Periglacial ramparted depressions (presumed ground ice features) in Nottinghamshire, UK

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Abstract: Ground ice mounds such as pingos, lithalsas (mineral palsas) and frost blisters, can be preserved in relict form as periglacial ramparted depressions (PRDs) in the sedimentary record. Recent investigation of cropmarks, visible in Google Earth imagery in Nottinghamshire, has pinpointed two particular locations (Bingham and Retford) where buried PRDs are preserved in the subsoil. They are found in association with polygonal patterned ground, a sign of former permafrost during at least some stage in their development in the Devensian period. We speculate on likely origins in terms of permafrost context (continuous or discontinuous) and whether ice was formed by segregation (lithalsa-like) or intrusion (pingo-like). Relict features reported in The Netherlands and Belgium may share similar origins. A probable periglacial chronology in the Late Devensian substage is suggested.

Ground ice mounds are distinctive domed features developed in present day periglacial terrain, typically taking the form of circular or oval pingos, palsas, lithalsas (mineral palsas) and seasonal frost blisters (Fig. 1). Ground ice that makes up their cores exists at a range of scales (Fig. 2). Frost heave mechanisms can take the form of intrusion (both expulsion and artesian), gravitational flow (ice wedges and vein ice), cryosuction (layered segregation ice) and capillary force (pore ice) (Ballantyne 2018). In relict form, mounds have usually undergone an inversion of relief, as transfer of material from the raised dome and collapsed ice-cores results in depressions surrounded by circular ramparts. Where debris has radially moved off the mound crest by gelifluction, there should be sedimentary evidence preserved in a rampart surrounding a central crater. Once formed, the crater is likely to be backfilled by mass movement or wind deflation so that the landform will be less easily recognised. The possibility of non-periglacial processes producing depressions (such as kettle holes, dolines, gas emission craters, bomb craters, quarry pits) needs to be addressed and eliminated from any enquiry. Co-existence of polygonal patterned ground with crop-marked PRDs is particularly helpful in reconstructing past context, since it demonstrates the presence of former continuous permafrost; relict lithalsas (by definition) however are more associated with discontinuous permafrost.

Pingos

The largest and most iconic of the ground ice mounds is the hydrostatic (or closed-system) pingo (Figs. 1A and 2A). Typically found in the Tuktoyaktuk Peninsula, Northwest Territories, Canada (Mackay 1998), such pingos are formed on floodplains by pressurised groundwater in enclosed water bodies (taliks) beneath drained lake basins in areas of continuous permafrost. Intrusion (or expulsion) ice forms where freezing water creates hydrostatic pressure within the talik, forcing pore water to be expelled from coarse-grained sands and gravels to form the dome-shaped ice core.

Hydraulic (or open-system) pingos have different origins, normally being raised by pressurised groundwater at slope-foot sites usually in areas of discontinuous permafrost (Figs. 1B and 2B). Open-system pingos in Svalbard (formerly Spitsbergen) and East Greenland however are located in continuous permafrost; with considerable backing relief and artesian pressure amplified by sub-glacial meltwater, they are twice as large as those found in the discontinuous zone of central Alaska and Yukon Territory (French 2007). There remains much uncertainty, however, about pingo genesis and development (Ballantyne 2018). Some appear to have insufficient relief to generate the necessary hydraulic lift with low-pressure springs (Yoshikawa 2013), while others can display both intrusion and segregation ice within the same structure (Hammock et al 2021). Gurney and Worsley (1997) have drawn attention to the fact that similar pingo structures can result from different initial conditions, including hydrostatic intrusion within lake bed taliks and melted buried ice masses, and hydraulic pressure from former river channels and independent spring points. The conventional hydrostatic/hydraulic dichotomy may not always apply. The notion of open/closed hybrids has recently been tested by Hornum et al (2020) who claim that talik intrusion and hydraulic head are not necessarily required to form pingos; basal permafrost aggradation alone might be sufficient to drive sub-permafrost groundwater pressure.

Palsas

Palsas are small- to medium-scale perennial peat-covered, ice-cored mounds, occurring almost anywhere in the discontinuous permafrost zone where favourable conditions permit (Pissart 2013; Ballantyne 2018). Deep peat cover (mires) is essential for formation, and limited snow cover ensures maximum winter cooling. They are clustered, 7–10 m in height, and can attain 30 m in diameter. Internally, they consist of domed segregation ice. In the decay phase, removal of the insulating peat layer exposes the core ice to melting, and eventual collapse leaves little or no trace of its former presence. With no recognisable ramparts therefore, peat palsas have poor preservation potential in relict form.

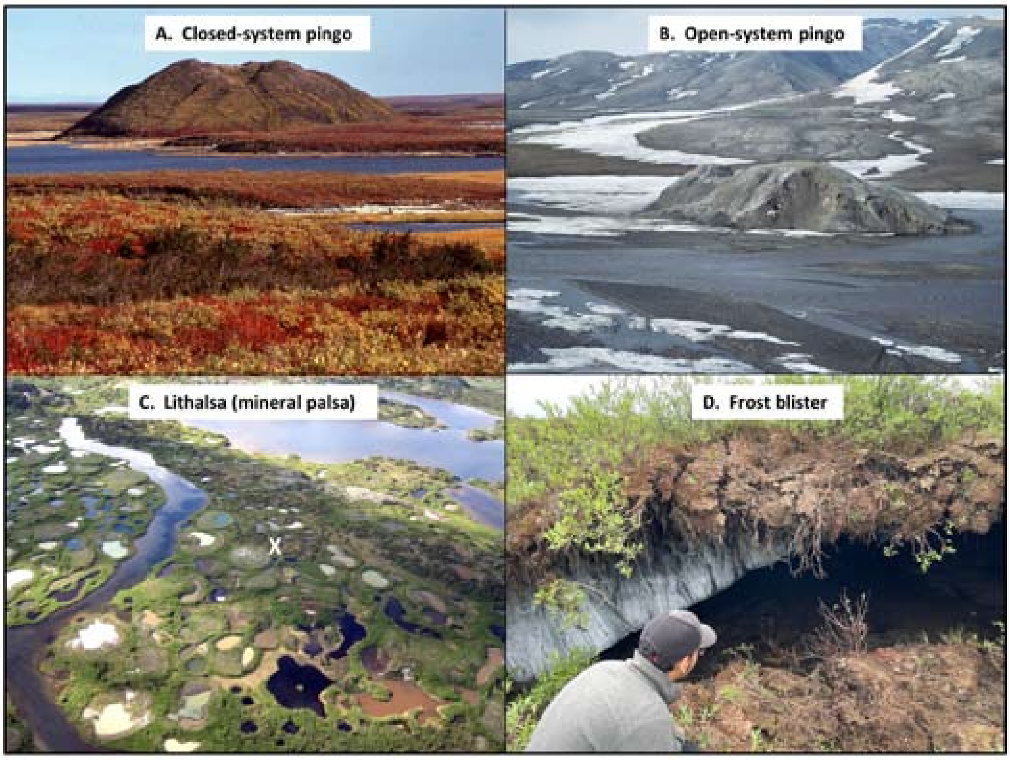


__Figure 1__. Four examples of present day ground ice mound formation:
(A) Ibyuk, Tuktoyaktuk, NWT (August 1990), height 49 m (highest known in Canada), width 300 m (photo courtesy of Julian Murton); (B) Riverbed pingo, Adventdalen, Svalbard (1991), height 12 m, width 140–200 m one of several inland pingos maintained by spring-fed sub-glacial groundwater (Yoshikawa 2013) (copyright with permission from John Wiley and Sons); (C) The 'BGR' permafrost mound (X), Northern Quebec lithalsa field (July 2004), height 3.4 m, width 50 m (Calmels et al 2008) (copyright with permission from Elsevier); (D) Frost blister, Inuvik-Tuktoyaktuk Highway (October 2021) (photo courtesy of Aurora Research Institute, Aurora College, Inuvik, NWT).

