (width and height) of ridges vary as one should expect to satisfy volume - continuity in mass movements? In Figure 10 for example we should expect ridges that have slid from sharp bends to have bulges because of longitudinal shortening as a consequence of the bend geometry. Although we have not quantitatively analysed this, and there would be some difficulty in doing so because of post-formation modifications of ridges, it is apparent from Figure 11 that such bulging or bulking-up seems to occur in numerous places, which is consistent with the hypothesis of slope failure.

Figure 10. Cartoon representation of slope failure from a sharp concave bend in an escarpment. In this concave geometry, ridges that have slid further from the escarpment must be shorter in length because of convergence, and so to conserve mass they would bulge or bulk-up especially in the zone of maximum convergence.

Figure 11. In numerous places ridge bulging is observed where the escarpment geometry and slope provide downhill convergent flow-paths for potential mass movements (cf. Fig. 10). This is consistent with the hypothesis of the ridge-trough systems resulting from slope failure. A) In the semi-circular embayment two concentric ridges get shorter and bulkier in the downhill direction and which culminates as a single almost conical pile of sediment. In B) and C) ridges tend to be wider where they have come from more concave parts of the escarpment compared with straighter sections of the rim. In D), looking at the southern embayment it is notable that the highest and widest parts of most the ridges align with the apex of the ninety degree bend in the escarpment.

The sharply-inscribed trough in Figure 7B is interpreted as an important confirmation of bank failure. That GCLs are usually more subdued than this indicates that subsequent modification has taken place for most of them, probably by the flow of the base of the ice sheet or by meltwater drainage through the tunnel valley. If floods subsequently travelled down these tunnel valleys, they would further modify the landforms - perhaps with longitudinal vortices developing in places - but they are not required in the hypothesis we erect here.

Submarine slope failures, such as shown in Figure 9D remarkably resemble many aspects of GCLs, notably the conformity of sinuous ridges and troughs to the headwall scarp, the mimicry of cusps and defects and the bulbous incision. The morphological similarity would be even greater if a flowing medium (ice, or water flowing subglacially) was to subsequently erode and smooth the features approximately parallel to their orientation, something that is likely to occur in tunnel valley settings.

The formation of GCLs by high-energy subglacial meltwater flows has a number of problems. Primarily, it is difficult to envisage how sinuous GCLs with sharp cusps (Fig. 4 and Polish examples in Lesemann et al. 2010, their Fig. 2) could form during a broad, sheet-like flow. Furrows created by longitudinal vortices are linear or diverge smoothly around obstacles (cf. Carling *et al.,* 2009 and references therein). Indeed, longitudinal vortices typically develop from fully turbulent flow in straight or relatively straight channels (e.g. Einstein and Li, 1958; Karctz, 1967); any irregularity is likely to induce additional turbulent structure that breaks up the longitudinal pattern of vorticity (Baker, 1979). Secondly, the troughs between the GCLs are sometimes discontinuous, producing chains of linear troughs or depressions. This is difficult to reconcile with longitudinal vortices, although Sjorgen *et al.,* (2002) invoked vertical vortices (kolks) to explain the formation of incipient tunnel valleys characterised by linked potholes. However, this does not fit with the regular spacing of the ridges and troughs, or their longitudinal geometry.

The bulbous widenings that we show in tunnel valleys often contain GCLs and the two features are linked in our hypothesis of subglacial slope failure. Either steady or catastrophic subsequent water flow down such tunnel valleys could degrade or entirely erode away GCLs, and there is clear evidence in places of such erosion occurring by secondary channel incision (Fig. 6). On Victoria Island a tunnel valley has been reported (Brennand and Sharpe, 1993) showing numerous similar bulbous incisions (scalloped margins in their description) and of similar (kilometre) scale and in places containing some residual hills or ridges. We suggest that these embayments may also be subglacial slope-failure escarpments, but with most of the mass-wasted material (the GCLs) removed by subsequent erosion. Alternatively, in their hypothesis (Brennand and Sharpe, 1993) the scalloped margins are interpreted to have been formed by turbulent scouring that occurred in a subglacial sheet-flow flood that is reconstructed to have crossed the tunnel valley at an oblique angle.

Summary and conclusions

Here we have reported on new findings of glacial curvilineations in parts of the states of South Dakota, Minnesota and Iowa, USA (Fig. 3). A total of 871 sets across 19 tunnel valleys were found and mapped, extending their known locations beyond those reported in Poland and Denmark. This confirms the wider existence of these enigmatic landforms, and we expect that many more examples will be found given the increased availability of high resolution digital elevation models. GCLs are mostly found in tunnel valleys, but we interpret some as having formed in a shallow subglacial lake or swamp. Our observations are combined with those described in Poland (Lesemman *et al.,* 2010; 2014) to produce an inventory of their morphological properties and their relationship to tunnel valleys. We find aspects of their context and morphology difficult to explain using the existing hypothesis of erosion by longitudinal vortices that develop in subglacial floods. We instead suggest that GCLs are produced by subglacial bank and slope failures which locally widen tunnel valleys, or that occur near subglacial lake shores. Further investigation is required to test our hypothesis and to ascertain the mechanisms of the proposed mass movements which may have occurred by rotational or translational slope failure or by creep deformation. Our preferred mechanism is that slope movement occurred where subglacial water was emplaced over previously perma-frozen ground, which may occur when ice advances over permafrost.. Under such circumstances, sediment blocks thawed by the water may easily glide over a frozen décollement at low slope angles; analogous to subaerial active-layer glides in permafrost environments (French, 1996). Permafrost spring sapping may have provided lines of weakness for slope failure

