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**Earth Surface
Processes and Landforms**

**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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1 Glacial curvilineations found along the southern 2 sector of the Laurentide Ice sheet and a 3 hypothesis of formation involving subglacial slope 4 failure in tunnel valleys and subglacial lakes

5
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9 **Abstract**

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

34
35 **Key words;** glacial curvilineations; tunnel valleys; permafrost; subglacial lakes; slope
36 failure.

37 Introduction

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

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53 *Figure 1. Polish glacial curvilineations (GCLs). A) Morphological map (by Olszewski,*
54 *2001) of some GCLs near Zbójenko in Poland, reproduced from Piotrowski and*
55 *Wysota (2001). At the time of publication, the repeated parallel and sinuous ridges*
56 *were interpreted as drumlins. B) A wider view of the landscape, also near Zbójenko,*
57 *(but exact relationship to those in A not known) showing a parallel series of smooth*
58 *and slightly sinuous ridges and troughs contouring across a gentle slope (falling to*
59 *the right) and running parallel to the upper escarpment (left). Topographic profile*
60 *(along the white line) shows the slope context but is not of high enough resolution to*
61 *reveal relief of the individual ridges and troughs (metres in amplitude). Obliquely-*
62 *viewed satellite image draped on a digital elevation model, looking NW and centred*
63 *on 53° 01' 43" N; 19° 04' 35" E, around 5 km NW of Zbójenko, Poland. Topographic*
64 *and satellite data from Google Earth.*

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

75 So far, just one (post-drumlin) theory for GCL formation exists; erosion by
76 longitudinal-vortices produced in subglacial meltwater floods emerging from either
77 sub- or supraglacial lakes and directed down tunnel valleys (Fig. 2; Lesemann *et al.*,

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3 78 2010; 2014). The finding of large (1.5 m) well-rounded boulders at the distal end of
4 79 some tunnel valleys is interpreted to support such high energy flows.
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8 81 *Figure 2. A mechanism of GCL formation whereby subglacial meltwater drainage*
9 82 *events erode into pre-existing sediments (reproduced from Lesemann et al., 2010).*
10 83 *In this hypothesis, erosion is concentrated as a consequence of the development of*
11 84 *pairs of counter-rotating longitudinal vortices which cut the troughs and leave*
12 85 *remnant intervening ridges.*
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14 86 While using newly-available high resolution elevation data to map and analyse tunnel
15 87 valleys for parts of the formerly glaciated USA (reported in Livingstone and Clark,
16 88 2016) we found numerous examples of parallel sets of ridges and troughs that match
17 89 the descriptions of GCLs reported from Poland. In this paper, we report on these
18 90 landforms, classifying them as GCLs, providing the first evidence for their existence
19 91 in North America. Our work is restricted to morphological properties and their
20 92 landform associations and we describe and illustrate their key properties. We find
21 93 that some of these new observations are difficult to explain using the existing
22 94 hypothesis of erosion by longitudinal vortices in subglacial floods. We therefore
23 95 propose a new hypothesis for creation of these enigmatic landforms; subglacial
24 96 slope failure of the banks of tunnel valleys.
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30 98 **Dataset and methods**

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32 99 The main data source used was the USA's National Elevation Dataset (NED)
33 100 (<http://nationalmap.gov/elevation.html>), which is a seamless digital elevation model
34 101 (DEM) with a resolution of 1/3 arc seconds (~10 m) across the entire study area, and
35 102 1/9 arc seconds (~3 m) in some locations. We investigated a large area (ca. 750,000
36 103 km²) making a complete and thorough search for tunnel valleys and GCLs visible in
37 104 the DEM within the box defined by 82-102°W; 40-48°N, covering parts of the states
38 105 of North and South Dakota, Minnesota, Iowa, Wisconsin, Ohio, Indiana, Illinois and
39 106 Michigan. The DEM was manipulated and displayed in a GIS (ArcGIS 10.1) to render
40 107 images for visual interpretation of landforms using a variety of processing methods of
41 108 combined solar-shading and colour-rendition of elevations (e.g. Smith and Clark
42 109 2005). Extensive tunnel valley systems were mapped (Livingstone and Clark 2016)
43 110 and the locations of all features resembling Polish GCLs were identified from their
44 111 ridge crestlines. To help understand the morphology of GCL terrains and their
45 112 relation to tunnel valleys numerous topographic profiles were extracted from the
46 113 DEM.
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53 115 **Observations**

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3 117 *Figure 3. A. Distribution of GCL locations. A total of 871 ridge and trough sets were*
4 118 *found within 19 different tunnel valleys. Subsequent figures in this paper are marked*
5 119 *by black boxes. Southernmost ice extent of Last Glacial Maximum (LGM) is shown*
6 120 *by thick blue line. Dashed black line indicates still-stand positions associated with*
7 121 *known moraines. B. Known moraines and major ice lobes of the area, redrawn from*
8 122 *information in Wright et al. (1973) and Jennings (2006). Darker blue indicates*
9 123 *younger moraines.*

12 124 Numerous features were discovered, which so closely visually resemble glacial
13 125 curvilineations described in Poland (compare Figures here with Figure 2 in
14 126 Lesemann *et al.* 2010) that we regard them to be the same landform type. GCLs
15 127 were found to be common with a total of 871 sets across 19 tunnel valleys. Figure 3
16 128 provides an overview of their locations along with the distribution of tunnel valleys
17 129 where they were identified in South Dakota, Minnesota and Iowa. No GCLs were
18 130 found outside of tunnel valleys or depressions linked to tunnel valleys. We illustrate
19 131 some of the GCLs to show their typical scale, form and spatial contexts, and use
20 132 these observations to build an inventory of morphological characteristics.

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26 134 *Figure 4. Within a prominent widening in a tunnel valley of two anabranches (water*
27 135 *flow to the southeast) are numerous GCLs that parallel and mimic the shape of the*
28 136 *tunnel valley edge. Topographic profiles (see method for source data and note high*
29 137 *vertical exaggeration - x725) indicate the relief across the valley, with individual*
30 138 *GCLs (arrowed) typically 1 to 10 m in amplitude. The town of Pinewood, Beltrami*
31 139 *County in Minnesota is located near the image centre. See Figure 5 for an oblique*
32 140 *view of this landscape.*

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37 142 *Figure 5. Obliquely-viewed satellite image draped on a DEM looking NW across the*
38 143 *Pinewood GCLs of Figure 4 and centred on 47° 36' N; 95° 06' W. Image is 4.25 km*
39 144 *in width. Overall this is a low relief landscape with the tunnel valley around 20 m*
40 145 *deep and with individual GCLs (some arrowed) of around 2 metres in amplitude.*
41 146 *Topographic and satellite data from Google Earth.*

42
43 147 The Pinewood GCLs in Minnesota (Figs. 4 and 5) occur in a prominent widening of
44 148 the tunnel valley and do not exist immediately up or downstream. Perhaps GCLs are
45 149 more likely to form in wider valleys or their processes of formation actually contribute
46 150 to the widening. The GCLs display the usual parallelism with the tunnel valley edge
47 151 as reported in Polish examples (Lesemann *et al.*, 2010; 2014) and we note here that
48 152 they often have cusped forms and defects that mimic the tunnel valley edge, but
49 153 which degrade with distance (Fig. 4). The ridges (see topographic profiles) mostly
50 154 seem to decline in elevation away from tunnel valley edges although this is not
51 155 always so. They are never higher than the local edge of the tunnel valley. GCL
52 156 trough-ridge sets extend for 0.5 to 4 km in length and there are examples of
53 157 discontinuous troughs with sudden terminations (Fig. 4). Secondary valley incision

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3 158 that seems to have truncated some GCLs (near downstream end of the tunnel valley
4 159 in Fig. 4) indicates that there has been more than one phase of overall land-forming
5 160 and valley cutting.