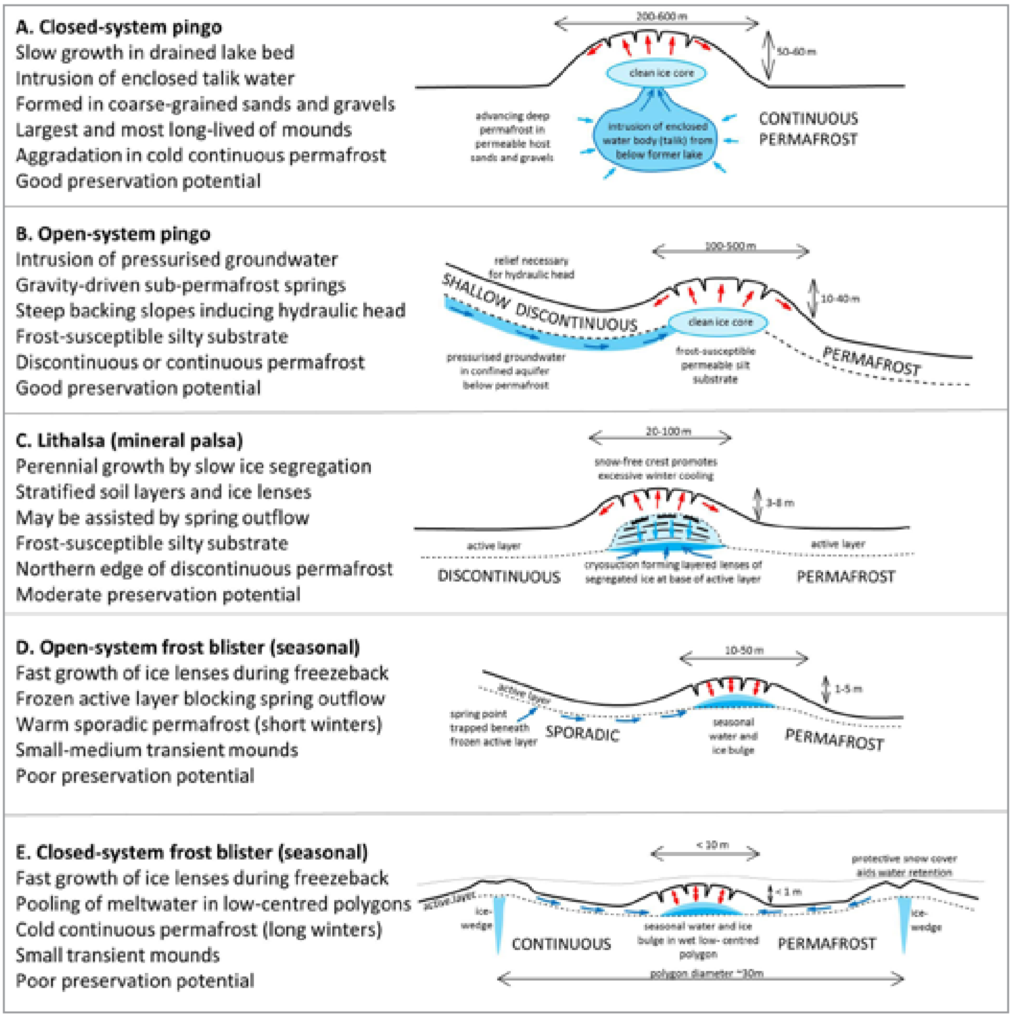


__Figure 2__. Mechanisms for ground ice mound formation, adapted from (A) Mackay (1998), (B) Ballantyne (2018), (C) Calmels et al (2008), (D) Van Everdingen (1982) and (E) Morse and Burn (2014).

Lithalsas

Lithalsas (or mineral palsas) are distinct from peat palsas. They are confined to zones of discontinuous permafrost, such as northern Sweden and sub-arctic North America (Calmels et al 2008; Wolfe et al 2014). A characteristic feature of lithalsas is the internal layering of dirty ice lenses and sediment (segregation ice) running approximately parallel to the ground surface, and capable of raising circular ground-ice mounds up to 8 m high and 100 m in diameter (Figs. 1C and 2C). Segregated ice layers are generally thicker towards the top, suggesting downward aggradation within the active layer. During freezing, water lower in the unfrozen soil profile is drawn upwards by capillary force (cryosuction) towards the freezing front. Perennial lithalsas grow slowly, forming dehydrated and compacted mounds that can persist for many years. Unlike peat palsas, they decay and collapse with well-defined ramparts and are thus better preserved in relict form (Pissart 2002).

Numerous lithalsa mounds, craters and ring-walled ponds occur in northern Quebec at high density (Calmels et al 2008) (Fig. 1C). Typically, they form in frost-susceptible silty soils, capillary attraction occurring best in a silty matrix compared to coarse sand or clay (Pissart 2002). Continued cryosuction can only occur if there is repeated groundwater discharge, such as at a spring or seep line, feeding the structure, year on year. Lithalsas are considerably less common than peat palsas, and this is thought to reflect very specific initial conditions, namely, a peat-free frost-susceptible silty substrate, cryosuction fed by repeated groundwater flow, and narrow temperature constraints including mean annual temperatures of between –4°C and –6°C and summer maximum temperatures of between 8°C and 11°C (Pissart 2013). Lithalsas occur in clustered fields, often in overlapping networks (Fig. 1C); by contrast, pingos are typically more isolated or found in small groups as double or triple sets.

Seasonal frost mounds (frost blisters)

Compared to perennial pingos and lithalsas, seasonal frost mounds (or frost blisters) are smaller in scale and only short-lived (Figs. 1D and 2D, E). They form by fast ice lens formation during freezeback where water is temporarily trapped in the active layer, either by a blocked spring point in discontinuous permafrost (van Everdingen 1982), or by snowmelt accumulating within the low centres of ice-wedge polygons in continuous permafrost (Morse and Burn 2014). Frost blisters in North Fork Pass and Wolf Creek (Yukon, Canada) can collapse and vanish entirely by the end of summer, though some can persist for up to 10 years; transient ice lenses are vulnerable to summer warmth and thus poorly preserved, while segregated ice, more deeply located in lithalsas, is better preserved (Toni Lewkowicz, *pers. comm.*).

Periglacial ramparted depressions in the British Isles

The British Isles retain unusually good evidence of relict ramparted depressions, comparable to similar features identified in continental Western Europe (Fig. 3). The distribution of pingo-like remnants is spatially restricted; none for example have been located in France (Andrieux et al 2016). Lithalsa remnants are also very confined geographically, reflecting narrow palaeoclimatic limits, restricted to the northern boundary of the discontinuous permafrost zone.

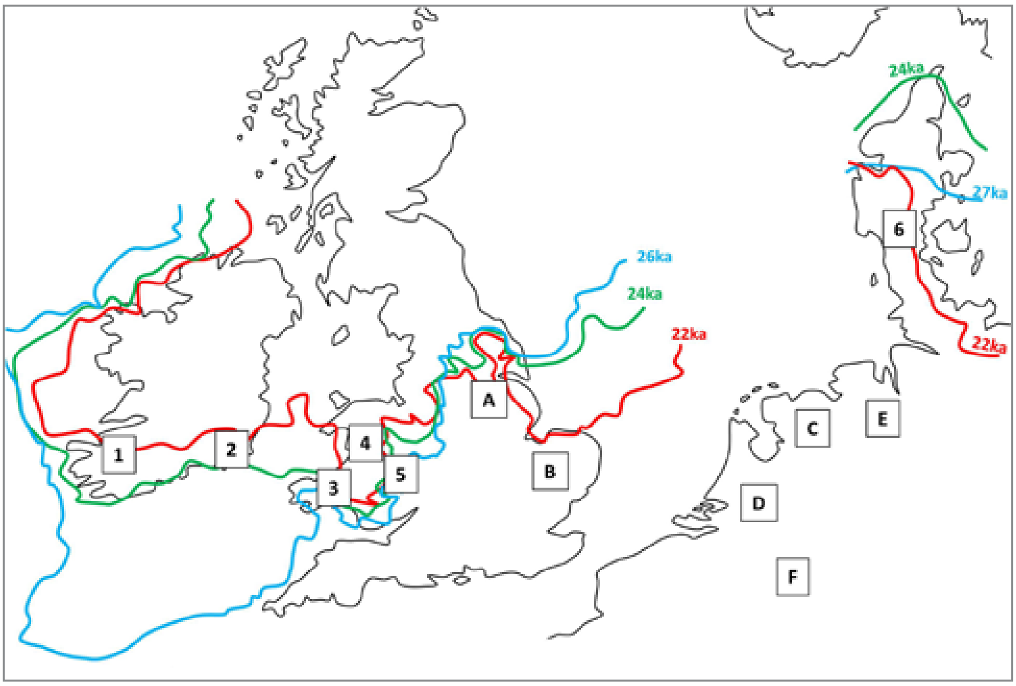
Presumed PRDs have been described from southern Ireland and SW Wales (Ballantyne and Harris 1994 and references therein) at one time regarded as pingo remnants. More recent re-evaluation however suggests that most, if not all, such depressions would now be regarded as remnant lithalsas (Yoshikawa 2013; Ballantyne 2018). Initial views of PRDs in coastal south-west Wales and Hautes Fagnes (Ardennes), for example, have been comprehensively revised (Pissart 2002; Demoulin et al 2018) in favour of a lithalsa model. In addition, Gurney et al (2010) and Ross et al (2020), using LiDAR and geophysical tomography to examine depressions in cratered glacial moraine within the limit of the Last Glacial Maximum (LGM)/Late Devensian, confirmed ice-stagnation kettle holes as an alternative explanation. In Shropshire, Gurney and Worsley (1996) identified PRDs as relict lithalsas (rather than open-system pingo scars), distinguishable from nearby kettle holes by clear ramparts and overlapping clusters.

Some of the most impressive examples of former ground ice mounds in England are found in Norfolk (East Walton, Thompson Common and Beachamwell) (Sparks et al 1972; West 2015). Originally described as ‘presumed ground ice depressions’, these craters were regarded as untypically pingoid, being both too small and too closely packed, though clearly spring-fed in the manner of hydraulic open-system pingos. Further analyses by Clay (2015) and Bromfield (2017) have pointed to possible lithalsa origins. Continued work by the Norfolk Wildlife Trust favours a more polygenetic approach, including possible doline collapse in some cases (Lorna Linch, Tim Holt-Wilson and Gilbert Addison, *pers. comms.*)

Periglacial ramparted depressions in Nottinghamshire

Google Earth imagery from summer 2018 has revealed well-differentiated soil variations and cropmarks showing widespread polygonised river terraces and bedrock throughout the East Midlands. These are thought to be indicative of former continuous permafrost mostly of Late Devensian age (30–11 ka BP) or earlier. Results are outlined in Baker et al (2021) and Baker (2022), and can be viewed in Google Earth Pro at https://tinyurl.com/groundpatterning or via IceAgeInsights.org. Figure 4 shows the location of the sites referred to in the Bingham area and River Idle catchment.

