Widespread pre-Devensian and Devensian periglacial patterned ground in the East Midlands revealed in summer 2018 satellite imagery

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Abstract: This paper reports on the discovery of over 60 sites in the East Midlands exhibiting new evidence for periglacial structures and patterned ground visible in satellite imagery from summer 2018. These include dilated joints, gulls and cambers in the bedrock surfaces of Permian and Jurassic outcrops. Widespread polygonised river deposits occur in the Lower Trent terrace sequence, most notably around the Lincoln Gap. Sites of polygonised bedrock in the Devon-Smite catchment, at both high and low elevation, are reported; these are thought to represent the roots of truncated ice-wedge casts without cover deposits, implying the existence of a former terrace and a drained lake bed. The paper speculates on the likelihood of multiple glacial ponding by a late Middle Pleistocene ice advance as a prelude to polygonisation across periglacial drained lake beds. Links to online resources are provided.

Ground surface patterning constitutes some of the most distinctive and diagnostic evidence for former periglaciation (Ballantyne and Harris 1994). Modern day periglacial patterns are a response to ground ice heave, hydrostatic pressure and thermal contraction (Washburn 1973). Well-documented relict patterned ground is found widely in southern Britain and East Anglia but it is less conspicuous in the East Midlands and the North-east. Baker *et al.* (2013) collated evidence for periglacial phenomena in the Trent Valley, mainly consisting of involutions, a handful of ice-wedge/ice-vein casts and a single example of patterned ground. In Eastern England, east of the Trent, a wider distribution of periglacial phenomena was mapped by Straw (1979), who recorded about twenty sites of ice-wedge casts, sand wedges and gulls but only two cases of patterned ground.