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9 162 *Figure 6. Two widenings in a tunnel valley (flow to the east) displaying GCLs that*
10 163 *parallel the valley edge. The westernmost widening is especially bulbous and*
11 164 *mirrored on both sides; atypical compared to valley widening in rivers where*
12 165 *meander cuts alternate on valley sides. These GCLs are 10 km NW of Austin, south*
13 166 *Minnesota, a modern river (Turtle Creek) runs parallel but further south than the*
14 167 *tunnel valley. Arrows on the X' to X topographic profile mark the GCL ridge summits.*

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17 168 North-west of Austin, in south Minnesota, GCLs of a few metres in relief occupy two
18 169 widenings in a tunnel valley (Fig. 6). The tunnel valleys were formed at the eastern
19 170 limit of the Des Moines Ice Lobe (Wright et al., 1973). The bulbous nature of these
20 171 widenings locally and abruptly increase the width of the valley from 0.5 to 2 km and
21 172 back to 0.5 km. This is unusual compared to valleys produced by flowing water
22 173 which typically do not have such abrupt changes and gradually widen downstream.
23 174 Again, the ridges mimic the shape of the valley edges. Just to the north of this tunnel
24 175 valley is a 6 x 3 km depression of 10 m depth (Fig. 7), down-flow from a tunnel valley
25 176 and with two higher-level outflows that cut through a moraine at its eastern edge. We
26 177 speculate that this as a shallow subglacial lake or swamp, although, alternatively, it
27 178 could just be seen as an unusual widening and blockage in a tunnel valley; where to
28 179 draw the line between these two styles of drainage? As usual the GCLs mimic the
29 180 edge of the depression (notably the higher southern rim), but unlike earlier
30 181 examples, the geometry is different regarding likely water flow-paths through the
31 182 system. In particular, the GCLs do not align with the likely water flow paths out of the
32 183 eastern outflows, and actually lie orthogonal in some instances. A further key
33 184 observation is that running exactly parallel to the rim of the depression in the NE
34 185 (Fig. 7B) is a prominent and sharply inscribed trough (~ 6 m depth) bounded by a
35 186 ridge. We interpret this as an incipient or fresh GCL, which contrasts with more
36 187 subdued examples elsewhere. That this type of sharply-defined GCL is so rare
37 188 suggests there has been post-formation modification of most of the ridges and
38 189 troughs. Finally, in the centre of the depression (Fig. 7A) GCLs appear to cross-cut
39 190 each other forming a palimpsest landscape signature indicative of multiple events or
40 191 phases. Because the ridges in this basin have a fairly consistent orientation (NE-SW)
41 192 rather than following the curved geometry of the basin rim an alternative
42 193 interpretation could be that they are Ribbed (Rogen) Moraine formed under ice
43 194 flowing towards the southeast. Here they are certainly of a similar scale and
44 195 appearance to ribbed moraine (cf. Dunlop and Clark 2006).

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49 197 *Figure 7. A) Ridge-trough systems in a depression that we interpret as GCLs that*
50 198 *formed in a small subglacial lake or swamp, fed from the west by a tunnel valley and*
51 199 *with at least two overflows to the east. Note that these GCLs do not align with the*

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

207

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

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

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

- 223 1. Occur near southern margins of palaeo ice sheets in low-relief landscapes.
- 224 2. Occur in single thread tunnel valleys or in anabranching tunnel valley systems,
 225 sometimes upstream of topographic barriers such as moraine complexes.
 226 They have not been found outside of depressions acting as conduits or stores
 227 of subglacial meltwater.
- 228 3. GCLs reported here occur in tunnel valleys with low along-stream slope
 229 gradients (typically 0.06° to 0.34°) and either rising or falling. This is similar to
 230 those reported in Poland, where GCLs occur in tunnel valleys that rise up
 231 ~110 m over a distance of 20 km (0.31°; Lesemann *et al.*, 2014).
- 232 4. Occur at prominent widenings (> doublings) of tunnel valleys and sometimes
 233 in bulbous incisions into the valley sides.
- 234 5. The GCL ridge crests are either at or below the level of the surrounding
 235 topography and mostly decline in elevation towards valley bottoms.
- 236 6. GCLs occur in sets, are sinuous and lie parallel to their neighbouring ridges.
- 237 7. GCLs closely parallel the edge of the tunnel valley or depression, sometimes
 238 with abrupt (~90° over 100 m) changes in direction

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3 239 8. Where tunnel valley rims have cusps or defects in their planform shape, these
4 240 are often mirrored in adjacent GCLs and this mimicry can sometimes be seen
5 241 to degrade with distance towards the central axis of the valley.
6 242
7 242 9. GCLs mostly align with the broad water flow-paths expected down tunnel
8 243 valleys but this is not always the case (e.g. Fig. 7).
9 244
10 244 10. GCLs reported here have a median wavelength of 150 m (min. = 41 m, max.
11 245 = 627 m) and a median height of 4 m (min. = 1 m, max. = 26 m). The majority
12 246 (90%) of the GCLs have a wavelength of 70-325 m and are 1-16 m high which
13 247 is within the range of those reported from Poland (Lesemann *et al.*, 2010).
14 248
15 248 11. GCL ridges and troughs are roughly symmetrical.
16 249
17 249 12. GCL lengths are mostly of the order of a km, but segments can sometimes be
18 250 linked over a 10 km distance.
19 251
20 251 13. GCLs have been observed where two sets appear to cross-cut each other
21 252 (e.g. Fig. 7).
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254 **A new hypothesis for the formation of glacial curvilineations**

255 Hypothesis development is typically inspired by specific observations that require
256 256 explanation, and the path taken is often frustratingly sensitive to which observations
257 257 are seen as primary versus of a tangential nature. Baker and Twidale (1991) discuss
258 258 this issue and encourage geomorphologists to develop imaginative hypotheses. A
259 259 key primary observation for us is that GCLs tend to mimic the tunnel valley edge
260 260 even when it changes direction abruptly (e.g. a 90° kink), and that there are often
261 261 sharply defined cusps or defects that are repeated (see annotation in Fig. 4 and in
262 262 Lesemann *et al.*, 2010 figure 2 of Polish examples;). These abrupt changes in
263 263 direction make it problematic for longitudinal vortices to have created GCLs because
264 264 we presume they would become disrupted at such points (see later). Parallel
265 265 repetition of cusps and defects however, is common in growth rings such as occur in
266 266 tree rings or corals viewed in section. This implies incremental production, rather
267 267 than the necessity of having the GCL-fields simultaneously form in a single or a few
268 268 flood events. That GCLs have only been found where widening occurs also seems of
269 269 prime importance; the simplest explanation being that the GCLs are part of the
270 270 process of widening. Taking our two primary observations along with the presumed
271 271 context of requiring subglacially-flowing water (GCLs arise in tunnel valleys) we
272 272 construct a new hypothesis for the formation of GCLs, which we suggest is more
273 273 plausible than the existing one. We exclude subaerial formation of GCLs because in
274 274 our survey of the whole area (750,000 km²) we only found GCLs within tunnel
275 275 valleys, which are widely interpreted to have formed subglacially, as often shown by
276 276 their uphill-flowing long profiles. If GCLs formed subaerially then we would expect to
277 277 find them on other slopes in the terrain.