Figure 3. *Position of ramparted depressions in relation to Last Glacial Maximum (GS-2) ice limits. Most credible ice limits at 26 ka, 24 ka and 22 ka based on Hughes et al (2015) and Clark et al (2022). Numbered sites within or near the LGM boundary: (1, 2) southern Ireland, (3) SW Wales, (4) central Wales and Shropshire, (5) Herefordshire, (6) S Jutland. Lettered sites beyond the LGM boundary: (A) Nottinghamshire (this study), (B) Norfolk, (C, D) N and S Netherlands, (E) NW Germany, (F) Ardennes.*



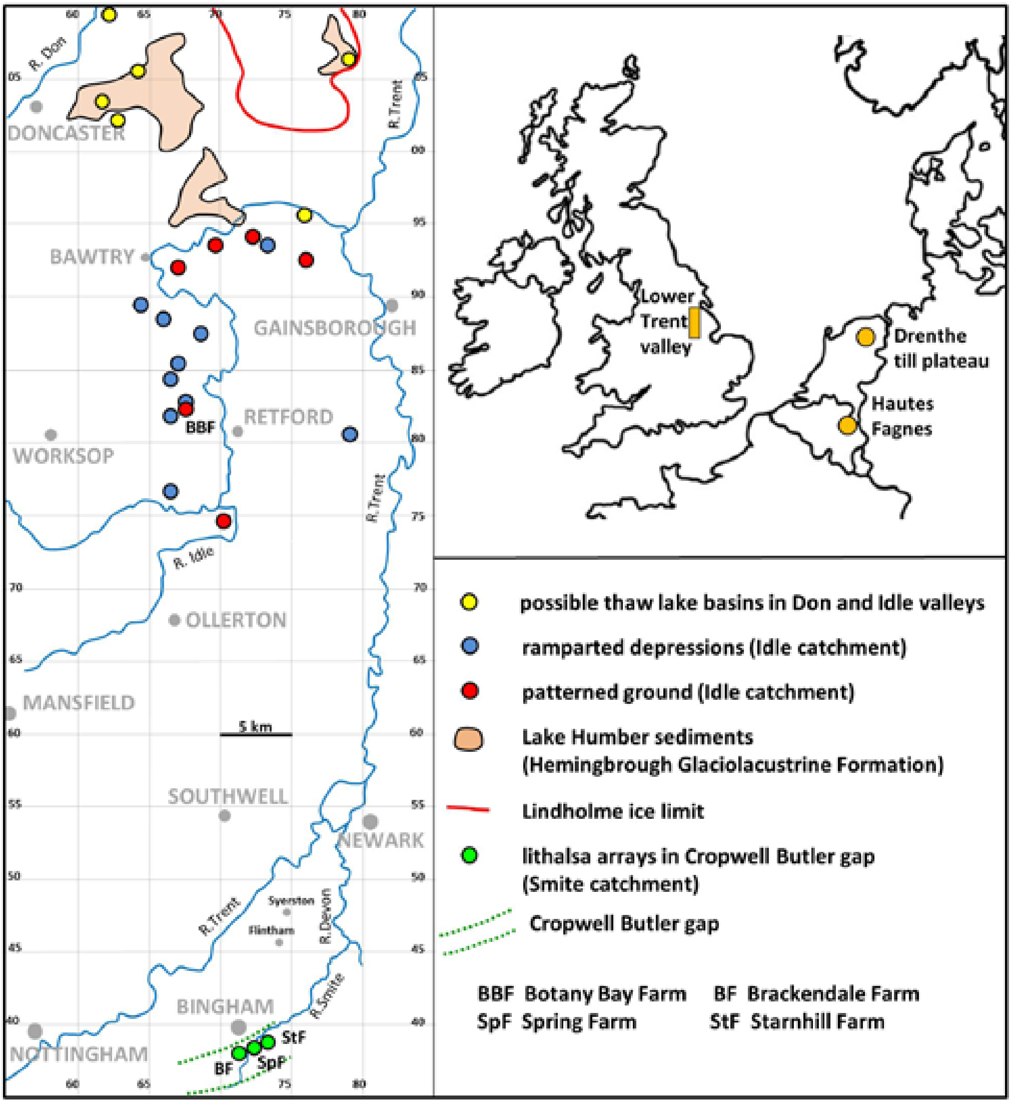


Figure 4. *Location of sites mentioned in the text. Ramparted depressions and patterned ground in the River Idle catchment derived from Google Earth imagery (July 2015). Thaw lake basins after Gaunt (1994). Outcrop of Lake Humber sediments from BGS online DiGimap. Lindholme ice limit after Friend et al (2016).*

1. The Bingham area (SK 700 390)

In the Smite-Devon catchment, south and south-east of Bingham (Figs. 5 and 6), polygonal and cellular patterned ground is mainly confined to outcrops of well-cemented dolomitic siltstone and sandstone known locally as 'skerry', interbedded with mudstones of the Edwalton Member of the Sidmouth Mudstone Formation, Mercia Mudstone Group (MMG) (Howard et al 2008). Polygons give way eastwards to arrays of small ramparted depressions (Fig. 6). This confined area (about 5 km by 2 km) consists of a gently sloping, largely undissected dipslope of skerry, forming the north side of the Cropwell Butler gap (Fig. 4), a low col cutting through the Trent-Smite interfluve at about 45 m OD (Fig. 5). Bingham lies about 60 km west of the LGM ice limit in Lincolnshire, and 65 km east of the limit in Staffordshire.

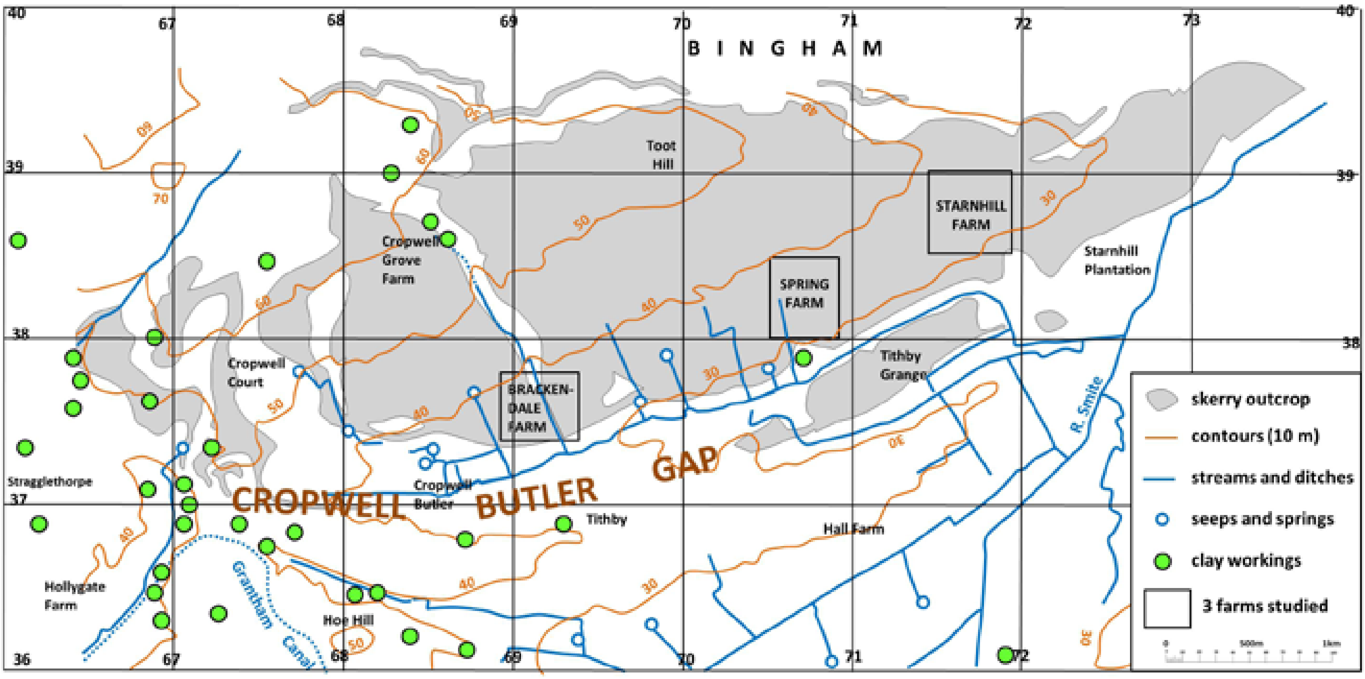


Figure 5. Bingham dipslope: relief, drainage and quarry pits. Clay workings based on Charsley et al (1990) and 25-inch OS map sheet XLIII (1915). Springs and seep point locations based on 6-inch OS sheets XLIII SE (1920) and SW (1950). Skerry outcrop reproduced from BGS DiGimap.