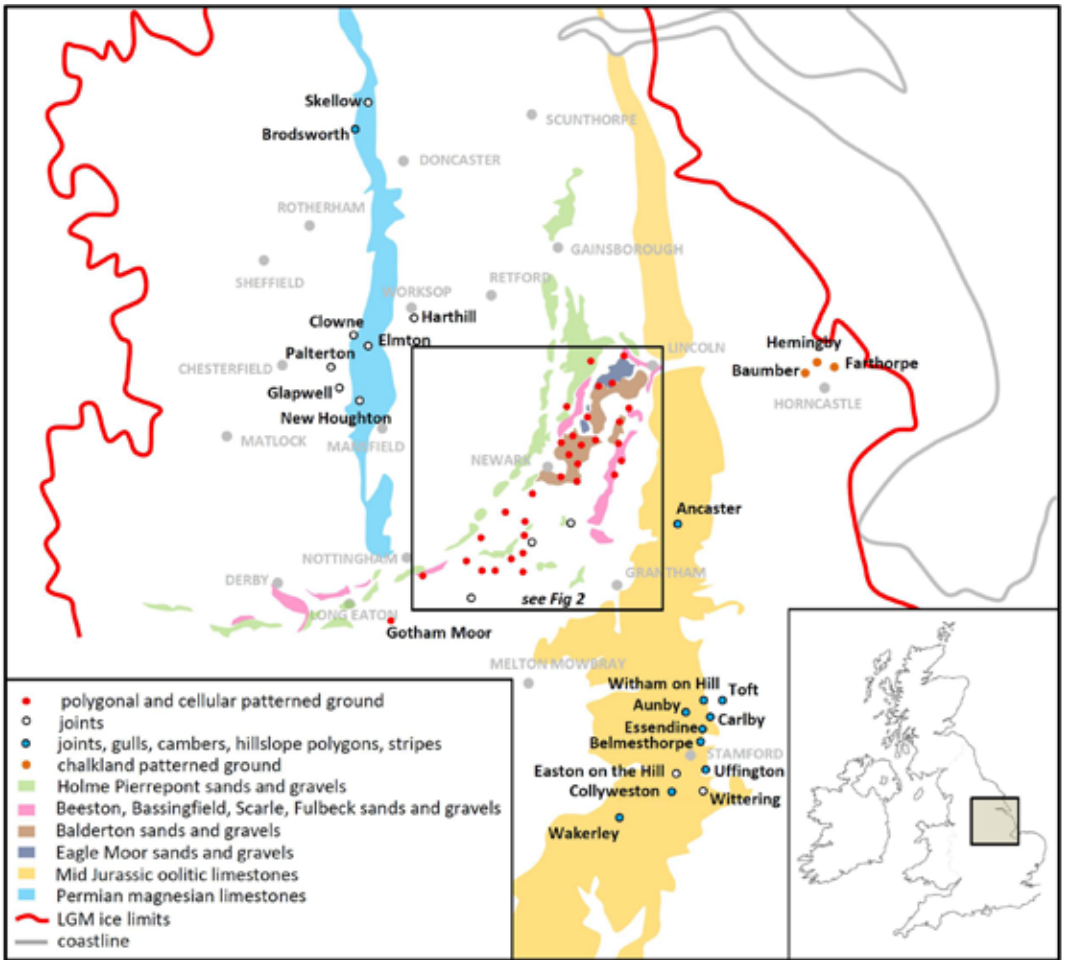

Figure 1. *Distribution and variety of all patterned ground sites in the East Midlands detected in 2018 Google Earth imagery (including three in 2007).*

Worsley (2014) gives a clear explanation of the formation, decay and casting of ice wedges with well-illustrated examples of polygonal ground in arctic Canada. In the Devensian or Last Glacial Stage (115 ka to 11.6 ka) the East Midlands and Vale of York were placed in an ice-free enclave surrounded by clear glacial limits on three sides and should have felt the full impact of periglaciation; yet available evidence up to now has been thin on the ground, either lost irretrievably to erosion or deeply buried. It was a surprise therefore to discover from recent satellite imagery (Google Earth, July 2018) that widespread buried patterned ground still survives in many places. Over 60 sites have been identified so far (Figs 1 and 2) revealing distinct subsoil features that have hitherto lain buried and undetected. This article reports our preliminary findings.

The 2018 satellite imagery

The exceptional heatwave of summer 2018 revealed numerous unknown archaeological sites in new cropmarks and parched earth (Historic England 2018). Some periglacial phenomena were also reported at this time (Hoare 2019; Berry *et al.* 2020). In this study, initial discovery of polygonised bedrock surfaces at Thorpe (Fig. 9) in the Devon-Smite catchment was our starting point, followed by a comprehensive search of available Google Earth Pro imagery across the region. Visual inspection was undertaken in repeated row-by-row transects from the Peak District in the west to the North Sea coast in the east, attention being focused on regularity of geometry, clear definition of features, and sites of known ice-wedge casts.

Google Earth Pro (a public online service) allows free access to historical imagery dating back 20 years or more. A historical image search bar set to July 2018 generates the most recently available data up to that date covering about a one month window with various satellite transits on June 25th, July 4th, July 5th, and July 18th. There can be substantial variation in appearance of patterning from week to week and month to month (due to differences in vegetation growth and agricultural practice); weather conditions can also vary and interfere with visibility. In one case, where July focus was poor, a later date (Sept 24th) was selected. Small-scale stripe patterning in the Lincolnshire Wolds was surprisingly not visible in 2018, but was visible in January 2007 imagery (Fig. 13).

Three satellite companies provide imagery to the Google Earth tile mosaic: CNES/Airbus, Maxar Technologies, and Landsat/Copernicus, each monitoring at medium pixel resolutions between 1 m and 15 m. Purchase of commercial high resolution was considered but limited by budgetary constraints. Various options to enhance imagery were explored (Chris Brooke, *pers. comm.*). Locations were identified using Google Earth Pro on desktop version 7.3 (2020) available at http://