We conclude by describing a sequence of events that could lead to the landforms and the associations between them. Under a thin ice margin, subglacially-flowing meltwater organised itself into a series of conduits that cut down into the substrate initiating and forming tunnel valleys. As argued in Livingstone and Clark (2016) most of the tunnel valleys along this margin appear to have steadily formed by headward growth, although notable examples also exist that are better explained by formation or occupation by flood events. In our hypothesis the GCLs form either by subglacial slope failures adjacent to meltwater conduits (Fig. 9A), helping tunnel valleys widen, or within a ponded water body that has wholly filled the tunnel valley (Fig. 9B), manifested as linear subglacial lakes or swamps with slowly flowing water. Such ponding or slow water flow might be permitted by the shallow surface ice slope that drives water out. In this model GCLs are the geomorphological signature of tunnel valley widening events that may subsequently have been modified by water flowing through the valleys.

If the association of GCL formation with permafrost is found to hold, then GCLs may become an important indicator of the palaeo-distribution of permafrost. We note that in both the Polish and USA cases that the GCLs occur in ice lobes close to the maximum southern extent of their ice sheets, prone to re-advances, and that may have therefore advanced over ground subject to permafrost. French and Miller (2014) and Ewertowski (2009) report evidence of permafrost conditions proximal to these ice margins and Hooke and Jennings (2006), have proposed permafrost and cold-based ice along this ice margin to be important for the production of tunnel valleys.

Acknowledgements

Roger Hooke is thanked for his referee comments and which included the insightful remarks on ridge bulging in relation to escarpment geometry and which we have developed here in Figs 10 and 11. David Sharpe is also thanked for comments that helped improve the clarity of the paper and for alerting us to scalloped tunnel valley edges on Victoria Island, Arctic Canada.

References

Adamczyk A, Sobiech M, Urbańska A, Wysota W. 2015. Geomorphometric analysis of glacial curvilineations (GCL) in Dobrzyń Lakeland, Central Poland. In: Geomorphometry for Geosciences, Jasiewicz J., Zwoliński Zb., Mitasova H., Hengl T. (eds), 2015. Adam Mickiewicz University in Poznań. Geomorphometry.org

Baker, V.R., 1979. Erosional processes in channelized water flows on Mars. *Journal of Geophysical Research* **84**: 7985–7993.

Baker, V.R., Twidale, C.R., 1991. The reenchantment of geomorphology. *Geomorphology* **4**, 73–100.

Bennett, R., Rochon, A., Schell, T., Bartlett, J., Blasco, S., Hughes-Clarke, J., Scott, D., MacDonald, A., Rainey, W., 2004, Cruise report, Amundsen 2004-804: Beaufort Sea / Amundsen Gulf / Northwest Passage, June 23 -August 27, 2004: *Geological Survey of Canada, Open File* **5798**, 111 p.

Brennand, T.A., Sharpe, D.R., 1993. Ice-sheet dynamics and subglacial meltwater regime inferred from form and sedimentology of glaciofluvial systems: Victoria Island, District of Franklin, Northwest Territories. *Canadian Journal of Earth Sciences* **30**: 928–944.

Carling, P.A., Herget, J., Lanz, J.K., Richardson, K., Pacifici, A., 2009. Channel-scale erosional bedforms in bedrock and in loose granular material: character, processes and implications. Megaflooding on Earth and Mars: Morphology, Modelling, and Water Release Mechanisms. Cambridge University Press, Cambridge 13–32.

Dunlop, P., Clark, C.D., 2006. The morphological characteristics of ribbed moraine. *Quaternary Science Reviews* **25**: 1668–1691.

Einstein, H.A., Li, H., 1958. Secondary currents in straight channels. *Eos Trans. AGU* **39**: 1085–1088.

Ewertowski M. 2009. Ice-wedge pseudomorphs and frost-cracking structures in Weichselian sediments, central-west Poland. *Permafrost and Periglacial Processes* **20**: 316–330. DOI: 10.1002/ppp.657

French, H.M., 1996. The Periglacial Environment, 2nd ed. Addison Wesley Longman, Harlow.

French H.M., Millar S.W.S. 2014. Permafrost at the time of the Last Glacial Maximum (LGM) in North America. *Boreas* **43** : 667–677. DOI: 10.1111/bor.12036

Geological Survey (US), Fullerton, D.S., Bush, C.A. and Pennell, J.N., 2003. Map of Surficial Deposits and Materials in the Eastern and Central United States, East of 102° West Longitude. Reston, VA: US Geological Survey.

Głębicki P, Marks L. 2009. The origin of drumlins at Zbójno, Central Poland. *Geologija* **51**: 131–138. DOI: 10.2478/v10056-009-0014-0

Głębicki P., Marks L. The origin of drumlins at Zbójno, Central Poland. *Geologija. Vilnius*. 2009. **51**: No. 3–4 (67–68). P. 131–138.

Hampton M.A., Lee H.J., Locat J. 1996. Submarine landslides. *Reviews of Geophysics* **34**: 33–59. DOI: 10.1029/95RG03287

Harris, K.L., 2007. M-177 Quaternary geology of the Fosston 30'x 60'quadrangle, northwest Minnesota.

Hobbs, H.C. and Goebel, J.E., 1982. S-01 Geologic map of Minnesota, Quaternary geology.

Hooke, R.L., Jennings, C.E., 2006. On the formation of the tunnel valleys of the southern Laurentide ice sheet. *Quaternary Science Reviews* **25**: 1364–1372.