278 We suggest that GCLs are the record of subglacial slope or bank failures at the edge
279 279 of tunnel valleys or near subglacial lake shores. In this hypothesis the GCL-troughs

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3 280 are the opened fractures between blocks that have been transported downslope by
4 281 land-sliding. It is these slope or bank failures which locally widened the tunnel
5 282 valleys, while the bulbous incisions (e.g. Fig. 7) are the headwall scarps of the mass
6 283 movements. Figure 9 illustrates likely processes and contexts, either with water in a
7 284 channel occupying part of a wider tunnel valley (Fig. 9A) or in a depression wholly
8 285 filled with water (Fig. 9B), such as a subglacial lake or a completely filled tunnel
9 286 valley (i.e. tunnel channel). A down-cutting subglacial river in a wider valley (Fig. 9A)
10 287 steepens the valley flanks and in our hypothesis leads to tension cracks
11 288 incrementally developing, which then act as lines of weakness for downslope
12 289 movement. Although the tension cracking happened incrementally, in this model, the
13 290 actual slides could have been incremental and retrogressive or have occurred during
14 291 a single failure event, or some mix of these. In this model the flow of water is not
15 292 responsible for forming the GCLs but it is likely to subsequently modify and smooth
16 293 the ridges. If ice flow adjacent to tunnel valleys was sufficiently directed inwards
17 294 toward the tunnel valley axis (to replace melting) it might be that ice flow over the
18 295 valley lip drove or contributed to the tension cracking and block slides, in a
19 296 mechanism similar to that proposed by Kleman and Hattestrand, (1999) for the
20 297 formation of ribbed moraine.
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27 299 Permafrozen conditions are thought to have persisted in-front of and under the toe of
28 300 ice lobes in Minnesota and surrounding states during deglaciation (Wright, 1973;
29 301 French & Miller, 2014). If bank failure and downslope movement occurred wholly
30 302 within a subglacial water body (Fig. 9B) then we suggest that it may have been
31 303 facilitated by perma-frozen ground acting as glide-planes. Such a situation may
32 304 occur when an ice margin advances over a permafrozen forefield. For example, in
33 305 Figures 4, 6 and 8, we observe that GCLs occur in tunnel valleys incised through
34 306 prominent moraine positions. This may be indicative of tunnel valley and GCL
35 307 formation during re-advances across frozen ground. Where subglacial water
36 308 becomes emplaced, say as a subglacial lake, over permafrost, heating of the
37 309 substrate may permit intact thawed blocks (warmed by subglacial water) to slide over
38 310 underlying frozen ground; analogous to active layer-detachments and retrogressive-
39 311 thaw slides (Fig. 9C) (French, 1996).. Alternatively, weaknesses beneath the blocks
40 312 could have been produced by networks of conduits (soil piping) from permafrost
41 313 spring sapping. In this idea, groundwater cannot easily percolate downwards once it
42 314 reaches a frozen permafrost layer so is forced to drain laterally in a series of soil
43 315 pipes and then causes concentrated erosion (sapping) where it emerges. Given that
44 316 typical slope angles from the tunnel valley rims to centre-lines are so low (typically
45 317 0.5° to 1.5°) we suspect that permafrost is a required condition, noting that subaerial
46 318 slope movements in these environments and at such angles are commonly reported
47 319 (French, 1996). Alternatively, because submarine landslides can occur in glacial
48 320 sediments on slopes of as low as 0.01° to 0.5° (Hampton *et al.* 1996) then slides in
49 321 subglacial water bodies could also occur at these low angles. A further possibility is
50 322 that the ridges and troughs comprising GCLs are folds from downslope creep
51 323 deformation, although the sharp trough observed in Figure 7B and that we interpret
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3 324 as an opened tension crack argues against this in that particular case. Subglacial
4 325 earthquakes from stick-slip movement of the glacier sole might have acted as
5 326 triggers for landslides.

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8 329 *Figure 9. Formation of GCLs by subglacial bank and slope failure in tunnel valleys*
9 330 *and subglacial lakes. A) Cartoon of a tunnel valley down-cutting into underlying*
10 331 *sediments, steepening the adjacent slopes promoting tension cracks from which*
11 332 *landslides occur. Slides could happen incrementally or en masse. B) Bank failure*
12 333 *within a subglacial water body such as a lake or in a wholly-filled tunnel valley, again*
13 334 *occurring incrementally or in a single event. Where subglacial water is emplaced*
14 335 *over a permafrozen substrate, heating of the latter may promote zones of weakness*
15 336 *or glide-planes from which landslides might develop. C) A possible analogue;*
16 337 *widening of a channel by thermokarst slope failure of a permafrost river bank. D) At a*
17 338 *much larger scale (image 9 km across), these are submarine landslides in glacial*
18 339 *sediments on the MacKenzie River delta in NW Canada (modified from Bennett et al.*
19 340 *2004). Note the parallelism between troughs and ridges and replication of cusps and*
20 341 *nicks from the headwall scarp.*
21 342

22 343 **Discussion**

23 344 We have not investigated the sedimentary composition of the GCLs reported here
24 345 and know of no work that directly relates such information to the morphology of the
25 346 ridges and troughs (but see below). In this paper we merely presume that GCL
26 347 creation came after deposition of the sediments such that they are unrelated from a
27 348 process-point of view. This presumption is based on the findings of an intensive
28 349 investigation of GCL sediment-landform relationships in Poland (Lesemman *et al.*,
29 350 2010, 2014), where the ridge-trough morphology was found to be unrelated (came
30 351 after) to the sediments. Our search of Quaternary and hydrogeologic maps of
31 352 Minnesota and the County Geological Atlas series of the Minnesota Geological
32 353 Survey (e.g. Hobbs & Goebel, 1982; Fullerton *et al.*, 2003; Harris, 2007) revealed
33 354 limited information on GCL sediment-landform relationships. On a Quaternary
34 355 geology map (Harris, 2007), the GCL ridges in Figure 4 are shown to have a wide
35 356 variety of surface geological expressions: ranging from unsorted and unbedded
36 357 sand, silt and clay, commonly with pebbles and interpreted as slope deposits;
37 358 moderately to poorly sorted sand and gravel interpreted as deposited by meltwater
38 359 rivers; and unbedded and unsorted sediments with mixes of sand and gravel and
39 360 glacial sediments interpreted to have been draped over the landscape. These
40 361 sediments and interpretations are readily associated with deposition in tunnel
41 362 valleys. If the mapped surface expressions are taken as being representative of their
42 363 internal composition (aside from the draped units) then in common with the Polish
43 364 investigations they suggest a variety of depositional contexts unrelated to the
44 365 morphology of the ridge-troughs. A subset of the GCLs we show in Figure 4 were