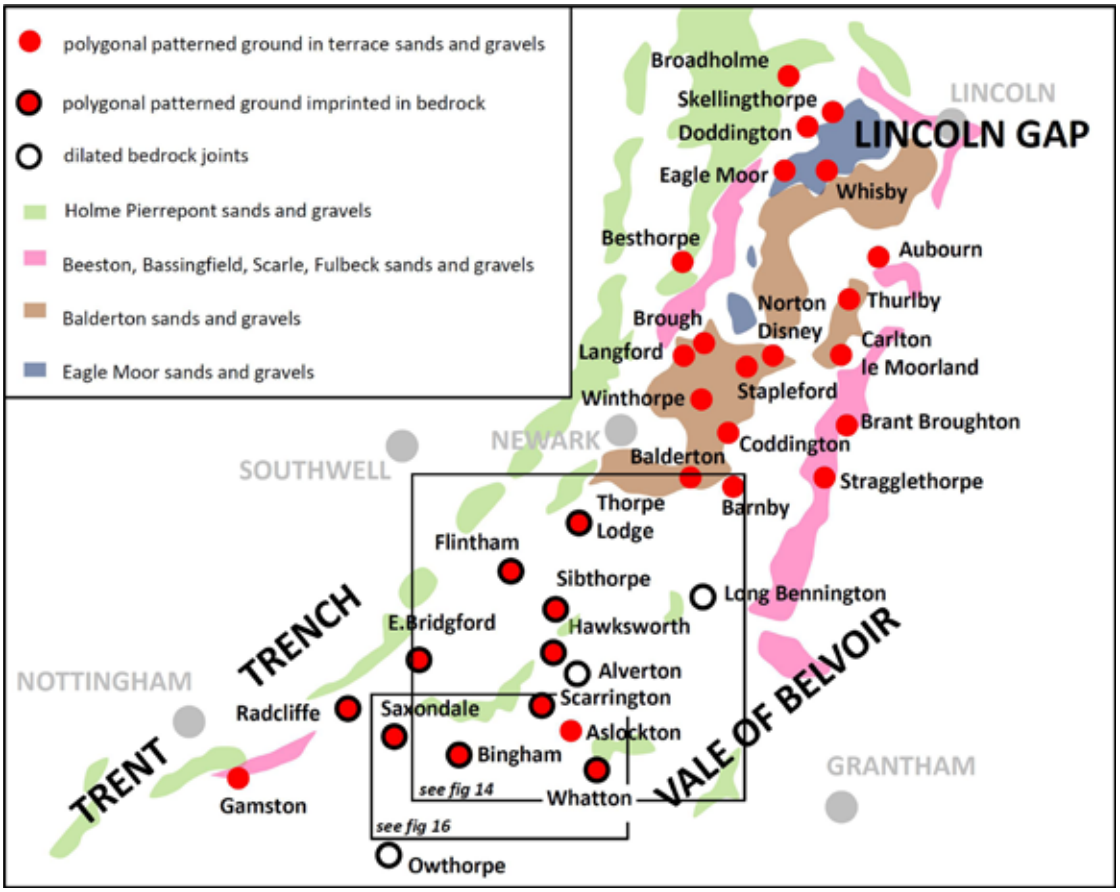

***Figure 2**. Detailed location of sites in the central area covering the Trent Trench, Devon-Smite and Witham valleys, and the Lincoln Gap.*

www.google.com/earth/index.html (accessed 23 July 2021). A placemark recorded the historical imagery date of visible ground patterning and geological features. These were saved to a Keyhole Markup Language file (kml). Contours at 10 m intervals (in Fig. 16) were generated from LiDAR Composite 2020 DTM 2 m tiles (downloaded from the DEFRA/Environment Agency website, Open Government Licence v3) using QGIS 3.12 raster contour tool. Geological substrates were determined by reference to BGS DiGMaps (BGS 2021), Howard *et al.* (2009) and Bridgland *et al.* (2014). Images were examined carefully for archaeological features or recent cultivation, according to principles outlined in Wilson (1982). David Knight (*pers. comm*.) has noted, for example, that the Balderton Terrace surface at Hall Farm, Langford, is a 'very busy archaeological landscape' with cropmarks for linear ditches, pits and rings that are difficult to disentangle from polygonal periglacial features.