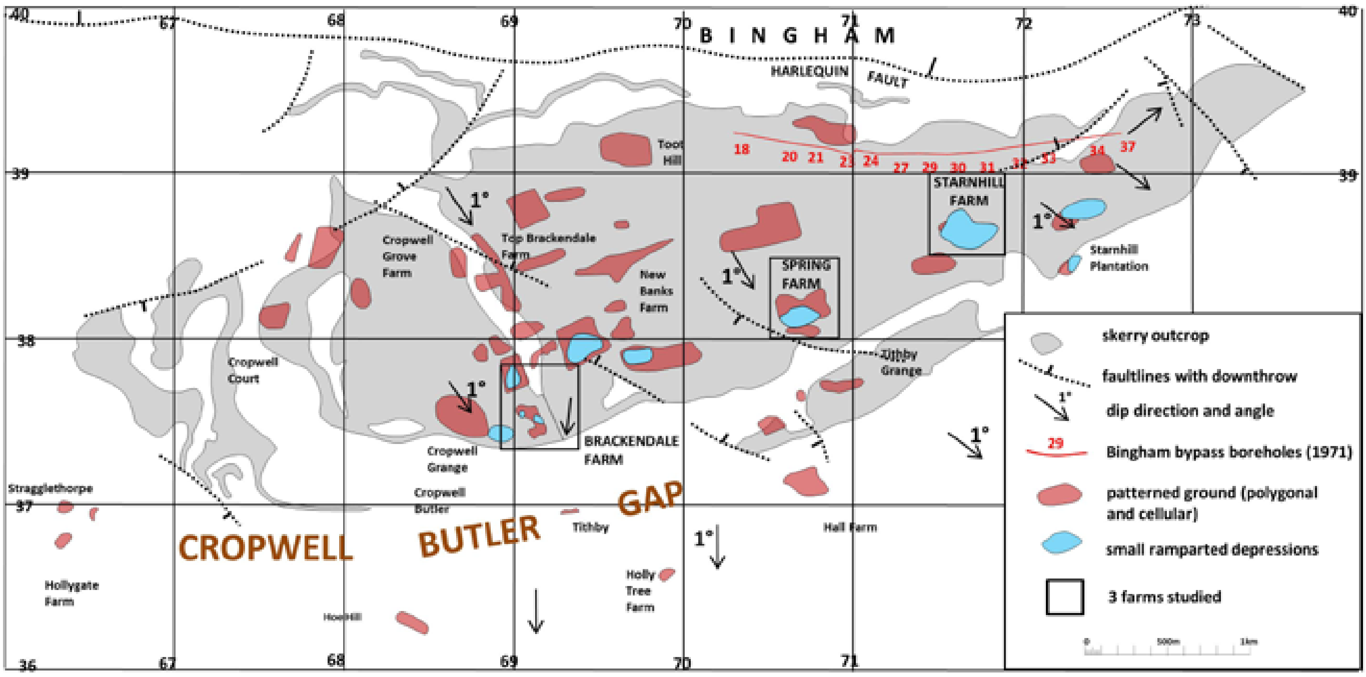


Figure 6. Bingham dipslope: distribution of skerry outcrop, faultlines, patterned ground and presumed lithalsa arrays. Geological data reproduced from BGS mapping (Lowe 1989a and 1989b) and BGS online core log records. Google Earth imagery obtained from 2010 and 2018 scans.

There are a number of possible non-periglacial explanations for depressions in this area. Figure 5 shows man-made depressions and pits mapped on the 1915 OS 25” revision of Nottinghamshire XLIII sheet (numbers 2–4, 6–8, and 10–12). Most of these coincide with Charsley et al’s (1990) map of clay workings, especially those in the vicinity of old brick and tile works. These are quite large, 30–90 m in diameter, and are widely scattered across mudstone outcrops, located in field corners or along field margins. They are thus easily distinguished from potential PRDs on the skerry outcrops. Historic England HERs (Historic Environment Records) confirm that both Stragglethorpe and Tithby (Fig. 5) were Starfish Bombing Decoy sites (HER 653/364 Sf30c and Q91a), but no surviving bomb craters have been reported from the area (Geoff Ashton, *pers. comm.*). Locally, the MMG (Branscombe Mudstone and Sidmouth Mudstone formations) are notably gypsiferous and vulnerable to gypsum dissolution. Triassic mudstones of the MMG however lack the open hydrological geometry of the Permian formations that is responsible for doline subsidence in North Yorkshire (Anthony Cooper, *pers. comm.*) Localised doline collapse is therefore considered unlikely.

Hydrogeological context

Thin, repeating bands of skerries are commonly found throughout the Sidmouth Mudstone Formation. They consist of hardened greenish-grey dolomitic siltstones or fine sandstones, which are permeable and (like Cretaceous chalk) particularly frost-susceptible. Skerries were first described by Lamplugh et al (1908) and Lamplugh and Gibson (1910) who recognised the importance of differential resistance and gentle structural dip contributing to broad shallow troughs and low ridges around Bingham. In the BGS revision, Lowe (1989a, 1989b) noted their complex outcrop patterns reflecting a multiplicity of horizons and some minor faulting (increasing westwards towards Cotgrave and Radcliffe).

Hobbs et al (2002) comment that skerries are highly permeable and act as pathways for groundwater, generating spring lines. Field inspection confirms that a few small seeps still exist on the dipslope (Figs. 5 and 7) particularly where skerries are faulted against adjacent mudstone. There is no agreement on the number and thickness of skerry horizons; many are < 0.3 m thick (Horton et al 2017), some occasionally 1–3 m thick. Howard et al (2009) contrast a typical 0.5 m skerry at Tythby Grange with an unusually thick 4 m horizon at depth in the Cropwell Bridge borehole.

The Bingham skerry outcrop is mapped mainly as a broad single unit (Figs. 5 and 6) where surface slope is very close to the value of regional dip (about 1° to south-east). In fact, the outcrop consists of many thin alternations of siltstones as shown along a proposed bypass road in 1971 (BGS online core log records). About 7 bands are confirmed in 10 m of mudstone, each approximately 1.5 m apart, dipping gently south-eastwards (from 40 m OD to about 25 m OD) towards the River Smite. There is insufficient backing relief (15 m) to have generated hydraulic pressures necessary to maintain spring outflow for intrusion ice in open system pingos (Colin Ballantyne, *pers. comm.*), but slow upwelling of low-pressure groundwater could have maintained small-scale intrusion and ice segregation.

***Figure** 7. Faulted skerry ledge generating groundwater seep at Brackendale Farm (SK 699 379) (March 2023). This, and another at Spring Farm (SK 705 378), located where skerry ledges are faulted against mudstone in minor NW–SE faults at about 30 m OD.*

The periglacial land surface

Figure 6 shows that the Bingham skerry outcrop (7 km²) is polygonised over about 25% of its surface. Another extensive area of skerry (12 km²) outcrops around Flintham and Syerston (Fig. 4), being a continuation of the Bingham skerry down-faulted 40 m to the north along the Harlequin Fault (Howard et al 2009). Only 2% of the Flintham surface is polygonised, displaying fewer and poorly-preserved patterns, certainly nothing like the density and clarity of the impressive network at Bingham.

Google Earth imagery was obtained largely from June 2018, with some additional coverage detected in January 2010. At highest resolution, enhanced images were examined closely for all cropmarks showing 2- or 3-way angular junctions to determine the polygonal network. Surviving patterned ground at Brackendale Farm and Spring Farm (Fig. 8) reveals polygons of around 9 m diameter (5–20 m) grading into cellular patterns in places. The geometry is mainly one of regular, low-centred, secondary, hexagonal polygons, indicative of mature ice-wedge thermal contraction in continuous permafrost.

By contrast, there are many small circular or oval ramparted depressions detected at high density across Brackendale Farm, Spring Farm, and Starnhill Farm (Figs. 8 and 9). LiDAR 1 m DTM hillshade imagery (Environment Agency 2020) suggests that micro-relief probably does not exceed 1 m in amplitude; visible cropmarks are thought to reveal subsoil corrugations buried by modern hillwash beneath the plough layer.

The largest of such features achieve diameters of 15–18 m; many smaller, clustered and overlapping craters are also visible (with 2–15 m diameters, mean 6.7 m) (Fig. 8). Estimated densities of PRDs range from 29/ha (Spring Farm) to 38/ha (Starnhill Farm) and 48/ha (Brackendale Farm). They are thought to be remnants of siltstone-based lithalsa mounds built principally by ice segregation, but also amplified by low-pressure intrusion from spring points located at faulted skerry outcrops. They appear to outnumber and replace polygons, increasingly so eastwards; a few are located within polygon centres. In addition, a number of crenulated lines are visible, thought to be hard skerry ledges running strike-parallel and cryoturbated between weaker mudstone layers (Fig. 9).