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3 366 interpreted from aerial photographs by Harris (2007) as beach ridges or nearshore
4 367 bars marking the former extent of Glacial Lake Agassiz. Given the close proximity of
5 368 Glacial Lake Agassiz to this site (tens of kms), we can understand the basis of this
6 369 interpretation, but regard it to be unlikely for two reasons. The sediments described
7 370 on the map (Harris, 2007) do not record the typically well-sorted nature of beach
8 371 ridges. Secondly, the broad distribution of GCLs across our study region and with
9 372 many far from known glacial lakes (> 100 km) weakens any interpretation that they
10 373 could all be beach ridges of a subaerial lake. We suggest that future investigations
11 374 into the composition of these landforms might be able to take this further, or that new
12 375 fieldwork specifically aimed at GCL landform-sediment relationship would be useful.

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16 376 Field observations and geophysical investigations could test our hypothesis of slope
17 377 failure; can distinctive sedimentary units be found straddling a number of ridges but
18 378 with elevation offsets indicating lateral and downslope movement? Can evidence be
19 379 found that distinguishes between the types of slope movement we have suggested?
20 380 Or just from a morphological point of view, does the volume (width and height) of
21 381 ridges vary as one should expect to satisfy volume - continuity in mass movements?
22 382 In Figure 10 for example we should expect ridges that have slid from sharp bends to
23 383 have bulges because of longitudinal shortening as a consequence of the bend
24 384 geometry. Although we have not quantitatively analysed this, and there would be
25 385 some difficulty in doing so because of post-formation modifications of ridges, it is
26 386 apparent from Figure 11 that such bulging or bulking-up seems to occur in numerous
27 387 places, which is consistent with the hypothesis of slope failure.

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34 389 *Figure 10. Cartoon representation of slope failure from a sharp concave bend in an*
35 390 *escarpment. In this concave geometry, ridges that have slid further from the*
36 391 *escarpment must be shorter in length because of convergence, and so to conserve*
37 392 *mass they would bulge or bulk-up especially in the zone of maximum convergence.*

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42 394 *Figure 11. In numerous places ridge bulging is observed where the escarpment*
43 395 *geometry and slope provide downhill convergent flow-paths for potential mass*
44 396 *movements (cf. Fig. 10). This is consistent with the hypothesis of the ridge-trough*
45 397 *systems resulting from slope failure. A) In the semi-circular embayment two*
46 398 *concentric ridges get shorter and bulkier in the downhill direction and which*
47 399 *culminates as a single almost conical pile of sediment. In B) and C) ridges tend to be*
48 400 *wider where they have come from more concave parts of the escarpment compared*
49 401 *with straighter sections of the rim. In D), looking at the southern embayment it is*
50 402 *notable that the highest and widest parts of most the ridges align with the apex of the*
51 403 *ninety degree bend in the escarpment.*

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55 404 The sharply-inscribed trough in Figure 7B is interpreted as an important confirmation
56 405 of bank failure. That GCLs are usually more subdued than this indicates that

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3 406 subsequent modification has taken place for most of them, probably by the flow of
4 407 the base of the ice sheet or by meltwater drainage through the tunnel valley. If floods
5 408 subsequently travelled down these tunnel valleys, they would further modify the
6 409 landforms - perhaps with longitudinal vortices developing in places - but they are not
7 410 required in the hypothesis we erect here.

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10 411 Submarine slope failures, such as shown in Figure 9D remarkably resemble many
11 412 aspects of GCLs, notably the conformity of sinuous ridges and troughs to the
12 413 headwall scarp, the mimicry of cusps and defects and the bulbous incision. The
13 414 morphological similarity would be even greater if a flowing medium (ice, or water
14 415 flowing subglacially) was to subsequently erode and smooth the features
15 416 approximately parallel to their orientation, something that is likely to occur in tunnel
16 417 valley settings.

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19 418 The formation of GCLs by high-energy subglacial meltwater flows has a number of
20 419 problems. Primarily, it is difficult to envisage how sinuous GCLs with sharp cusps
21 420 (Fig. 4 and Polish examples in Lesemann *et al.* 2010, their Fig. 2) could form during
22 421 a broad, sheet-like flow. Furrows created by longitudinal vortices are linear or
23 422 diverge smoothly around obstacles (cf. Carling *et al.*, 2009 and references therein).
24 423 Indeed, longitudinal vortices typically develop from fully turbulent flow in straight or
25 424 relatively straight channels (e.g. Einstein and Li, 1958; Karctz, 1967); any irregularity
26 425 is likely to induce additional turbulent structure that breaks up the longitudinal pattern
27 426 of vorticity (Baker, 1979). Secondly, the troughs between the GCLs are sometimes
28 427 discontinuous, producing chains of linear troughs or depressions. This is difficult to
29 428 reconcile with longitudinal vortices, although Sjorgen *et al.*, (2002) invoked vertical
30 429 vortices (kolks) to explain the formation of incipient tunnel valleys characterised by
31 430 linked potholes. However, this does not fit with the regular spacing of the ridges and
32 431 troughs, or their longitudinal geometry.

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37 432 The bulbous widenings that we show in tunnel valleys often contain GCLs and the
38 433 two features are linked in our hypothesis of subglacial slope failure. Either steady or
39 434 catastrophic subsequent water flow down such tunnel valleys could degrade or
40 435 entirely erode away GCLs, and there is clear evidence in places of such erosion
41 436 occurring by secondary channel incision (Fig. 6). On Victoria Island a tunnel valley
42 437 has been reported (Brennand and Sharpe, 1993) showing numerous similar bulbous
43 438 incisions (scalloped margins in their description) and of similar (kilometre) scale and
44 439 in places containing some residual hills or ridges. We suggest that these
45 440 embayments may also be subglacial slope-failure escarpments, but with most of the
46 441 mass-wasted material (the GCLs) removed by subsequent erosion. Alternatively, in
47 442 their hypothesis (Brennand and Sharpe, 1993) the scalloped margins are interpreted
48 443 to have been formed by turbulent scouring that occurred in a subglacial sheet-flow
49 444 flood that is reconstructed to have crossed the tunnel valley at an oblique angle.

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446 **Summary and conclusions**

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

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

484 If the association of GCL formation with permafrost is found to hold, then GCLs may
485 become an important indicator of the palaeo-distribution of permafrost. We note that
486 in both the Polish and USA cases that the GCLs occur in ice lobes close to the
487 maximum southern extent of their ice sheets, prone to re-advances, and that may

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3 488 have therefore advanced over ground subject to permafrost. French and Miller
4 489 (2014) and Ewertowski (2009) report evidence of permafrost conditions proximal to
5 490 these ice margins and Hooke and Jennings (2006), have proposed permafrost and
6 491 cold-based ice along this ice margin to be important for the production of tunnel
7 492 valleys.