Geometry of relict thermal contraction cracks

While regular polygons (tetragonal, pentagonal and hexagonal) appear to be typical, many shape variations are recognised: circles, irregular and incomplete polygons, nets, stripes and steps. Washburn (1973) was the first to propose a distinction between sorted polygons (possessing a border of stones surrounding finer central material) and non-sorted polygons (lacking a stony border but delineated by microrelief and/or vegetation). Non-sorted polygons are generally larger than sorted and are associated with ice wedging and cryoturbation in periglacial lowlands. Sorted polygons are commonly smaller and can occur in a variety of environments. The distinction between polygons and nets (partly elongated or garlanded) and stripes (fully stretched and more parallel) relates to slope angle; both are ultimately destroyed by rapid solifluction on steep slopes. Ice wedges develop within both continuous and discontinuous permafrost below the active layer, and are described as syngenetic or epigenetic depending on mode of growth. When seen in cross-section, syngenetic ice wedges tend to form a series of relatively narrow stacked chevron-like wedges relating to short-lived shallow wedge growth truncated when the next deposition of sediment occurs on an aggrading surface. Through time they appear to extend many meters underground. Epigenetic wedges form on a more stable surface with repeated cracking at a given locality causing them to widen through time. In 3D, both types may form part of a polygonal network spreading across alluvial floodplains, homogeneous flats or drained lake beds.

Ice-wedge polygons are highly variable in shape and dimension (Mackay 2000); they occur nearly everywhere on non-bedrock level terrain along the arctic coasts and islands of the Beaufort Sea. Polygon diameters vary from 10 to 60 m (average 20 m) and are generally larger in young basins, smaller in old; this results from increased subdivision over time. Similarly, colder conditions cause greater fragmentation (Ulrich *et al.* 2014), reducing polygon size. Accordingly, there is an inverse relationship between ice wedge size and polygon diameter, as shown by numerous observations of thermokarstic drained lake basins (Mackay 2000; Kanevskiy *et al.* 2013; Ulrich *et al.* 2014). Bedrock areas and sites with active sedimentation are rarely polygonised, but coastal plains, lake basins, deltas,

Criteria	Stage		
	Early	Mature	Late
1. Ice wedge size and wedge ice volume (WIV)	Small, shallow; low WIV	Medium	Large, deep; high WIV
2. Ice wedge generations	Single epigenetic	More complex syngenetic growth as wedges grow vertically in response to progressive infilling of troughs (but not alluvial)	
3. Boundary width	Narrow, ice-expanded rim	Medium, stabilising trough	Wide, degrading trough
4. Centredness	Low-centred (inner depression with raised rim)	High-centred (inner dome relative to thawing boundaries)	Low-centred, walled (differential resistance rendering trough infill higher than thawed surroundings)
5. Polygon size and subdivision	Large, primary (rectangular polygons)	Medium, secondary (regular tetragonal, pentagonal, hexagonal polygons)	Small, tertiary (reticulate and cellular polygons, and nets)

***Table 1**. Proposed evolutionary sequence for non-sorted epigenetic ice-wedge polygons on typical drained lake beds and homogeneous flat areas in continuous permafrost (without addition of alluvial deposits). Based on Mackay (2000), Kanevskiy et al. (2013) and Ulrich et al. (2014).*

tidal flats and low foothills typically feature large and extensive polygonal networks on the Arctic coastal fringe (Kanevskiy *et al.* 2013). On rising ground, however, hillslope ice wedges and earth hummocks may predominate, rarely reaching any appreciable size because growth is stunted by slow continuous mass movement (Mackay 2000); higher areas tend therefore to exhibit smaller and more cellular patterns. An evolutionary sequence for lowland drained lake bed and flat area polygons is proposed here (Table 1), but this may not necessarily apply in all cases of polygonal development.

In the Jurassic limestones, sandstones and ironstones of Midland England, periglaciation is indicated by the presence of gulls and cambers, and dilated joint cracks across rock pavements. Gulls in competent strata are opened by extensional hillslope mass movement and, where underlain by mudstones, caprock slumping or cambers may form (Horswill and Horton 1976). Harris *et al.* (1988) and Berry *et al.* (2020) recognise that some polygonal patterning may form by seasonal frost wedging rather than by full ice-wedge thermal contraction. Chalklands, such as the Lincolnshire Wolds, are recognised as a special case of patterned ground in terms of their high frost-susceptibility and resultant hummocky ground (Murton *et al.* 2003; Bateman *et al.* 2014).