Jennings, C.E., 2006. Terrestrial ice streams—a view from the lobe. *Geomorphology* **75**, 100–124.

Karcz, I., 1967. Harrow Marks, Current-Aligned Sedimentary Structures. *J. Geol*. **75**: 113–121.

Lesemann J-E, Piotrowski JA, Wysota W. 2010. 'Glacial curvilineations': New glacial landforms produced by longitudinal vortices in subglacial meltwater flows. *Geomorphology* **120**: 153–161. DOI: 10.1016/j.geomorph.2010.03.020

Lesemann J-E, Piotrowski JA, Wysota W. 2014. Genesis of the 'glacial curvilineation' landscape by meltwater processes under the former Scandinavian Ice Sheet, Poland. *Sedimentary Geology* **312**: 1–18.

Livingstone, S. J. Clark, C. D. 2016. Morphological properties of tunnel valleys of the southern sector of the Laurentide Ice Sheet and implications for their formation, *Earth Surf. Dynam.*, **4**: 567-589, doi:10.5194/esurf-4-567-2016, 2016.

Nechay W., 1927, Utwory lodowcowe Ziemi Dobrzyńskiej. *Sprawozdania Państwowego Instytutu Geologicznego* **4**: (1-2), 61-144.

Olszewski. 2001 In Piotrowski & Wysota (ed) Drumlins: the unsolved problem. Field excursion guide book for 6th International Drumlin Symposium, Poland.

Piotrowski, J.A., Wysota, W. 2001 (eds.) Field Excursion Guide Book of 6th International Drumlin Symposium June 17-23, pp. 63-68.

Sjogren, D., Fisher, T.G., Taylor, L.D., Jol, H.M., Munro-Stasiuk, M.J., 2002. Incipient tunnel channels. *Quaternary International* **90**: 41–56.

Smith, M.J., Clark, C.D., 2005. Methods for the visualization of digital elevation models for landform mapping. *Earth Surface Processes and Landforms* **30**, 885–900.

Waga, J.M., Fajer, M. 2016. Enigmatic glacigenic ridges from the Odra Glaciation in the vicinity of Krzepice (Wozniki-Wielun Upland, Poland). *Environmental and Socio-economic Studies* **4**: 33-40.

Wright, H.E. 1973. Tunnel valleys, glacial surges, and subglacial hydrology of the Superior Lobe, Minnesota. Geological Society of America Memoirs, **136**, 251-276.

Wright, H.E., Matsch, C.L., Cushing, E.J. 1973. Superior and Des Moines lobes. Geological Society of America Memoirs, **136**, 153-185.

Wysota W. 1994. Morphology, internal composition and origin of drumlins in the southeastern part of the Chelmno-Dobrzyń Lakeland, North Poland. *Sedimentary Geology* **91**: 345–364. DOI: 10.1016/0037-0738(94)90139-2