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11 494 **Acknowledgements**

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14 495 Roger Hooke is thanked for his referee comments and which included the insightful
15 496 remarks on ridge bulging in relation to escarpment geometry and which we have
16 497 developed here in Figs 10 and 11. David Sharpe is also thanked for comments that
17 498 helped improve the clarity of the paper and for alerting us to scalloped tunnel valley
18 499 edges on Victoria Island, Arctic Canada.

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22 501 **References**

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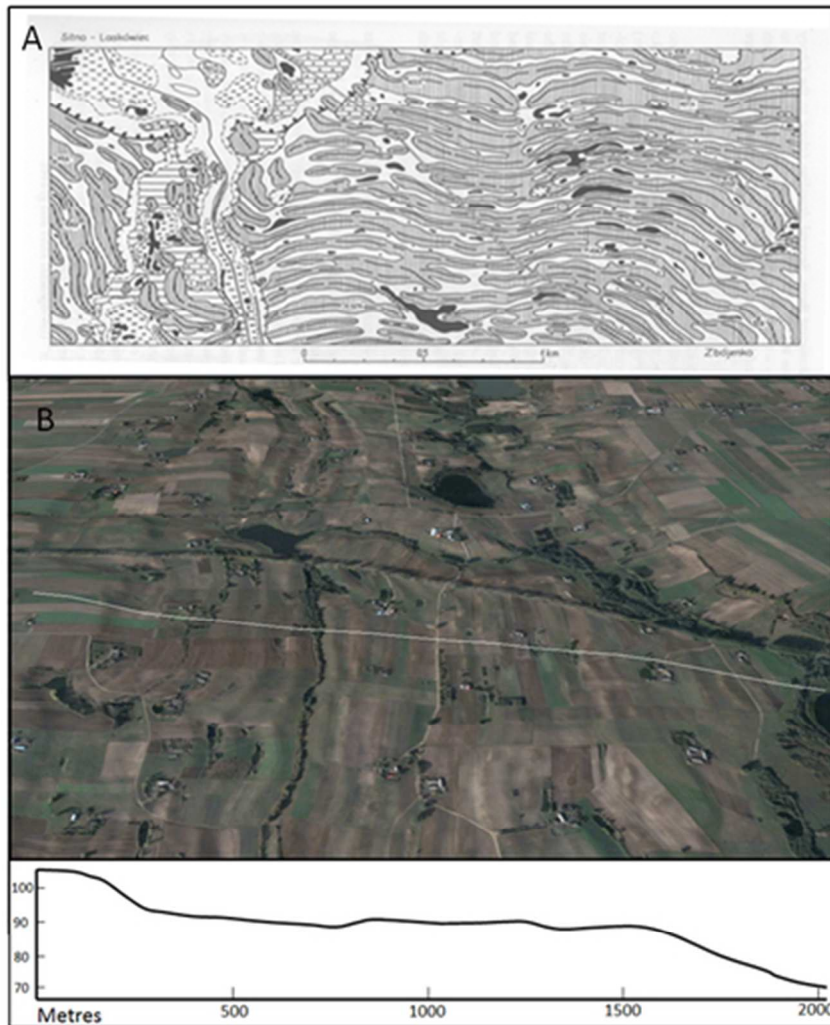


Figure 1. Polish glacial curvilineations (GCLs). A) Morphological map (by Olszewski, 2001) of some GCLs near Zbójenko in Poland, reproduced from Piotrowski and Wysota (2001). At the time of publication, the repeated parallel and sinuous ridges were interpreted as drumlins. B) A wider view of the landscape, 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 $53^{\circ} 01' 43''$ N; $19^{\circ} 04' 35''$ E, around 5 km NW of Zbójenko, Poland. Topographic and satellite data from Google Earth.

42x43mm (300 x 300 DPI)

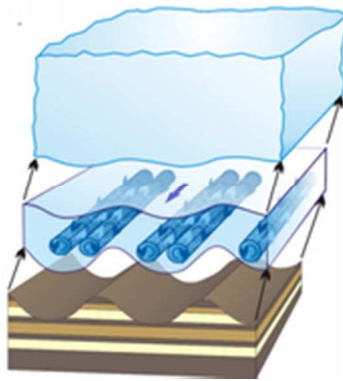


Figure 2. A mechanism of GCL formation whereby subglacial meltwater drainage events erode into pre-existing sediments (reproduced from Lesemann et al., 2010). In this hypothesis, erosion is concentrated as a consequence of the development of pairs of counter-rotating longitudinal vortices which cut the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

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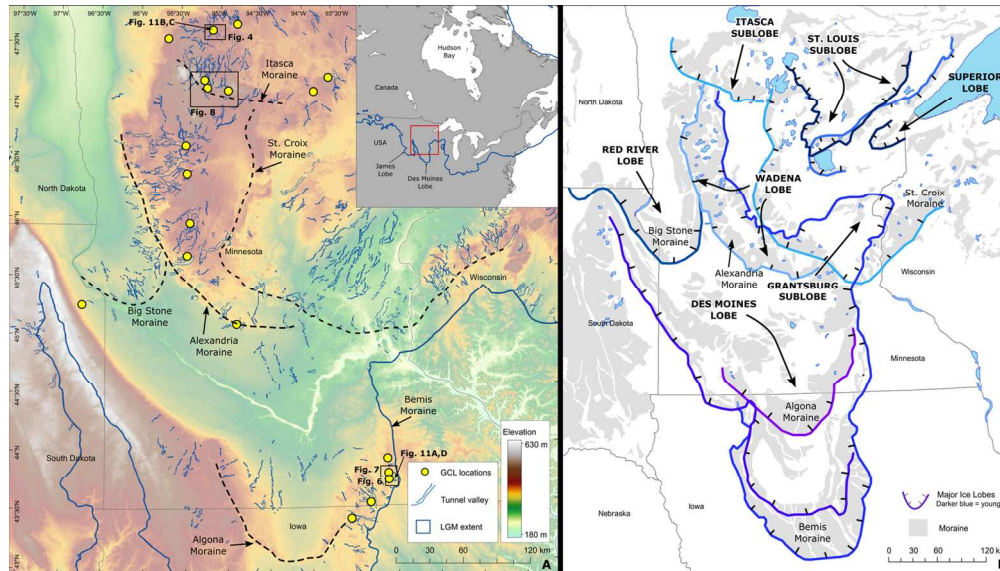


Figure 3. A. Distribution of GCL locations. A total of 871 ridge and trough sets were found within 19 different tunnel valleys. Subsequent figures in this paper are marked by black boxes. Southernmost ice extent of Last Glacial Maximum (LGM) is shown by thick blue line. Dashed black line indicates still-stand 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)