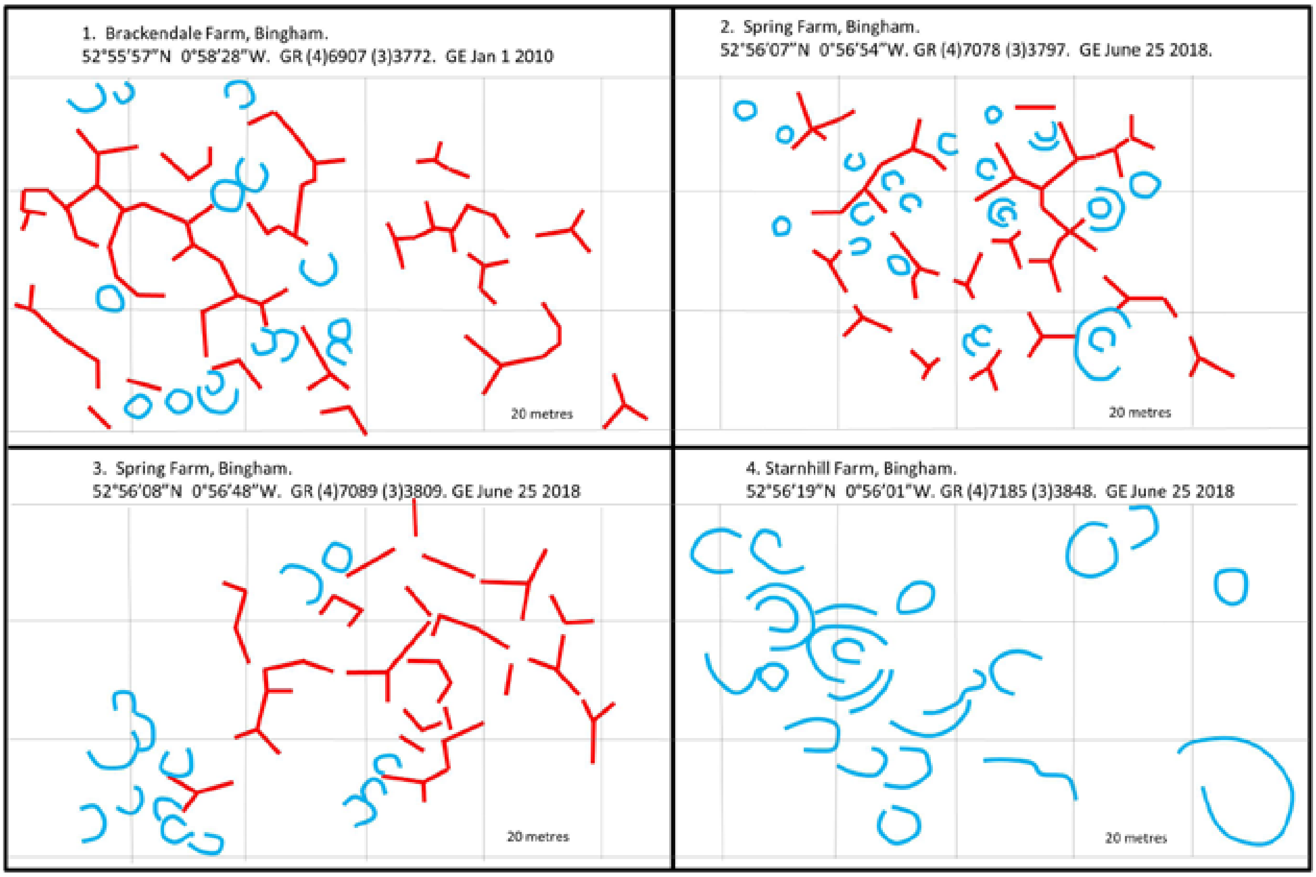


Figure 8*. Superimposition of presumed lithalsa scars over remnant polygons on the Bingham dipslope. All farms have a substrate of dolomitic siltstone. Small circular ramparted depressions (blue) appear to postdate and replace low-centred polygons (red), increasing in size eastwards (diameters 2–15 m). Thus, fragmented polygons at Brackendale Farm and Spring Farm lose definition eastwards, and little or no polygonal evidence survives at Starnhill Farm.*

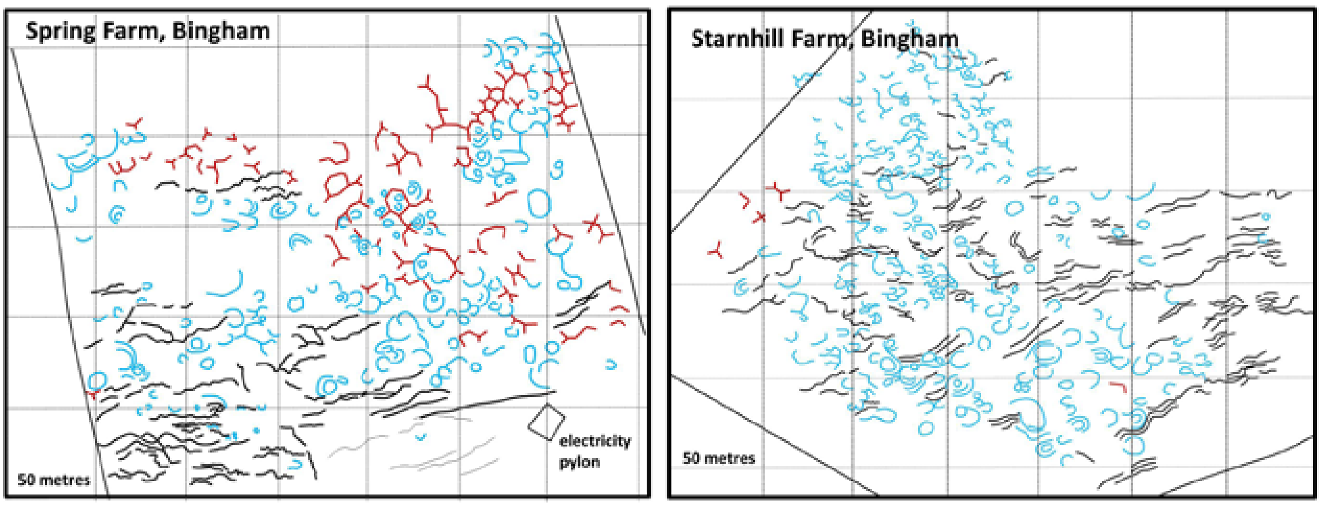


Figure 9*. Distribution of polygonal fragments (red) and presumed lithalsa scars (blue) on the Bingham dipslope at Spring Farm and Starnhill Farm, as interpreted from cropmarks in Google Earth images June 25 2018. Each image covers about 9 ha. Crenulated black lines are thought to be cryoturbated skerry ledges.*

Interpretation of the Google Earth imagery

The co-existence of polygons and presumed lithalsa scars on the Bingham dipslope is a significant and singular finding in the East Midlands; no other comparable examples have been located on Mercia Mudstone Group skerry outcrops. A combination of favourable conditions has preserved these superficial structures at Bingham, enabling a relative sequence of periglacial events to be reconstructed. Multiple overprinting has been observed in Norfolk, but there are no decipherable intersections of patterned ground and PRDs comparable to that seen in Bingham (Gilbert Addison, *pers. comm*).

The density of small PRDs is between 29 and 48/ha, equivalent to 2900–4800/km². Such concentrations are extremely high, some three orders of magnitude greater than Norfolk equivalents. Original field estimates at Walton Common (Sparks et al 1972) suggested densities of only 13–80/km², but analysis of Google Earth imagery of their sites reveals additional subsurface corrugation raising densities to as much as 130–700/km²; even so, these are still considerably less than those at Bingham. High concentrations of periglacial mounds can reach about 1700/km² in seasonal frost mounds in present day outer Mackenzie Delta, NWT (Morse and Burn 2014). Dimensions of these frost blisters are comparable (mean diameter 6.1 m, range 3.7–8.5 m); mounds are contained within low-centred polygons where meltwater accumulates and refreezes (Fig. 2). This suggests that the excessive numbers of small features observed at Bingham may have originated, in an earlier stage of a permafrost cycle, as transient frost blisters, with snowmelt accumulating within the many low-centred polygons. Only later in the cycle did incipient mounds evolve into more substantial lithalsas, within shallow discontinuous permafrost, constructed by ice segregation and low-pressure ice intrusion, before eventual collapse and decay. A sequence of periglacial processes on frost-susceptible skerry siltstone is envisaged thus:

1. A network of polygons developed in continuous permafrost, with skerry ledge cryoturbation.
2. Numerous incipient small seasonal frost blisters, forming foci within the low centres of polygons.
3. Small lithalsas growing by ice segregation at these foci.
4. Larger lithalsas swollen by open-system ice intrusion at faulted skerry ledge spring points.
5. A final decay phase, with many overlapping ring-walled craters marking the position of former mounds.

Possible equivalents in Belgium and The Netherlands

In terms of time of formation, the PRDs in the Trent valley should be compared, not with PRDs in southern Ireland or SW Wales (inside the Last Glacial Maximum limit) but with equivalent features in Norfolk, The Netherlands and Belgium (beyond the limit) (Fig. 3). The most significant evidence for lithalsa development in mainland Europe comes from the Hautes Fagnes district of the Ardennes (Pissart 2003; Demoulin et al 2018) (Fig. 4). Features there are both larger (30–90 m diameters, and 10 m ramparts) and higher (500 m OD) than those at Bingham. Dating by pollen stratigraphy, C14 and tephrochronology confirms formation in the Younger Dryas (12,900–11,700 years BP); formation by ice segregation within discontinuous permafrost, rather than ice intrusion, is thus implied. Demoulin et al (2018) identify a two-phased process in which the second half of the Younger Dryas (about 500 years), being wetter, favoured ice segregation, rather than the earlier colder and drier half. Their analysis also confirms the narrow palaeoclimatic limits which dictate that lithalsas are comparatively rare phenomena, confined to the northern boundary of the former discontinuous permafrost zone. Andrieux et al (2016) comment that PRDs in The Netherlands could have originated as either lithalsas or open-system pingos. Preliminary analysis of 2018 Google Earth imagery suggests that relict lithalsa fields might exist at some Dutch sites (Erm, Orvette, Sleen, Vlierendijk, Wilhelmsoord) on the Drenthe till plateau (Fig. 4) where dense clusters of small ramparted depressions are found in association with polygonal patterned ground. Similar evidence exists at Baarleheide and Ginhoven in The Campine (Belgium).