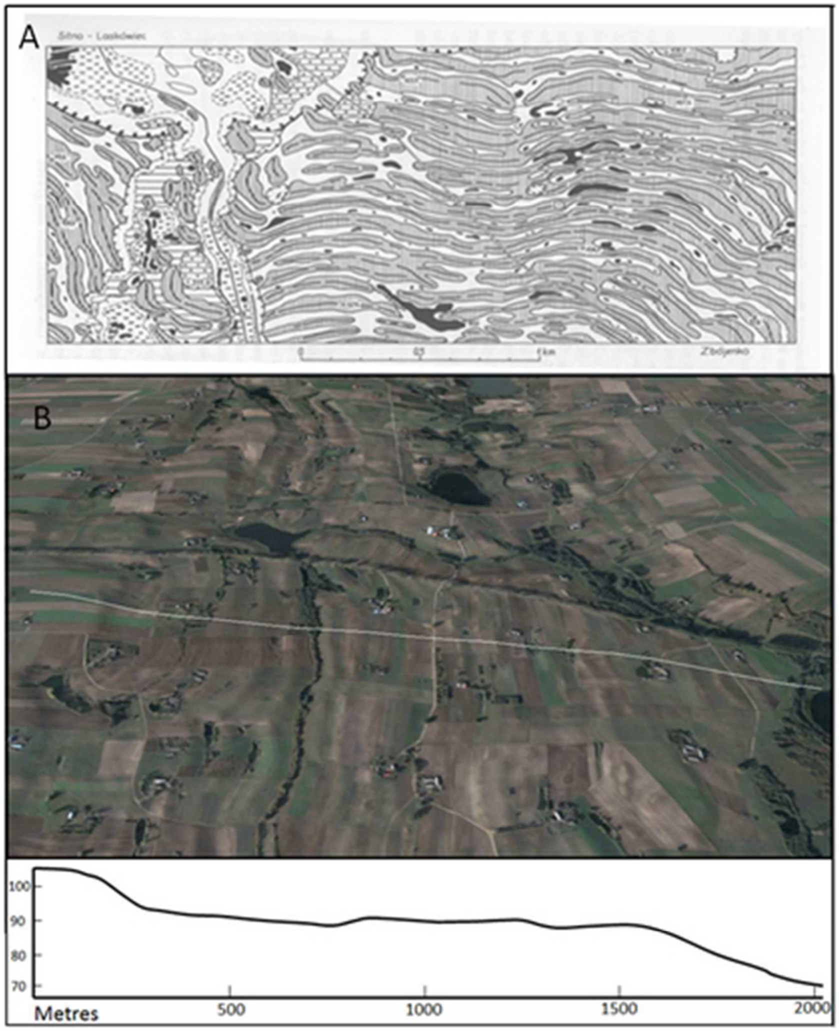

Figure 1. Polish glacial curvilineations (GCLs). A) Morphological map (by Olszewski, 2001) of some GCLs near Zbójenko in Poland, reproduced from Piotrowski and Wysota (2001). At the time of publication, the repeated parallel and sinuous ridges were interpreted as drumlins. B) A wider view of the landscape, also near Zbójenko, (but exact relationship to those in A not known) showing a parallel series of smooth and slightly sinuous ridges and troughs contouring across a gentle slope (falling to the right) and running parallel to the upper escarpment (left). Topographic profile (along the white line) shows the slope context but is not of high enough resolution to reveal relief of the individual ridges and troughs (metres in amplitude). Obliquely-viewed satellite image draped on a digital elevation model, looking NW and centred on 53° 01′ 43′′ N; 19° 04′ 35′′ E, around 5 km NW of Zbójenko, Poland. Topographic and satellite data from Google Earth.

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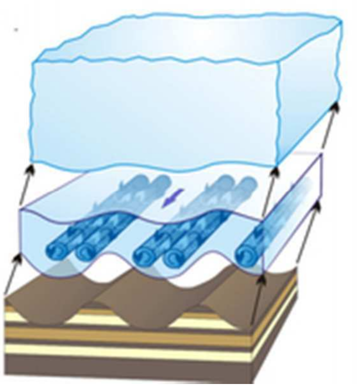

Figure 2. A mechanism of GCL formation whereby subglacial meltwater drainage events erode into pre-existing sediments (reproduced from Lesemann et al., 2010). In this hypothesis, erosion is concentrated as a consequence of the development of pairs of counter-rotating longitudinal vortices which cut the troughs and leave remnant intervening ridges.

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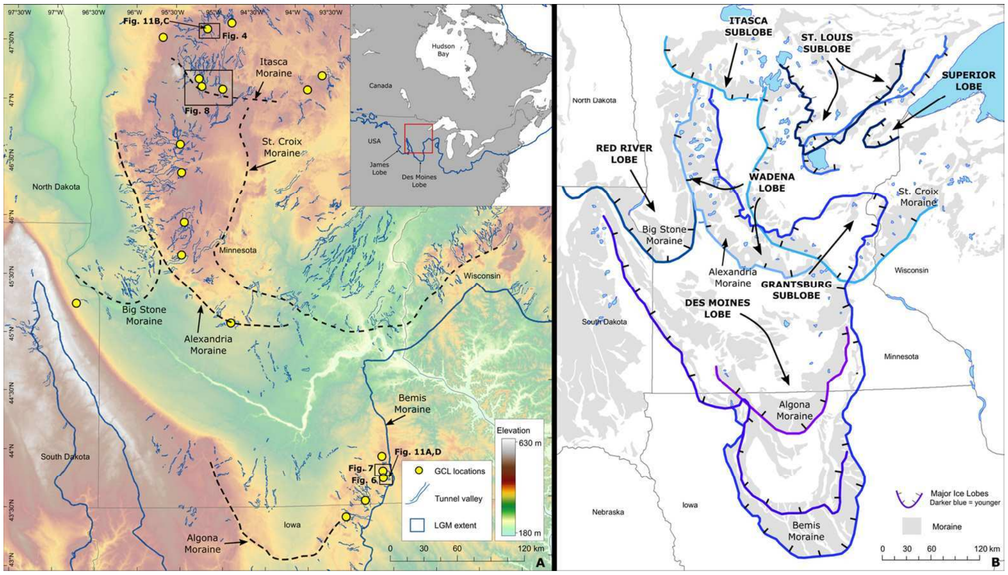

Figure 3. A. Distribution of GCL locations. A total of 871 ridge and trough sets were found within 19 different tunnel valleys. Subsequent figures in this paper are marked by black boxes. Southernmost ice extent of Last Glacial Maximum (LGM) is shown by thick blue line. Dashed black line indicates still-stand positions associated with known moraines. B. Known moraines and major ice lobes of the area, redrawn from information in Wright et al. (1973) and Jennings (2006). Darker blue indicates younger moraines.

137x77mm (300 x 300 DPI)