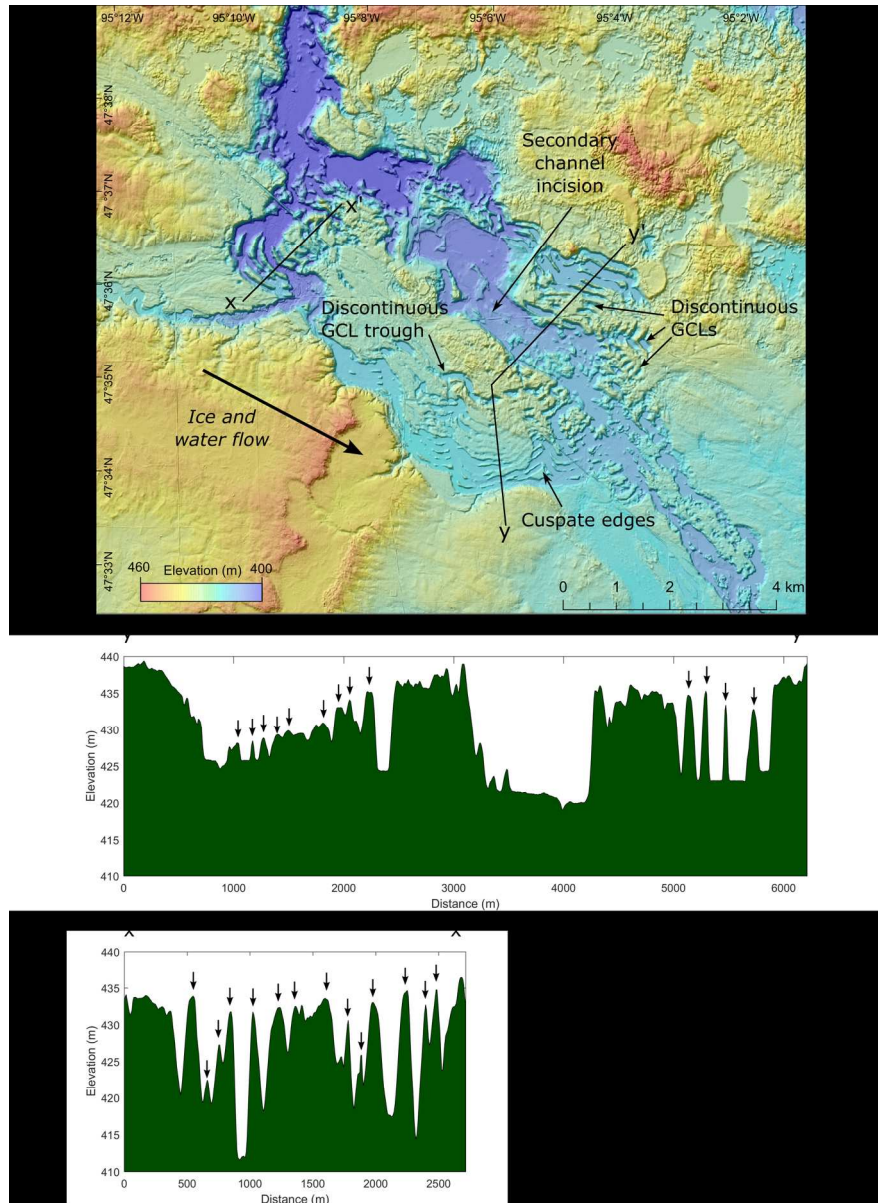


Figure 4. Within a prominent widening in a tunnel valley of two anabranches (water flow to the southeast) are numerous GCLs that parallel and mimic the shape of the tunnel valley edge. Topographic profiles (see method for source data and note high vertical exaggeration - x725) indicate the relief across the valley, with individual GCLs (arrows) 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.

156x213mm (300 x 300 DPI)

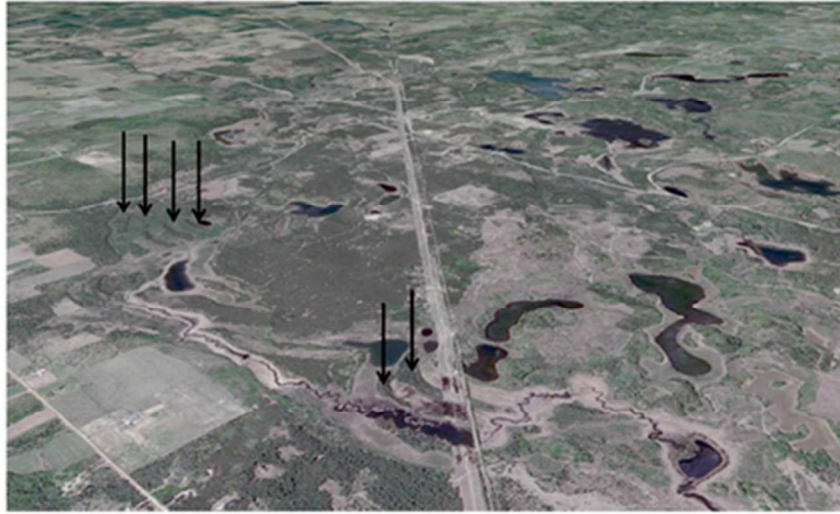


Figure 5. Obliquely-viewed satellite image draped on a DEM looking NW across the Pinewood GCLs of Figure 4 and centred on $47^{\circ} 36' N$; $95^{\circ} 06' W$. Image is 4.25 km in width. Overall this is a low relief landscape with the tunnel valley around 20 m deep and with individual GCLs (some arrowed)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

35x21mm (300 x 300 DPI)