2. Botany Bay Farm, Retford (SK 680 824)

Google Earth imagery of the River Idle catchment is not as good as that within the Middle and Lower Trent valley. July 2015 images provide the best available coverage; our mapping reveals a scatter of ramparted depressions (Fig. 4). Gaunt (1994) recognised large shallow (non-rimmed) depressions in the Don and Lower Trent valleys interpreted as sunken thermokarstic basins or alases (Ballantyne and Harris 1994). In the Idle valley and Humberhead Levels, many cryoturbated horizons, ventifacts and ice-wedge casts have been reported, but patterned ground (largely buried) has rarely been seen, and pingo-like structures have gone unrecognised. Anomalous valley-floor mounds do exist locally, and have been interpreted variously as minor bedrock structures such as cambering or valley-bulging (Smith et al 1973) or as superficial levées or blown sand (Gaunt 1994). However, many medium-sized ramparted annular features do exist (mainly preserved on Chester Formation sandstone or on the Idle First Terrace) that might qualify as PRDs (Fig. 10). A few sites relate to skerry-like siltstones within the Clarborough Member (Mercia Mudstone Group). Polygonal patterned ground survives in a few localities (Fig. 4). Unique among this group is a well-defined PRD cluster with associated patterned ground at Botany Bay Farm, near Retford.

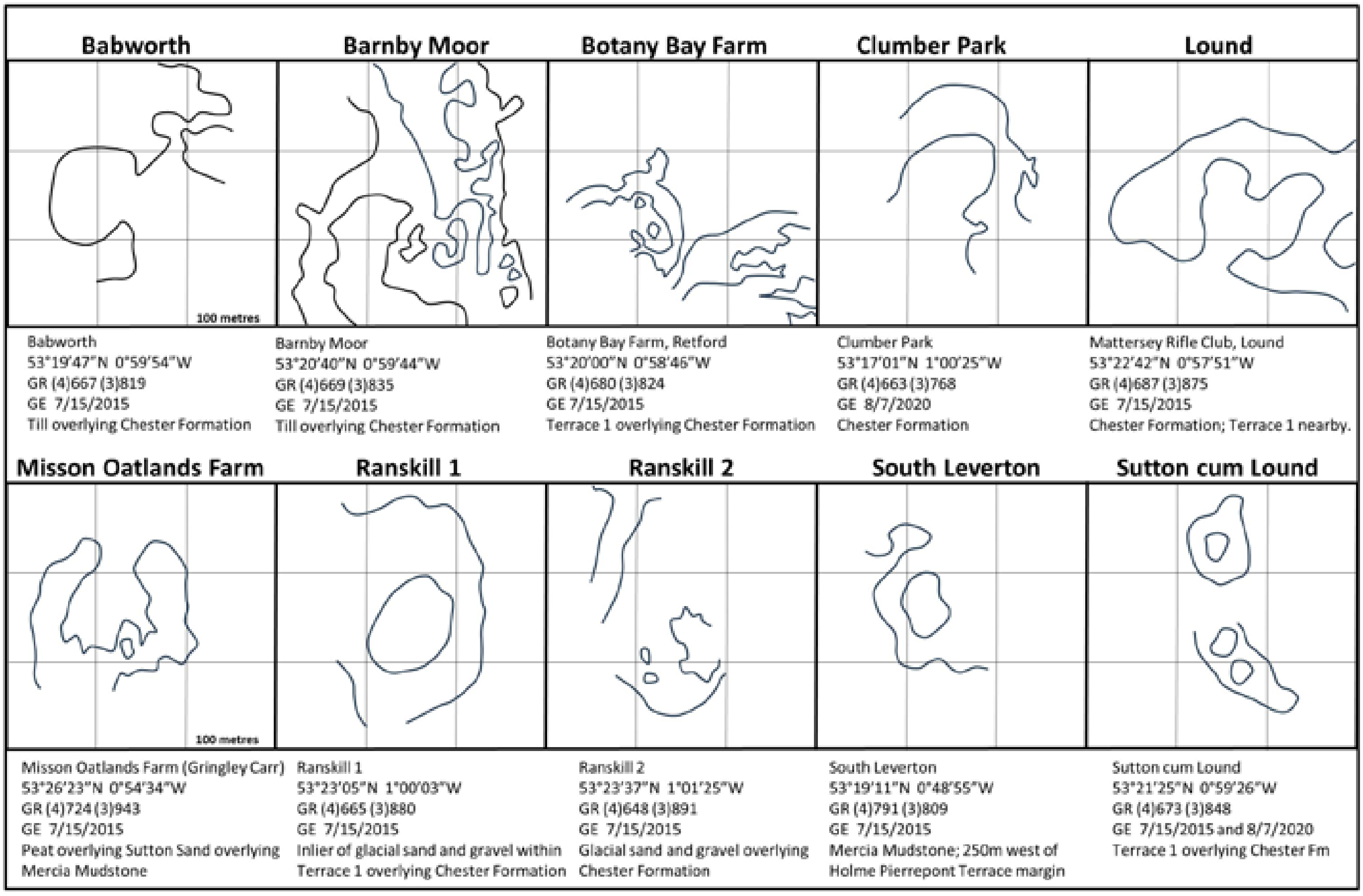


***Figure 10**. Cropmarks from Google Earth imagery (July 2015 and August 2020) showing outlines of annular ramparted depressions within the River Idle catchment and neighbouring areas that may have originated as ground ice mounds. Some are located near or in contact with polygonal patterned ground.*

The Botany Bay Farm site was first identified in cropmarks seen in 1976 and 1979 (Riley 1980; Garton and Brown 2002) (Fig. 11). In 2002 this took the form (much ploughed out now) of an almost complete ringed depression bisected by the Chesterfield Canal. It lies on a slight slope, facing north-east, at the mouth of a shallow dry valley (one of several) cut in till-capped Chester Formation sandstone, dissecting the east side of the Ryton-Idle watershed. A modest fall of 25 m in 2 km yields a shallow gradient of 1° from watershed to river terrace level. The structure was originally described as an irregular ring, at a height of 18–19 m OD, and about 150 m in diameter (Garton and Brown 2002). It was surrounded by a broad dark ring and a narrower pale halo, with a slight bulge to the north-east, and said to be superimposed over a palaeochannel with patterned ground. Its centre was thought to be 1.5–2.0 m lower than surrounding ground. Google Earth imagery (July 2015), supplemented by LiDAR hill-shading (© Environment Agency 2022), shows that there are, in fact, several overlapping annular rings (Fig. 11) delineated by darker rings and bounded by faint circular or semi-circular ramparts (suggestive of former ramparts, now much degraded). The main feature, PRD C, has a crater 120 m wide and 1.2 m deep with raised rims about 40 m wide, and a slightly raised centre. Total diameter (crater and rim) amounts to at least 180 m. Estimated diameters of PRDs A, B and C are 260 m, 240 m, and 180 m respectively (Figs. 11 and 12). A reasonable assumption then is that this cluster could represent overlapping remnants of large collapsed ice-cored mounds.

The morphology of the Botany Bay Farm group might be said to reflect open-system pingos, but for the fact that the hydraulic gradient is very small and unlikely to have generated adequate spring-fed intrusion (Colin Ballantyne, *pers. comm.*) High pressure artesian groundwater, erupting within shallow discontinuous permafrost below steep high backing slopes, is normally required to maintain open-system pingos (Yoshikawa 2013; Ballantyne 2018) (Fig. 2B). Currently, there are no spring points mapped in the vicinity. The site is located at the edge of the Idle valley First Terrace (at 18 m OD), a Late Devensian river terrace underlain by gravelly sands and sandy gravels (some notably coarse) 3–8 m thick (Smith et al 1973; Thomas 1981). Coarse-grained sandy substrates, being less frost-susceptible than silt-based ones, are less conducive to the formation of segregation ice.

Interpretation of the Google Earth imagery

The Botany Bay Farm periglacial evidence is thought to be unprecedented. No comparable PRD sites, either in the UK or the near continent, have been found with such a close intersection of cratered relief and patterned