Presence and absence of evidence in the geographical distribution

Murton and Ballantyne (2017) propose a series of five periglacial regions in Britain relating to exposure since glaciation and located beyond recognised glacial limits. The East Midlands falls within their Region 3, last glaciated in the Wolstonian period. There is no unanimity regarding the use of the Wolstonian stratotype (Gibbard and Turner 1990); it is a broad term covering a long interval of pre-Devensian time between MIS 11 and 5e (approximately 370 ka to 130 ka) during which glaciation could have impacted on the East Midlands region in one or more of three glacial phases (MIS10, 8 or 6). In Lincolnshire a glacial advance during this time was probably responsible for deposition of the Wragby, Calcethorpe and Heath Tills (Straw 2020); some areas of Kimmeridgian Oadby Till may also be of this age (Rose *et al.* 2021). In Region 3, therefore, the landscape was subject to periglacial conditions during both pre-Devensian and Devensian stages. The final phase of Late Devensian substage MIS 2 (Last Glacial Maximum) is considered to have experienced severe continuous permafrost, while the Younger Dryas stadial (12.9–11.6 ka) was probably marked by less severe, discontinuous permafrost.

The periglacial landscape is a palimpsest of repeated episodes resulting in a fragmented and incomplete record (Murton and Ballantyne 2017). We recognise that there are large tracts of the East Midlands region where patterning is not visible in the 2018 images, either because original conditions were unsuitable for formation, or later erosion and deposition has since removed or obscured them. No clear periglacial patterning, for example, has been detected across the Peak District, the Sherwood Sandstone Group outcrop, Charnwood, the Humberhead Levels, the Wreake valley, or the southern Vale of York. Further afield, polygonal patterning can be observed on Devensian glacial, glacio-fluvial and glacio-lacustrine deposits in various neighbouring locations such as northern Vale of York, south-west Stafford and west Wolverhampton, similar to those described by Shotton (1960) and Morgan (1971).

Within the East Midlands, instances of ice-wedge casts are well-known, as in the River Bain first terrace (Straw 2018), the River Glen first terrace (Briant *et al.* 2004), and the River Trent Holme Pierrepont Terrace at Hemington, Hoveringham and the type site (Howard 1995; A. S. Howard *et al.* 2009; Howard *et al.* 2011). Smaller ice-vein sand casts are reported from Westwoodside and Yarborough (Bateman *et al.* 2001; Murton *et al.* 2001) and at Farndon Fields (Tapete *et al.* 2017; Garton *et al.* 2020). None of these, however, appear to have generated visible polygons at ground level. It is clear then that the formation and survival of visible patterned ground is dependent on many contributory factors: environmental context, scale of structure, duration of ice wedge formation, frost-susceptibility, impeded drainage, silt content, and good preservation potential; absence of evidence results from unsuitable initial conditions, unimpeded drainage, coarse host sediment, or subsequent removal or deep burial. In the River Glen terrace sequence (Briant *et al.* 2004; Worsley 2014) Late Devensian polygon-related ice-wedge casts have been documented at Manor Pit, Baston. The roots of this polygonal network are preserved at depth in bedrock but concealed beneath 3–4 m of fluvial sands and gravels. At least two generations of ice-wedge casts are present, as lines of previous thermal contraction cracking were undoubtedly reopened and re-activated. A necessary prerequisite for such large intraformational ice wedges must have been former ice-rich cover deposits and active layers now no longer present.