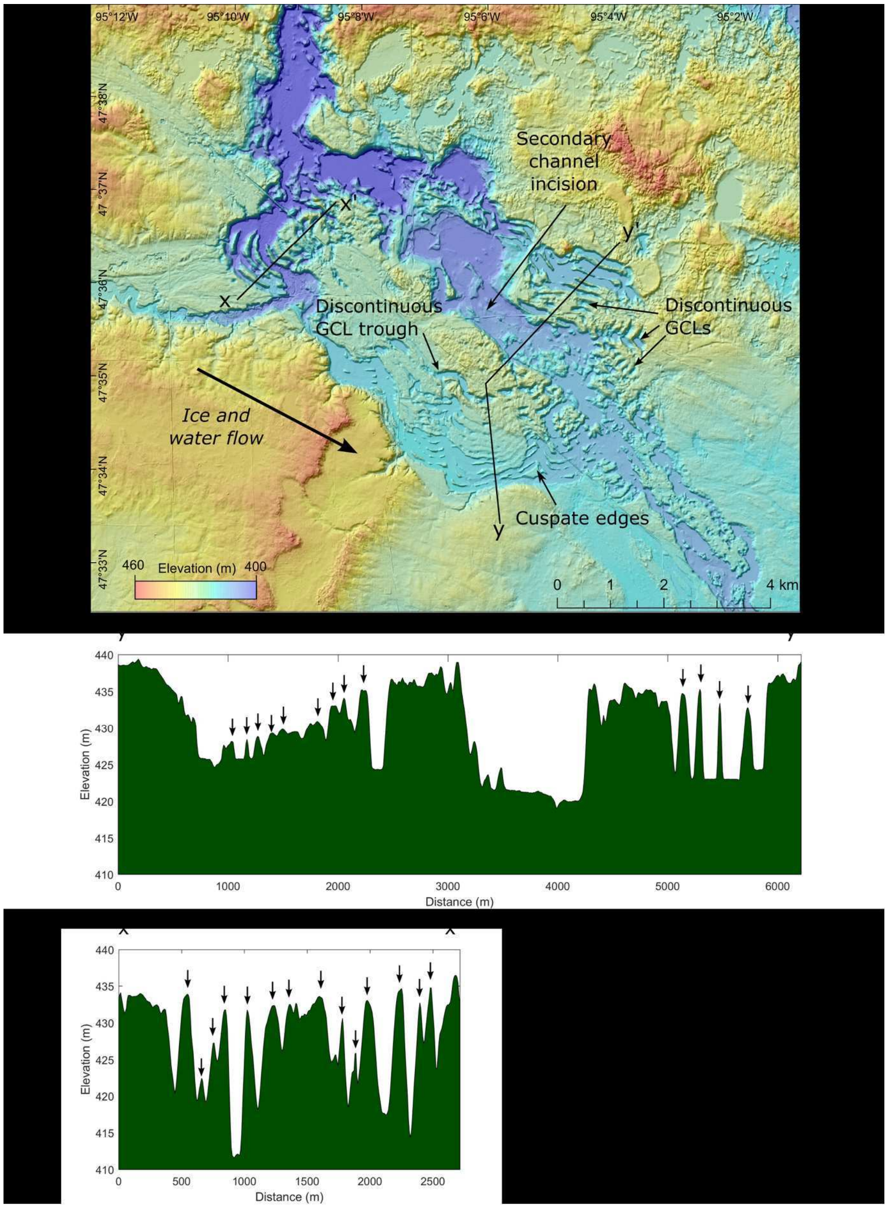

Figure 4. Within a prominent widening in a tunnel valley of two anabranches (water flow to the southeast) are numerous GCLs that parallel and mimic the shape of the tunnel valley edge. Topographic profiles (see method for source data and note high vertical exaggeration - x725) indicate the relief across the valley, with individual GCLs (arrowed) typically 1 to 10 m in amplitude. The town of Pinewood, Beltrami County in Minnesota is located near the image centre. See Figure 5 for an oblique view of this landscape.

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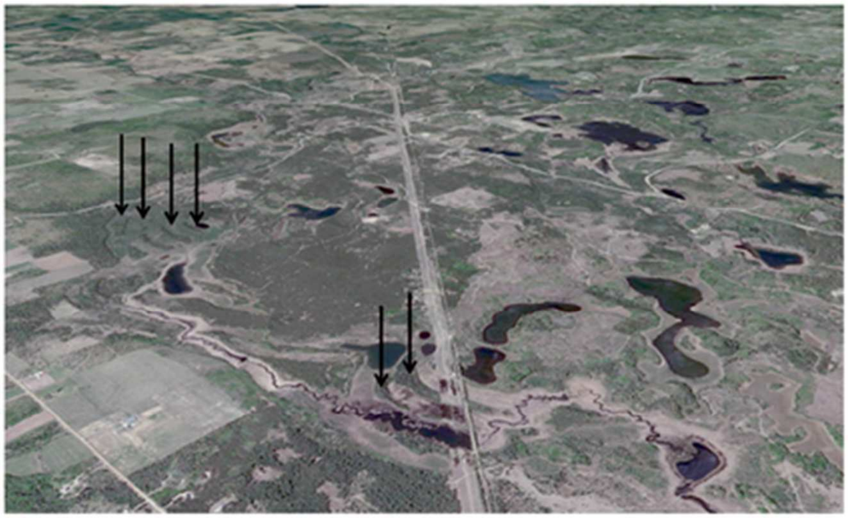

Figure 5. Obliquely-viewed satellite image draped on a DEM looking NW across the Pinewood GCLs of Figure 4 and centred on 47° 36′ N; 95° 06′ W. Image is 4.25 km in width. Overall this is a low relief landscape with the tunnel valley around 20 m deep and with individual GCLs (some arrowed) of around 2 metres in amplitude. Topographic and satellite data from Google Earth.