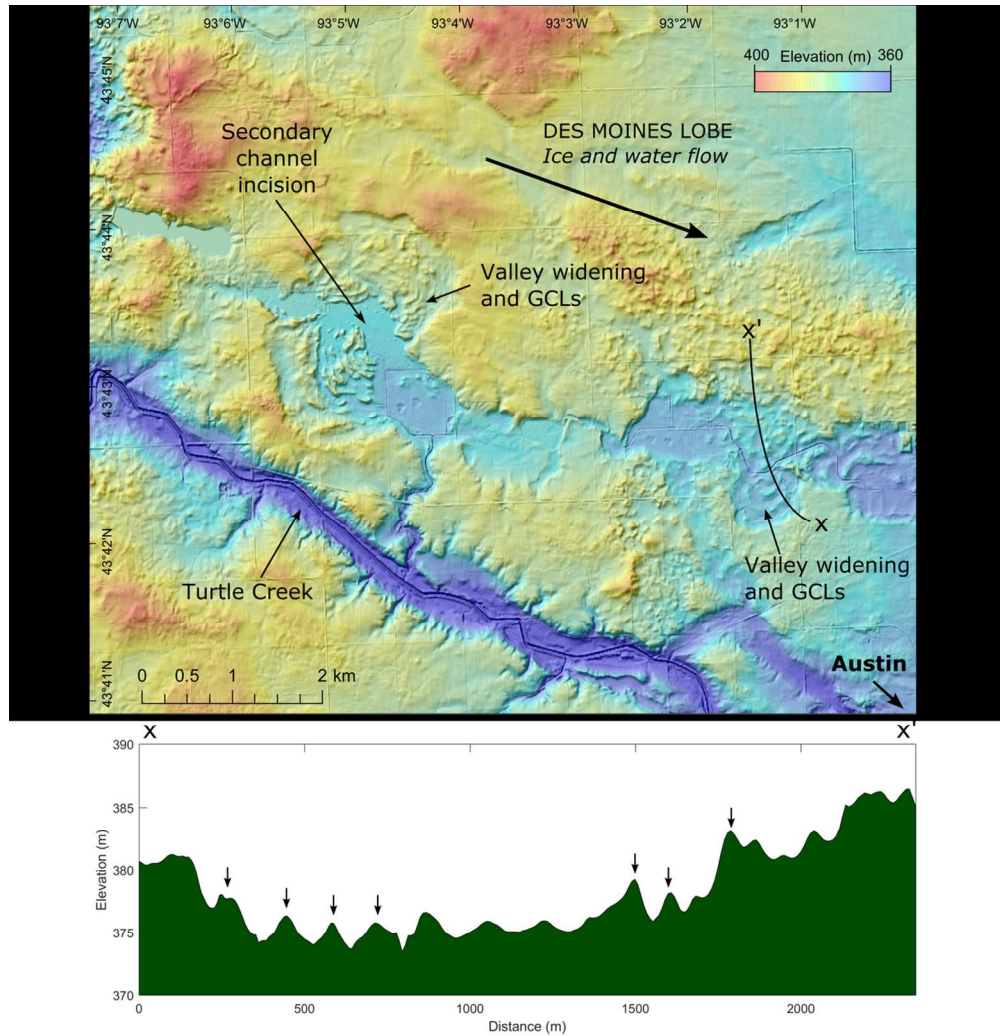


Figure 6. Two widenings in a tunnel valley (flow to the east) displaying GCLs that parallel the valley edge. The westernmost widening is especially bulbous and mirrored on both sides; atypical compared to valley widening in rivers where meander cuts alternate on valley sides. These GCLs are 10 km NW 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.

115x118mm (300 x 300 DPI)

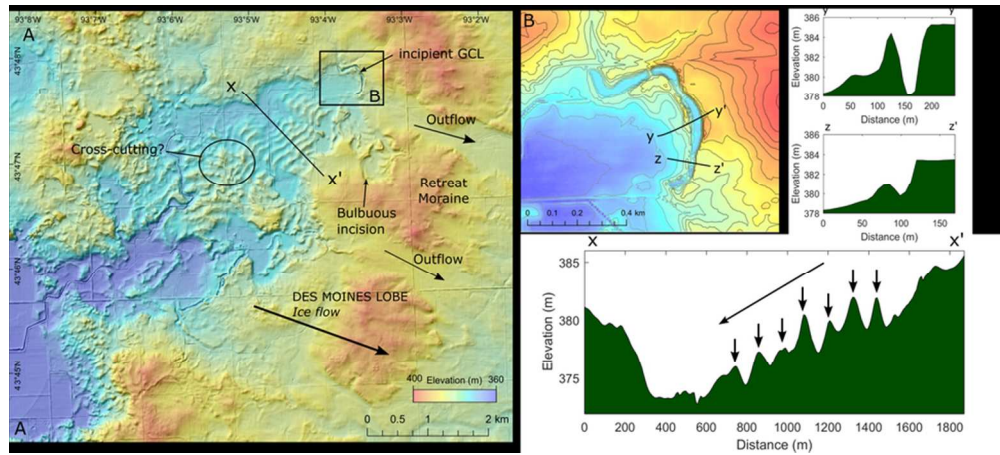


Figure 7. A) Ridge-trough systems in a depression that we interpret as GCLs that formed in a small subglacial lake or swamp, fed from the west by a tunnel valley and with at least two overflows to the east. Note that these GCLs do not align with the likely water flow-paths; they are not orientated towards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

82x36mm (300 x 300 DPI)