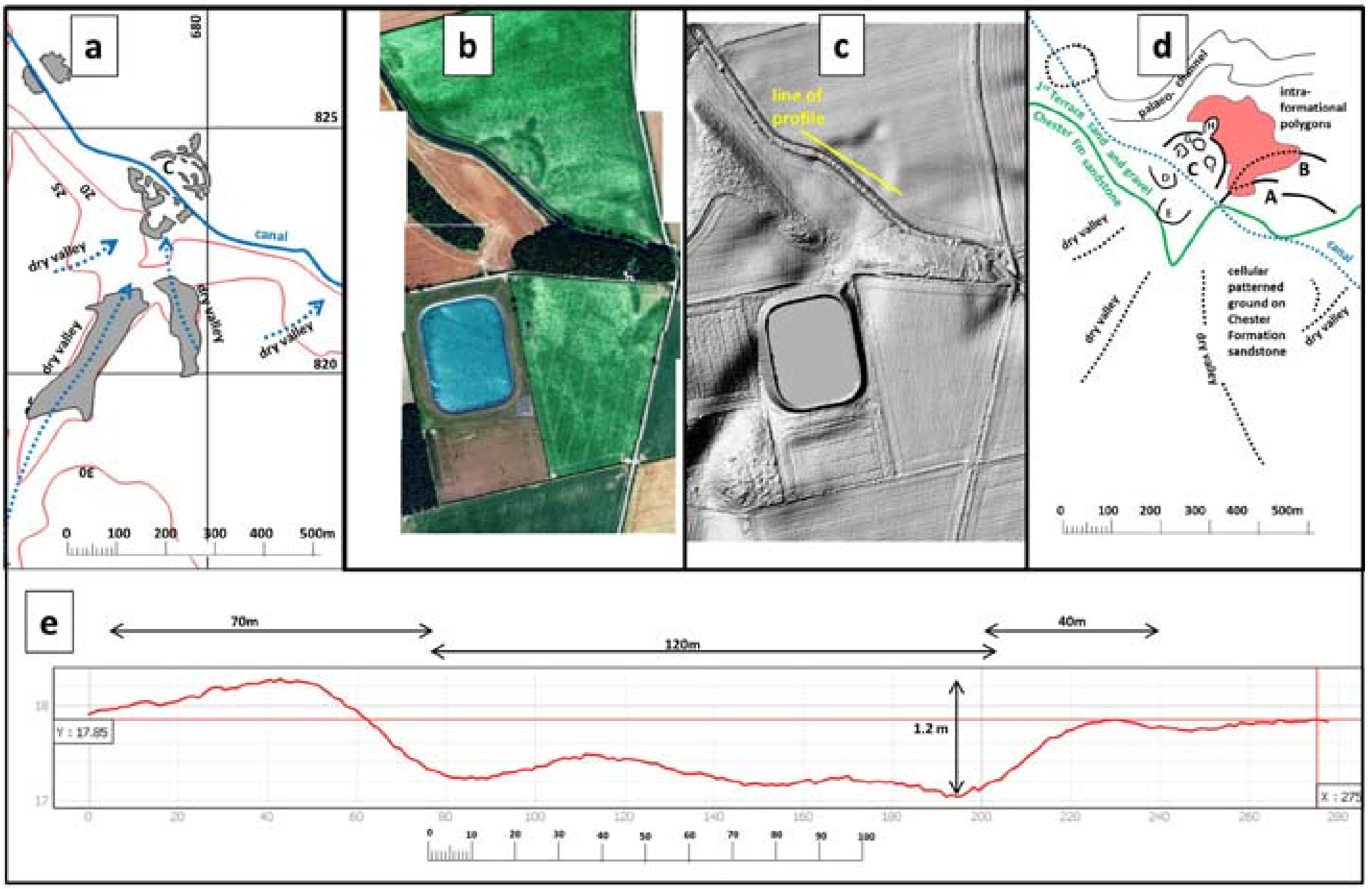


Figure 11. *Botany Bay Farm PRD cluster: (a) analysis of 1976 and 1979 aerial photos based on Keith Challis cropmark scan (Garton and Brown 2002); (b) photo mosaic of Google Earth cropmarks, July 15 2015; (c) DTM LiDAR 1 m multishade x 5 m vertical interval (copyright Environment Agency 2022) with line of profile; (d) interpretation of the Botany Bay Farm PRD cluster, based on combined aerial photo, GE imagery and LiDAR data; (e) profile of PRD C, 1 m DTM LiDAR data, x 20 vertical exaggeration using Terrain Profile tool in QGIS (QGIS.org).*

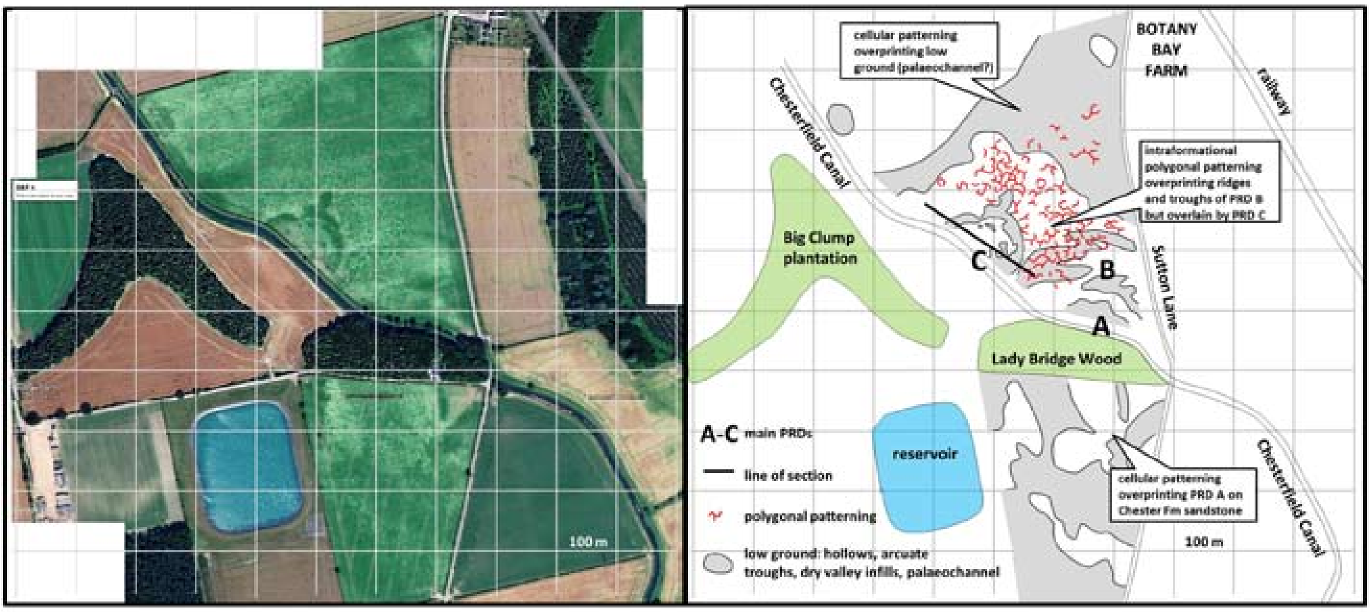


Figure 12. *Botany Bay Farm, Retford. Left: mosaic of Google Earth images, July 15 2015. Right: analysis of patterned ground and topography.*

ground. A possible equivalent may exist at Skinnand (Lincolnshire) but imagery there is somewhat indistinct (see https://tinyurl.com/groundpatterning). At 180–260 m in diameter, PRDs are particularly large at Botany Bay Farm. East Walton Common has probably the largest PRDs in Norfolk, but they do not exceed 100 m across (Gilbert Addison, *pers. comm.*)

Two points of interest merit attention. Firstly, the terrace surface is partly criss-crossed by polygonal patterned ground over an area of about 4 ha (Fig. 12). Measuring on average 13 m in diameter (range 8–20 m) these low-centred polygons are similar in scale to those at Bingham. Significantly, they occupy an intraformational horizon, i.e. they are imprinted over the ridge and trough of an earlier structure (PRD B) but are clearly overlain by the infill of a later depression (PRD C). Polygons, indicative of active ice-wedge aggradation within continuous permafrost, are identified here between two episodes of ice mound growth. Secondly, a number of small satellite features are detected, superimposed on the annular outline of PRD C — four to the north of the canal (F, G, H, I), and two (D, E) to the south, each about 20–50 m in diameter (Fig. 11). Secondary growth of this nature has been described by Mackay (1998) as a form of pulsation in which steady bulging of the main ice core is interrupted by small frost mounds as water lenses intermittently erupt through dilation cracks.

The Botany Bay Farm site is enigmatic. It satisfies size, shape and clustering criteria for open-system pingos, yet it lacks sufficient relief to drive hydraulic lift. Furthermore, one flank is clearly polygonised confirming continuous permafrost. It is apparently constructed on sandy gravel lacking fine-grained silt which could, otherwise, have promoted segregation. A relict lithalsa (or larger lithalsa plateau) therefore seems untenable. This is an example of 'problem pingos' (Ballantyne 2018). The main difficulty is to account for perennial spring flow within or above continuous permafrost, and to explain how very low artesian pressures, though adequate for segregation ice, could be responsible for strong hydraulic lift. There may be alternative sources of pressurised groundwater in the Botany Bay Farm area. Yoshikawa (2013) has proposed a four-fold classification:

1. A slope group: the conventional form of open-system pingo in which gravity-driven high-pressure artesian flow is maintained at a slopefoot backed by high ground.
2. A glacier group: in which groundwater is supplemented by subglacial meltwater from nearby "warm" glaciers.
3. An emergence group: where near-shore locations have recently undergone glacio-isostatic uplift, and freezing point is lowered by inherited saline groundwater.
4. A fault group: where additional groundwater emerges through fracture zones.

Of these alternatives, a slope mechanism (1) is considered unlikely, as relative relief is so limited. Direct glacial influence (2) is unlikely since the nearest ice limit (Lindholme advance) lies 20 km away (Friend et al 2016) (Fig. 4). Some continental workers have suggested forebulge collapse beyond the Scandinavian ice periphery as a possible mechanism for driving sub-permafrost groundwater; estimated ice thickness of around 500 m in eastern England (Clark et al 2022) could potentially have had a similar effect. Fault-guidance (4) might be applicable. Gurney and Worsley (1996) indicate that structures such as faults and intrusions provide hydraulic pathways through permafrost to sustain groundwater supply to the ice cores of hydraulic pingos. While BGS mapping shows no local faulting in the Babworth area, a concealed sub-terrace fault might potentially exist, in parallel with other NE-trending faults within the Chester Formation sandstone in East Retford (Smith et al 1973). With an impermeable base of Permian mudstones, the unconfined sandstone aquifer exceeds 200 m in thickness (Smedley et al 2018). Deeper faulting could have accessed saline groundwater circulation within lower Permian and Carboniferous strata. Thus, deep reserves of unfrozen groundwater could have provided volume and rate of inflow necessary for open-system intrusion into continuous permafrost. Basal permafrost aggradation (Hornum et al 2020) could be another explanation for pressurised groundwater where hydraulic head is weak.

An alternative model for Botany Bay Farm, though contentious, would be a closed-system (hydrostatic) mechanism. This would be consistent with size, shape and substrate, but inconsistent with observed clustering. Closed-system pingos (more common than open) are located in favourable environments such as abandoned river channels as well as drained lake beds (Yoshikawa 2013). Such a scenario might be envisaged within an abandoned channel of the proto-Idle, or perhaps an early strandline of Lake Humber (Fig. 4).