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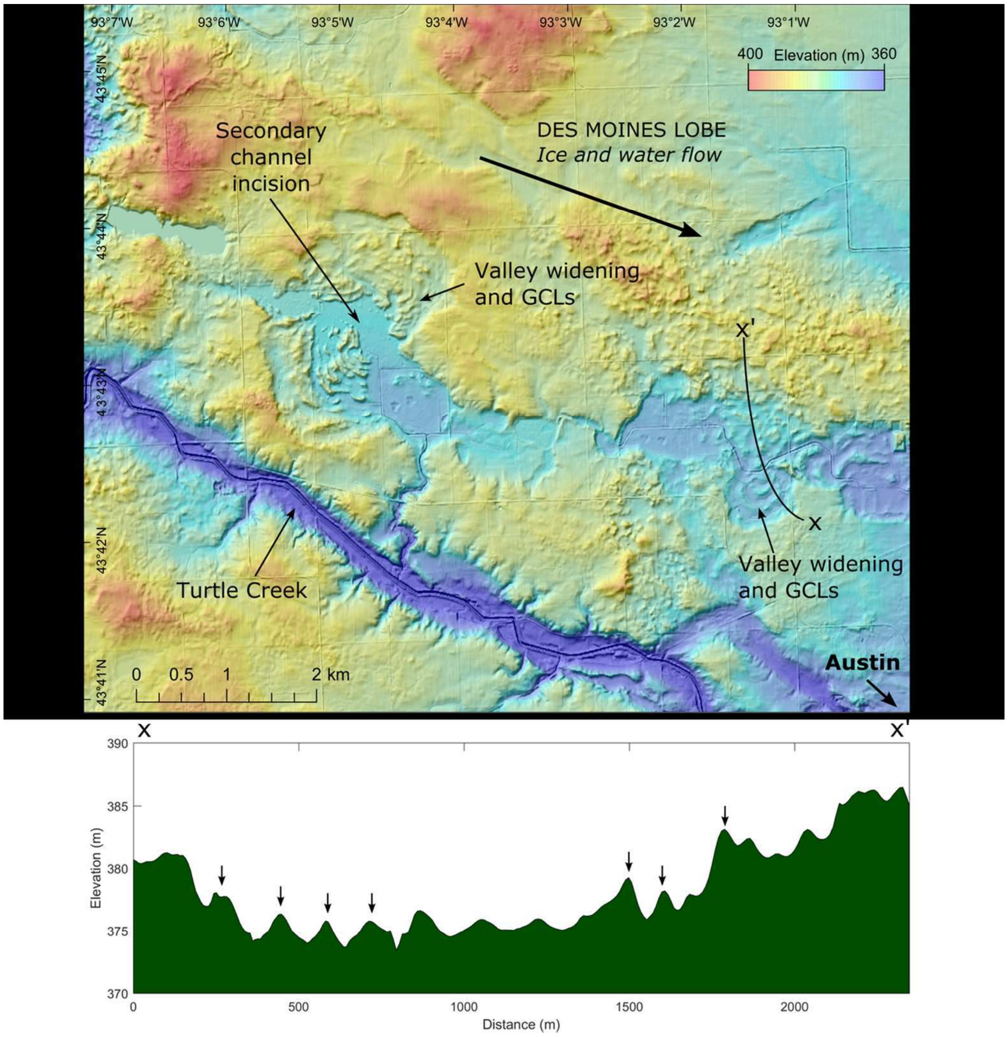

Figure 6. Two widenings in a tunnel valley (flow to the east) displaying GCLs that parallel the valley edge. The westernmost widening is especially bulbous and mirrored on both sides; atypical compared to valley widening in rivers where meander cuts alternate on valley sides. These GCLs are 10 km NW of Austin, south Minnesota, a modern river (Turtle Creek) runs parallel but further south than the tunnel valley. Arrows on the X’ to X topographic profile mark the GCL ridge summits.

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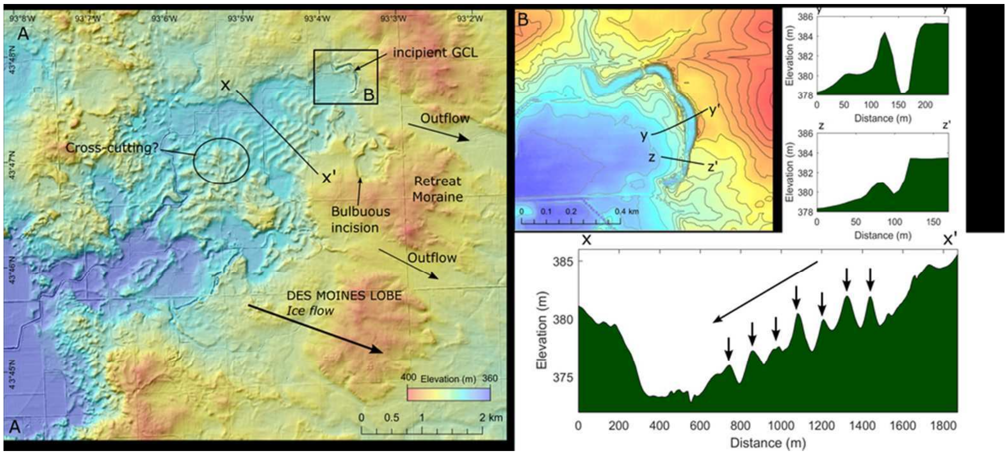

Figure 7. A) Ridge-trough systems in a depression that we interpret as GCLs that formed in a small subglacial lake or swamp, fed from the west by a tunnel valley and with at least two overflows to the east. Note that these GCLs do not align with the likely water flow-paths; they are not orientated towards the outflows and can even be observed at right angles in places. B) In the NE a sharply inscribed trough is found, which we find instructive. It exactly parallels the main break of slope. We interpret it as the opened crack behind a bank or slope failure at the edge of the lake. This incipient or fresh GCL contrasts with the more subdued GCLs elsewhere. The depression and GCLs are 14 km NNW of Austin, southern Minnesota, and formed at the eastern margin of the Des Moines Ice Lobe.