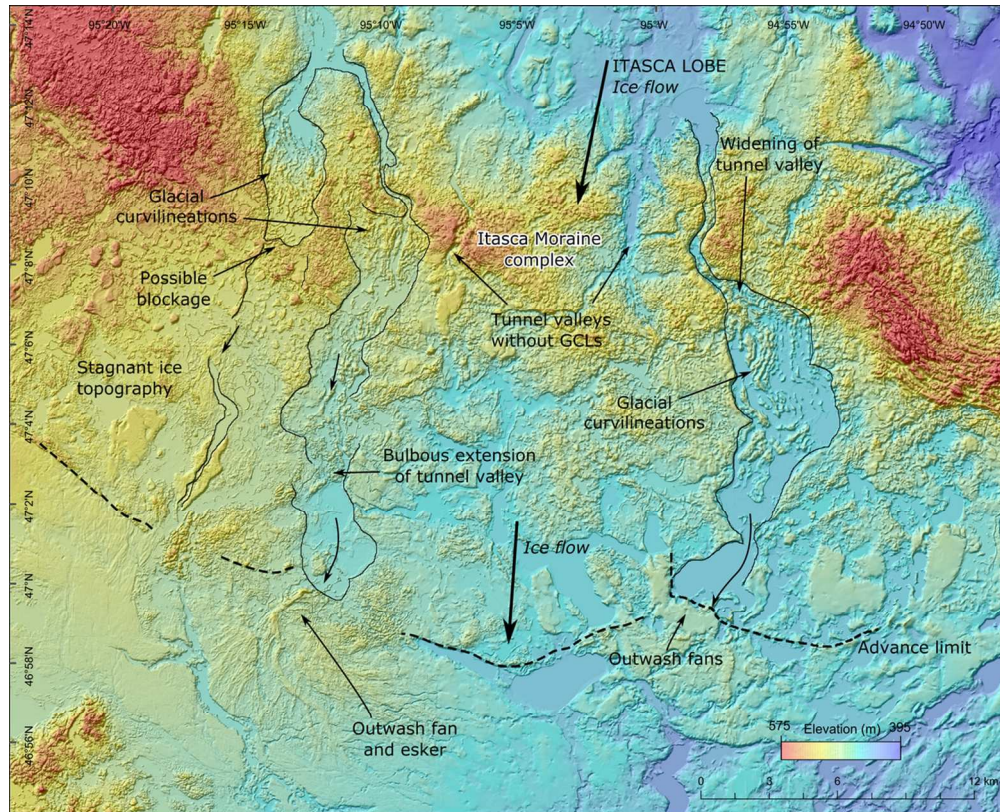


Figure 8. Three sets of GCLs located in tunnel valleys eroded into the higher ground which is part of the Itasca Moraine complex near Park Rapids, Minnesota. The eastern and central GCLs occupy prominent widenings of tunnel valleys downstream of the moraine complex and leading to outwash fans marking 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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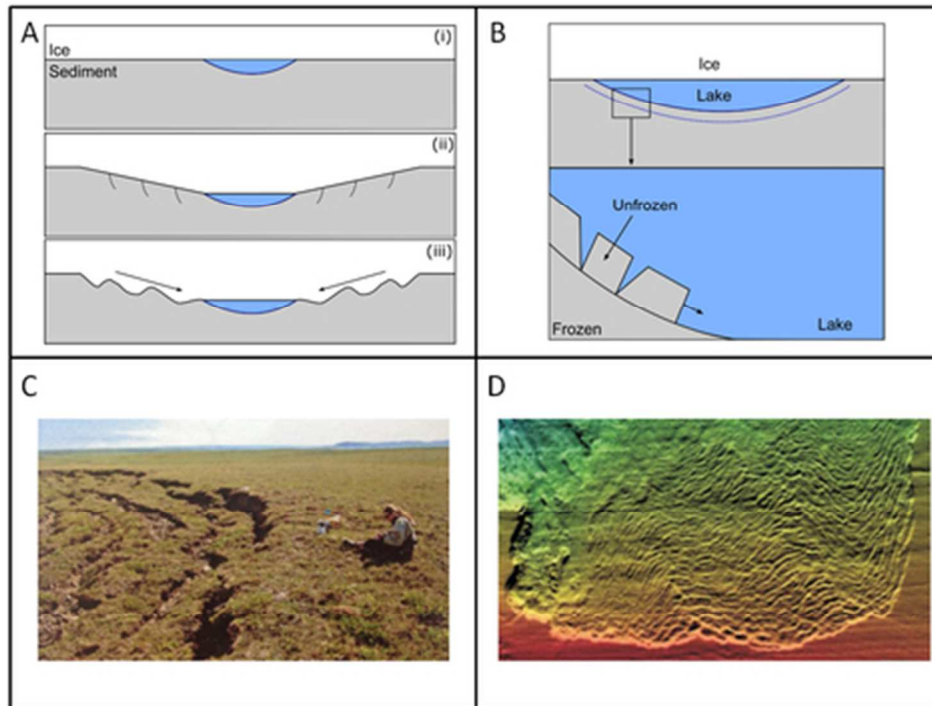


Figure 9. Formation of GCLs by subglacial bank and slope failure in tunnel valleys and subglacial lakes. A) Cartoon of a tunnel valley down-cutting into underlying sediments, steepening the adjacent slopes promoting tension cracks from which landslides occur. Slides could happen incrementally or en masse. 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 glacial 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)

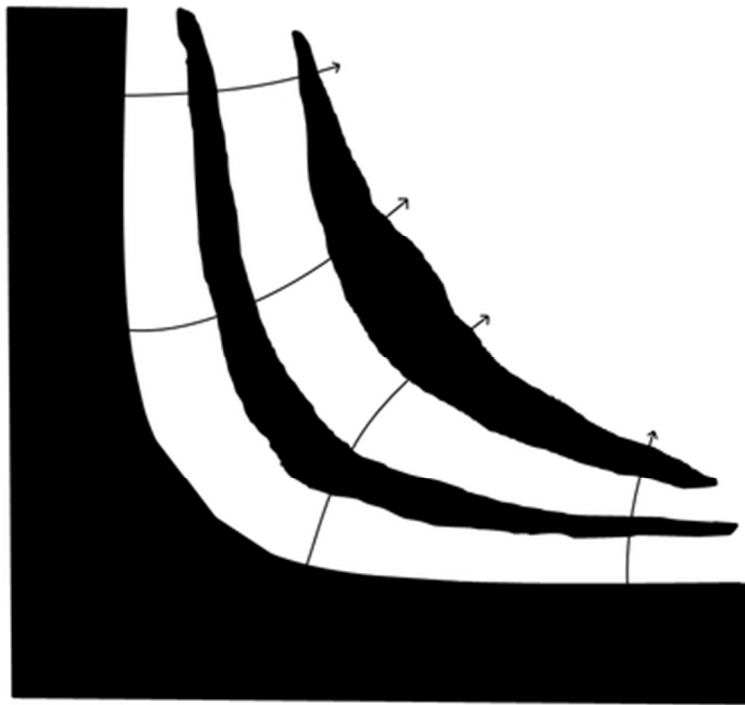


Figure 10. Cartoon representation of slope failure from a sharp concave bend in an escarpment. In this concave geometry, ridges that have slid further from the escarpment must be shorter in length because of convergence, and so to conserve mass they would bulge or bulk-up especially in the zone of maximum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

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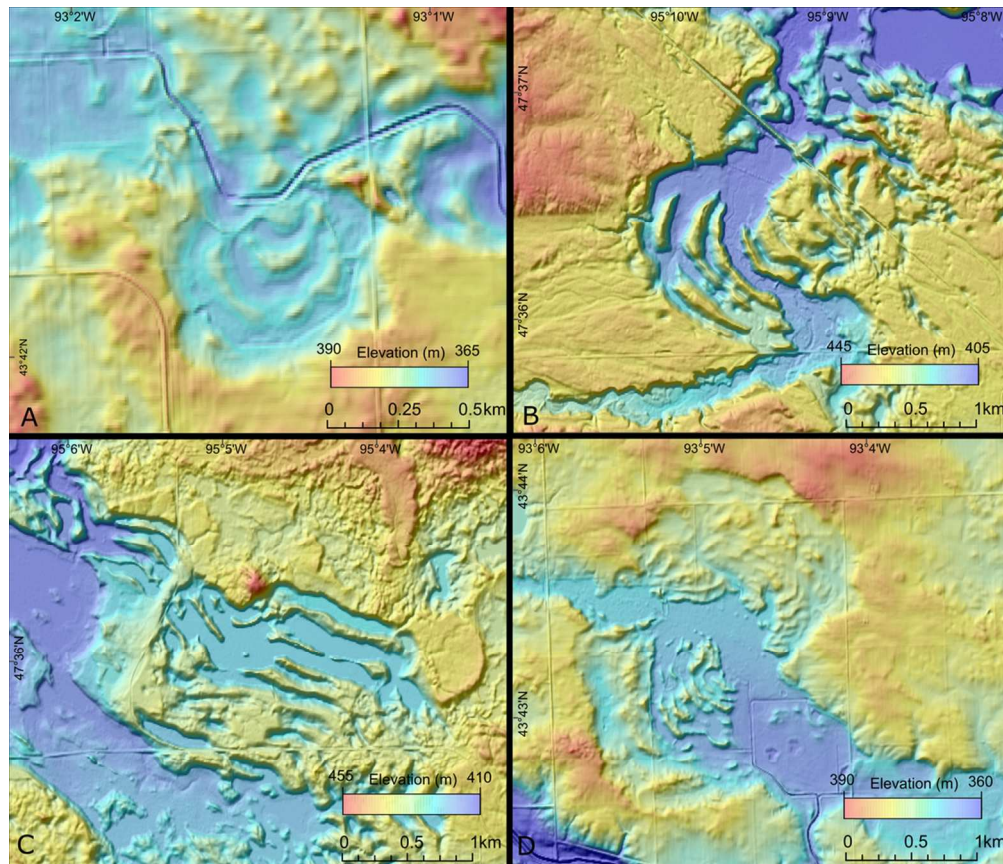


Figure 11. In numerous places ridge bulging is observed where the escarpment geometry and slope provide downhill convergent flow-paths for potential mass movements (cf. Fig. 10). This is consistent with the hypothesis of the ridge-trough systems resulting from slope failure. A) In the semi-circular embayment 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.

99x85mm (300 x 300 DPI)