In summary, an open-system model meets most criteria, but a potential source of perennial groundwater intrusion, perhaps fault-guided, is unconfirmed. Basal permafrost aggradation could also be a plausible explanation. A closed-system approach satisfies some criteria, though not observed clustering; a drained lake bed associated with an earlier phase of Lake Humber could have provided a possible talik source. Either model (hydraulic or hydrostatic), or a hybrid variant, would certainly be possible within continuous permafrost, and thus compatible with the polygonal evidence. Lithalsa ice segregation however would be incompatible with both substrate and polygonal imprint.

Possible equivalents in The Netherlands

It is interesting to note that both Pissart (2003) and Ballantyne (2018) regard the evidence for remnant pingos in The Netherlands as 'convincing' though reserving judgment as to their precise mode of formation. The idea of pingo remnants in The Netherlands has never been seriously challenged. Evidence is largely based on the work of De Gans (1982) in the Drenthe area, with more recent accounts in Hoek (2000), Kluiving et al (2010), De Bruijn (2012) and an overview in Huissteden and Vandenbergh (2022).

The Drenthe till plateau (Fig. 4) covers an area of about 3000 km² in north eastern Netherlands; thickness of till varies from 2 to 8 m. The plateau marks the south western margin of the Late Saalian Fennoscandian ice sheet. Westwards, till extends through Friesland to the North Sea coast; to the south it is bounded by push moraines and, to the east, the Hondsrug ice stream megaflute. The area lies about 250 km south-west of the Weichselian Late Pleniglacial ice limit (Fig. 3), and thus was exposed to the full impact of continuous permafrost in the Last Permafrost Maximum (25–17 ka) (Huissteden and Vandenberghe 2022), as evidenced by widespread ice wedging, polygonisation, cryoturbation, ground ice mound formation and coversand deposition. Kasse et al (2007) provide a chronological framework: Older Coversand I (25–17 ka) was truncated to form a deflation stone pavement (Beuningen Gravel Bed) (17.2–15.3 ka), a widespread marker horizon, followed by permafrost degradation. This was succeeded by Older Coversand II (15.3 ka) marking the end of the Late Pleniglacial, and the start of the Late Glacial warming (14.7 ka) (Fig. 13).

The website www.pingoruïne.nl contains a comprehensive database of depressions in the Drenthe area and throughout The Netherlands. PRDs are large, approximately 100–350 m in diameter, with crater depths of 4–5 m and ramparts up to 1.4 m high. They confirm formation at the end of the Late Pleniglacial, followed by collapse and infilling in the Bølling phase of the Late Glacial. Earlier research proposed a closed-system origin for these PRDs, though more recent assessments advocate open. If the open-system hydraulic model is adopted, some explanation for pressurised groundwater intrusion in areas of low relief must be sought. A number of researchers have examined the likely impact of forebulge collapse and salt diapirs on groundwater movement and depth of permafrost; these would have had implications for pingo formation. Huissteden and Vandenbergh (2022) speculate that some pingo scars could even have originated as gas emission craters during permafrost thaw.

A preliminary search of 2018 and 2020 Google Earth images in this area confirms the survival of a few buried depressions with clear annular outlines, some with associated patterned ground; potential sites exist at Eext, Erica, Oosterhesselen, Sleen and Waanderveld. Further work is being undertaken to confirm the nature of this new evidence. In the meantime, we propose that the Dutch evidence for remnant pingos provides a useful comparator for former ground-ice evolution in the East Midlands.

Chronology

In the absence of absolute dating, an approximate chronology can be estimated using polygonal patterned ground as an indicator horizon. Within the Lower Trent valley, some river terrace polygons appear to date to an early phase of the Holme Pierrepont Terrace sands and gravels (Howard et al 2011; Baker et al 2021), coinciding with predicted continuous permafrost during the Last Glacial Maximum (Dimlington Stadial, GS-4 to GS-2, 29–15 ka) (Fig. 13, column 8). The later Holme Pierrepont terrace surface lacks polygonal imprint throughout the Trent Trench suggesting that discontinuous permafrost in the shorter Younger Dryas (GS-1, 12.9–11.7 ka) was unable to generate sufficient thermal contraction. There is some evidence for ice-wedge formation in the Younger Dryas at Needham Market (Rose 1993) and Baston (Worsley 2014), but it remains to be seen whether this was sufficiently long or intense enough to have resulted in polygon formation. We propose, therefore, that the Botany Bay Farm complex is better assigned to GS-2 (Fig. 13, column 11). This would be consistent with the Lake Humber and Idle valley chronology recommended by Buckland et al (2019). Greenland ice-core chronology (Rasmussen et al 2014, column 6) identifies a few ‘flickering’ reversals, some as brief as 240–500 years (GI-4, GI-3, GI-2), during which short episodes of permafrost degradation might have alternated with permafrost aggradation. Polygonal growth at Bingham could also be placed in GS-2 (Fig. 13, column 10), with succeeding lithalsa development assigned either to the end of GS-2, or to GS-1 (Younger Dryas), after a hiatus in GI-1 (Windermere Interstadial). Small PRDs at Bingham are perhaps too shallow and vulnerable to have survived the full impact of Younger Dryas denudation, so are more likely to have developed with permafrost degradation at the end of the Younger Dryas.

Conclusions

Having been almost enclosed by Late Devensian ice limits (Fig. 3), the Lower Trent valley and tributaries must have been subject to intense continuous permafrost. While ground ice processes of ice wedging and patterned ground can be clearly demonstrated (Baker et al 2021), evidence for ground ice mound formation has proved elusive. This paper has presented new cropmark evidence in two contrasting localities, Bingham and Retford, where a combination of favourable factors has preserved PRDs in shallow buried micro-relief. There is continuing debate concerning the exact processes involved in present day ground ice development — whether ice accumulates by intrusion or segregation, and whether sub-permafrost groundwater is driven by hydrostatic or hydraulic mechanisms. Previous accounts of PRDs in the UK, though often clear on morphology, substrate and infill stratigraphy, were limited by a lack of chronological control and permafrost context. Here, Google Earth imagery confirms a clear association

	Marine Isotope Stage	British substages		Start date (ka)	Greenland stadials (GS), interstadials (GI)	Dutch coversand sequence		Lower Trent and Idle valley terrace sequence	Periglacial chronology: Bingham	Periglacial chronology: Botany Bay Farm
Holocene	MIS 1		Holocene	11.7						
Late (or Upper) Pleistocene	MIS 2	Late Devensian	Younger Dryas stadial	12.9	GS-1 12.9	Late Glacial	Younger Coversand II 12.3	Later Holme Pierrepont sands and gravels 13.0	Lithalsa growth Seasonal frost blisters	
			Windermere interstadial	14.7	GI-1 14.7		Usselo/Allerød 13.0-12.8	Tiln Bed and coversand 13.5	*hiatus*	
							Older Coversand II 15.3			
			Dimlington Stadial or LGM		GS-2a 17.5	Late (or Upper) Pleniglacial	Beuningen Gravel Bed 17.2		Ice-wedge polygons	PRD C Ice-wedge polygons PRD A, B
					GS-2b 21.0		Older Coversand I 25.2	Lake Humber silts and clays 19.2		
					GS-2c 23.0			Lake Humber littoral sands 23.4		
					GI-2 23.5			Earlier Holme Pierrepont sands and gravels, and River Idle Terrace 1 sands and gravels (33.0)		
					GS-3 27.5					
				29	GS-4 29.0					
	MIS 3	Middle Devensian	(Upton Warren Interstadial)		GS-5 32.0	Middle Pleniglacial		Finningley unit 3 solifluction diamict 35.7		
					GI-5 32.5					
					GS-6 33.5					
					etc.			Finningley unit 2 organic deposits 41.0		
				59				Finningley unit 1 ORG (Older river sands and gravels)		

***Figure 13**. Suggested periglacial chronology for Bingham lithalsa field and Botany Bay Farm PRDs: column 6 based on Rasmussen et al (2014); columns 7 and 8 (Kasse et al 2007); column 9 (Howard et al 1999; Buckland et al 2019).*

of PRDs with polygonal patterned ground, indicative of former continuous permafrost. At Bingham, small circular lithalsa scars (2–15 m in diameter, and at high densities of 2900–4800/km²) appear to overprint and replace older fragmented polygons on a substrate of frost-susceptible dolomitic siltstone. A context of discontinuous or sporadic permafrost is inferred, with small scale ground ice mounds raised, first by polygon-centred frost blisters, and later by ice segregation and low-pressure fault-guided spring intrusion. Chronologically, lithalsas most probably date to the Younger Dryas (GS-1), postdating a period of intense thermal contraction in GS-2. At Retford (Botany Bay Farm) a cluster of three large annular scars (180–260 m in diameter) suggests overlapping PRDs on a substrate of coarse terrace sands and gravels overlying Chester Formation sandstone. Degraded remains of a central depression (1.2 m deep) still survive, and there is an interbedded polygonised surface. A context of former continuous permafrost is implied, and a process of open-system pingo growth suggested. Neither substrate or polygonal imprint are compatible with lithalsa ice segregation. Groundwater intrusion (perhaps a hydrostatic-hydraulic hybrid) could have been driven by fault-guidance or basal permafrost aggradation. Chronologically, the cluster should date to GS-2 at the latest; episodes of permafrost degradation perhaps coincided with short thermal reversals (GI-4, GI-3, GI-2) during the Late Devensian substage. PRDs have a very restricted latitudinal range; the East Midlands probably shared these specific permafrost limits with equivalent structures in East Anglia and, across the Doggerland land bridge, The Netherlands and Belgium.

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