Four sub-regions

Well-defined periglacial patterning in over 60 sites across the East Midlands is confirmed in the satellite imagery (Figs 1 and 2). Four sub-regions are proposed:

A. The Upper Permian Cadeby Formation dipslope.

B. The Mid Jurassic formations of the Greater and Lesser Oolite Groups in South Kesteven and the Welland valley.

C. River terraces of the Lower Trent, Witham valley, Lincoln Gap, and Vale of Belvoir.

D. The Lincolnshire Wolds.

Sub-region	Site	Lat °N	Long °W	Grid ref	Height m OD	Sat	Date in 2018	Substrate	Patterned ground
Permian dipslope	Clowne	53.15	1.16	4495 3757	146	MT	June 25	Cadeby Fm dolostone	J (l)
	Elmton	53.15	1.14	4505 3740	120	MT	June 25	Cadeby Fm dolostone	J (r), Po (c), Pc
	Glapwell (Fig 3)	53.11	1.17	4479 3661	170	MT	June 25	Cadeby Fm dolostone	J (r), Pc
	Harthill	53.18	1.15	4496 3806	120	MT	June 25	Cadeby Fm dolostone	J (r), Po (c)
	New Houghton	53.10	1.16	4485 3645	160	MT	June 25	Cadeby Fm dolostone	J (r), Pc
	Palterton	53.12	1.17	4478 3679	179	MT	June 25	Cadeby Fm dolostone	J (l, r)
	Skellow/Carcroft	53.35	1.13	4519 4106	40	MT	July 17	Brotherton Fm dolostone	J (r)
Mid Jurassic outcrop (South Kesteven and Welland catchment)	Ancaster	52.58	0.31	4992 3428	75	L/C	Apr 20	Blisworth Limestone Fm	Po (c), St (p)
	Aunby	52.43	0.28	5025 3155	50	L/C	June 25	Blisworth Limestone /Rutland Fms	J (r), Gu, Ca, Po (c)
	Belmesthorpe	52.40	0.26	5046 3048	40	L/C	June 25	Blisworth Limestone Fm	J, Po (c)
	Carlby	52.42	0.27	5048 3139	30	L/C	June 25	Blisworth Limestone/Cornbrash Fms	Po (c), J
	Collyweston	52.36	0.33	4980 3025	40	L/C	June 25	Lower Lincolnshire Limestone Fm	St (d), Po (c) traces
	Easton on the Hill	52.37	0.30	5008 3050	80	L/C	June 25	Northampton Sand Formation	J (p) (30-40m) in box-stone jointing
	Essendine (Fig 4)	52.42	0.26	5056 3133	32	L/C	June 25	Blisworth Limestone Fm	J (b), Po (c)
	Toft	52.44	0.25	5063 3169	20	L/C	June 25	Blisworth Limestone Fm /Rutland Fm	J (r), Gu
	Uffington	52.39	0.25	5062 3085	27	L/C	June 25	Cornbrash Fm	J (r), Po (c), St (p)
	Wakerley	52.35	0.35	4961 3001	40	L/C	June 25	Lower Lincolnshire Limestone Fm	St (d)
	Witham on Hill 1 (Fig 5)	52.43	0.25	5061 3155	20	L/C	June 25	Cornbrash Fm	Gu, Ca, Po (c)
	Witham on Hill 3	52.43	0.27	5044 3156	45	L/C	June 25	Blisworth Fm/Rutland Fm	Po (c), J (r), Gu
	Wittering 1 (Fig 6)	52.36	0.25	5066 3016	52	L/C	June 25	Lower Lincolnshire Limestone Fm	J (p) (20-30m) in orthogonal jointing
Lincolnshire Wolds	Baumber (Fig 13)	53.14	0.09	5225 3735	65	L/C	Jan 2007	Calcethorpe Till over Kimmeridge Clay Fm	Po (c, n), St (c, d) on ridge
	Farthorpe Farm	53.14	0.06	5261 3737	70	L/C	Jan 2007	Calcethorpe Till over Kimmeridge Clay Fm	St (d)
	Hemingby	53.14	0.07	5248 3737	50	L/C	Jan 2007	Calcethorpe Till and Hemingby Terrace	St (b, c, d)
Nottingham area	Bradmore Moor	52.52	1.08	4574 3310	40	MT	July 4	Bunny sands and gravels/lake deposits	Po (s, r)
	Gotham Moor 1 (Fig 7)	52.52	1.11	4546 3306	30	MT	July 4	Bunny sands and gravels/lake deposits	Po (r, c) (5m), Pc in Barton gap
	Gotham Moor 2	52.52	1.10	4554 3306	33	MT	July 4	Bunny sands and gravels/lake deposits	Po (s, r), channelled
	Ruddington Moor	52.53	1.10	4558 3328	35	MT	July 4	Bunny sands and gravels/lake deposits	Po (r)
	Gamston	52.55	1.05	4608 3374	25	MT	July 4	Bassingfield sands and gravels	Po irregular, incomplete
	Aubourn (Fig 11)	53.08	0.37	4924 3624	12	C/A	July 5	Balderton sands and gravels	Po (r)
	Balderton (Barnby Road)	53.03	0.46	4820 3526	18	C/A	July 5	Balderton sands and gravels	Po incomplete
	Barnby	53.03	0.43	4851 3524	19	C/A	July 5	Balderton sands and gravels	Po (r) irregular
	Besthorpe	53.10	0.45	4832 3650	10	C/A	July 5	Holme Pierrepont sands and gravels (HPSG-A)	Po (5m), incomplete, channelled
	Brant Broughton	53.05	0.38	4912 3561	9	C/A	July 5	Fulbeck sands and gravels	Po, irregular, incomplete
	Broadholme (Fig 8)	53.14	0.39	4892 3733	7	C/A	July 5	Holme Pierrepont sands and gravels (HPSG-A)	Po (s, r) (10-15m)
	Brough (Glebe Farm)	53.07	0.44	4839 3589	18	C/A	July 5	Balderton sands and gravels	Po (r) (5m), irregular
	Carlton le Moorland 1	53.07	0.38	4912 3586	12	C/A	July 5	Balderton sands and gravels	Po (r, c), irregular
	Carlton le Moorland 2	53.06	0.37	4916 3572	8	C/A	July 5	Fulbeck sands and gravels	Po (c)
	Coddington 1 (moat)	53.04	0.45	4831 3539	32	C/A	July 5	Eagle Moor sands and gravels	Po, irregular
	Doddington	53.13	0.37	4918 3698	25	C/A	July 5	Eagle Moor sands and gravels	Po (r, c)
	Eagle Moor	53.11	0.40	4888 3681	32	C/A	July 5	Eagle Moor sands and gravels	Po, irregular, incomplete