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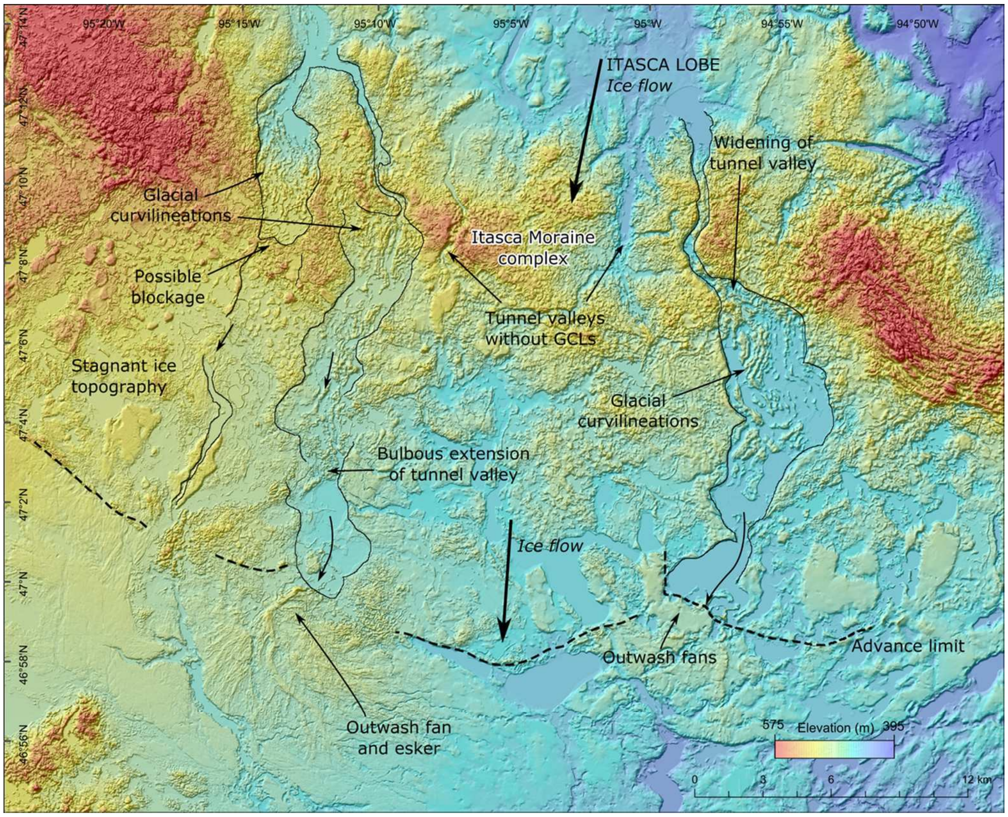

Figure 8. Three sets of GCLs located in tunnel valleys eroded into the higher ground which is part of the Ithasca Moraine complex near Park Rapids, Minnesota. The eastern and central GCLs occupy prominent widenings of tunnel valleys downstream of the moraine complex and leading to outwash fans marking the ice margin position at this time. The westernmost GCLs exist in the main axis of the moraine complex and upstream of an apparent blockage in the tunnel valley that continues further south. In this interpretation a subglacial lake likely existed here in which the GCLs developed.

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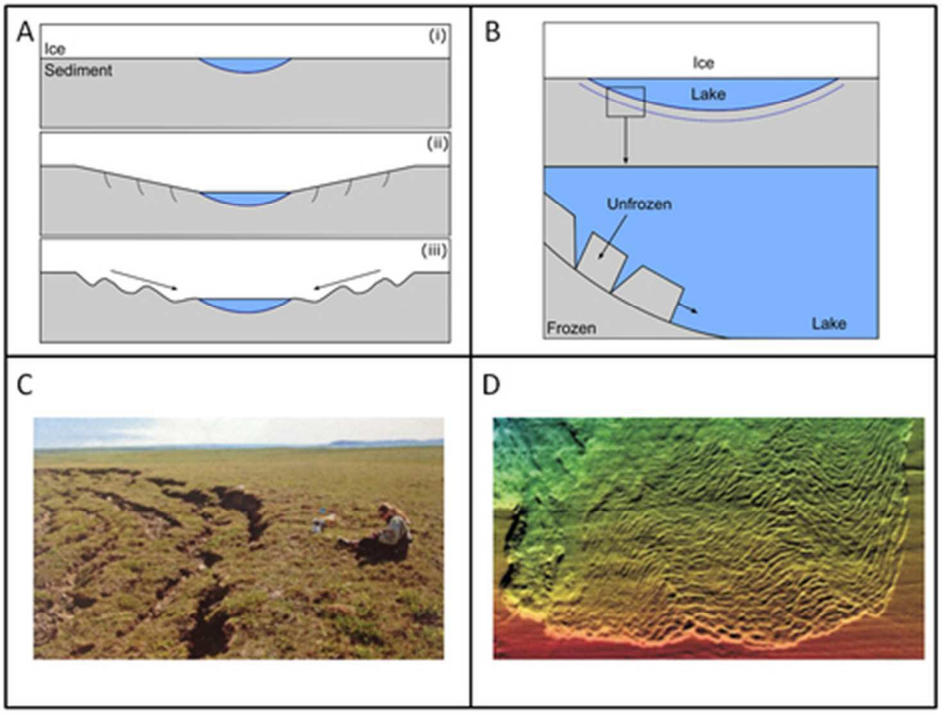

Figure 9. Formation of GCLs by subglacial bank and slope failure in tunnel valleys and subglacial lakes. A) Cartoon of a tunnel valley down-cutting into underlying sediments, steepening the adjacent slopes promoting tension cracks from which landslides occur. Slides could happen incrementally or en masse. B) Bank failure within a subglacial water body such as a lake or in a wholly-filled tunnel valley, again occurring incrementally or in a single event. Where subglacial water is emplaced over a permafrozen substrate, heating of the latter may promote zones of weakness or glide-planes from which landslides might develop. C) A possible analogue; widening of a channel by thermokarst slope failure of a permafrost river bank. D) At a much larger scale (image 9 km across), these are submarine landslides in glacigenic sediments on the MacKenzie River delta in NW Canada (modified from Bennett et al. 2004). Note the parallelism between troughs and ridges and replication of cusps and nicks from the headwall scarp.