Lower Trent and Witham valley in the vicinity of the Lincoln Gap	Langford (Langford Hall)	53.06	0.45	4828 3577	18	C/A	July 5	Balderton sands and gravels	Po (r) (5-10m)
	Long Bennington	53.00	0.46	4829 3447	24	C/A	July 5	Barnstone Limestone Mem	J (r), Po (s)
	Newark Airfield	53.05	0.45	4828 3556	18	C/A	July 5	Balderton sands and gravels	Po (s, r)
	Norton Disney	53.06	0.39	4888 3591	17	C/A	July 5	Balderton sands and gravels	Po (c) irregular
	Skellingthorpe	53.13	0.37	4923 3707	19	C/A	July 5	Eagle Moor sands & gravels/ Skellingthorpe Clay	Po (p, s) (30-50m)
	Stapleford (Moor Farm)	53.06	0.42	4864 3575	17	C/A	July 5	Balderton sands and gravels	Po irregular
	Stragglethorpe (Kart Circuit)	53.02	0.39	4898 3498	16	C/A	July 5	Fulbeck sands and gravels	Po (c) irregular, Pc
	Thurlby	53.08	0.37	4908 3614	13	C/A	July 5	Balderton sands and gravels	Po (r), irregular
	Whisby	53.11	0.39	4900 3675	30	C/A	July 5	Eagle Moor sands and gravels	Po (r, c) (10m), irregular
Devon-Smite valley (Vale of Belvoir)	Alverton	52.58	0.49	4794 3416	23	C/A	July 5	Barnstone Limestone Mem	J (r)
	Aslockton	52.57	0.52	4751 3408	25	MT	June 25	Whatton sands and gravels	Po (p) (5m)
	East Bridgford	52.58	0.57	4708 3422	28	MT	July 18	Edwalton Fm mudstone	Po (c), irregular
	Flintham	52.59	0.54	4734 3448	25	MT	July 18	Edwalton Fm skerry	Po (r), faint
	Hawksworth	52.58	0.52	4753 3422	18	C/A	July 5	Arden Sandstone Mem	Po (s) (10m)
	Orston	52.57	0.49	4777 3422	31	C/A	July 5	Barnstone Limestone Mem	J (r)
	Owthorpe	52.53	1.00	4671 3333	49	MT	June 25	Barnstone Limestone Mem	J (r)
	Scarrington	52.58	0.54	4738 3421	21	MT	July 18	Arden Sandstone Mem	Po (r), faint
	Sibthorpe	53.00	0.52	4764 3455	15	C/A	July 5	Edwalton Fm skerry	Po (s) (10-20m)
	Thorpe Lodge (Fig 9)	53.02	0.50	4778 3495	14	C/A	July 5	Arden Sandstone Mem	Po (s) (10-15m)
Cropwell Butler Gap	Bingham 2 Top Brackendale Fm	52.56	0.58	4691 3387	52	MT	June 25	Edwalton Fm skerry	Po (s, w), faint (5-10m)
	Bingham 3 (Toot Hill)	52.56	0.57	4697 3390	53	MT	June 25	Edwalton Fm skerry	Po (p, s), faint (5-10m)
	Bingham 6 (Spring Farm²) (Fig 10)	52.56	0.56	4707 3380	30	MT	June 25	Edwalton Fm skerry	Po (s, w) (5-10m)
	Bingham 7 (Starnhill Farm)	52.56	0.56	4719 3385	28	MT	June 25	Edwalton Fm skerry	Po (c, w) (10m)
	Bingham 8 (Vicars Croft)	52.56	0.55	4725 3382	26	MT	June 25	Edwalton Fm skerry	Po (s, p) (5m)
	Saxondale 1 (Fields Farm)	52.56	0.59	4678 3382	55	MT	June 25	Edwalton Fm skerry	Po (s, w) (5-10m), Pc
	Saxondale 2 (High Thorpe)	52.56	0.59	4679 3385	61	MT	June 25	Edwalton Fm skerry	Po, trace (10-15m)
	Radcliffe (Shelford Lodge Farm)	52.57	1.00	4661 3408	60	MT	June 25	Edwalton Fm skerry	Po (c), trace