39x30mm (300 x 300 DPI)

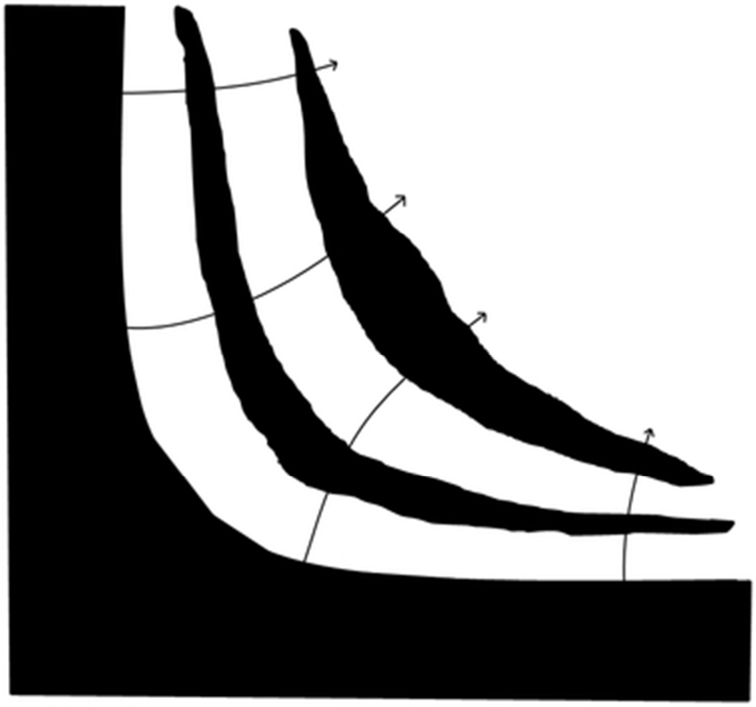

Figure 10. Cartoon representation of slope failure from a sharp concave bend in an escarpment. In this concave geometry, ridges that have slid further from the escarpment must be shorter in length because of convergence, and so to conserve mass they would bulge or bulk-up especially in the zone of maximum convergence.

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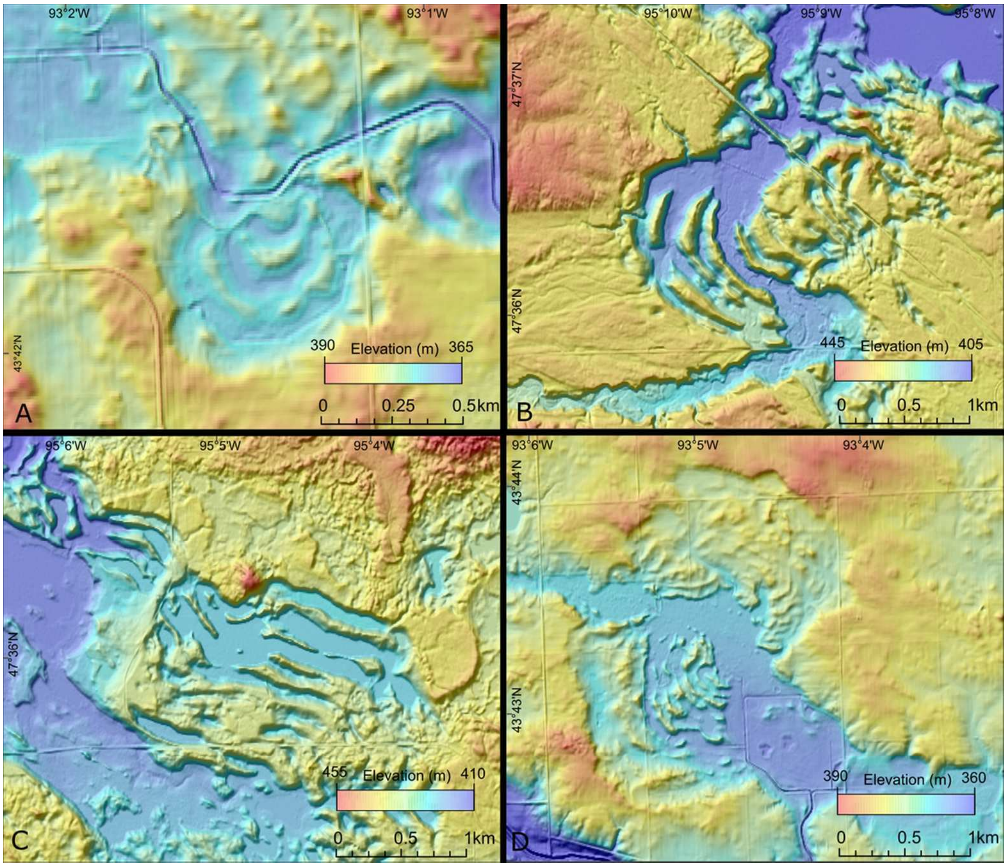

Figure 11. In numerous places ridge bulging is observed where the escarpment geometry and slope provide downhill convergent flow-paths for potential mass movements (cf. Fig. 10). This is consistent with the hypothesis of the ridge-trough systems resulting from slope failure. A) In the semi-circular embayment two concentric ridges get shorter and bulkier in the downhill direction and which culminates as a single almost conical pile of sediment. In B) and C) ridges tend to be wider where they have come from more concave parts of the escarpment compared with straighter sections of the rim. In D), looking at the southern embayment it is notable that the highest and widest parts of most the ridges align with the apex of the ninety degree bend in the escarpment.

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