Table 2. A list of sites in East Midlands displaying patterned ground in 2018 satellite images (including three in 2007). Abbreviations: Ca = cambers; Gu = gulls; J = dilated joints (beaded, linear, rectilinear, polygonal); Po = polygons (primary, secondary, reticulate, cellular, walled, net); in brackets, diameter in metres; St = stripes (bifurcating, convergent, divergent, parallel); Pc = palaeochannels. Satellite transits are MT Maxar Technologies, C/A CNES/Airbus, and L/C Landsat/Copernicus.

Results

A selection of 11 satellite images is presented in Figs 3–13, and further details of the 60+ sites, their location, height, transit date, satellite provider, patterned ground geometry and substrate are provided in Table 2. The ground patterning locations can be viewed in Google Earth Pro by downloading https://tinyurl.com/groundpatterning or via IceAgeInsights.org.

The Permian outcrop (Fig. 3)

The most westerly sites of periglacial patterning are detected across the Upper Permian Cadeby Formation dolostone (Lower Magnesian Limestone), consisting of relatively simple linear and rectilinear dilated joints across exposed limestone surfaces at heights of 120–170 m OD, but with few indications of polygonisation. However, Wilson (1982) and Riley (1987) recognise a quasi-polygonal network at Brodsworth, and Berry *et al.* (2020) identify similar features at Carcroft (Skellow) as cryogenic casts. Dredge (1992) examined weathering of well-drained dolostone pavements in arctic north-east Canada; seasonal frost wedging (volumetric expansion of freezing water) can widen macro joints across these surfaces, and where joint sets intersect, polygonal patterns may result. This may explain the presence of apparent polygons at Brodsworth. Elsewhere, a number of short palaeochannels can be observed in 2018 images, flowing eastwards off the Permian dipslope; at Elmton these run into Markland Grips and thence to Creswell Crags.

The Jurassic outcrop (Figs 4–6)

Outcrops of the Greater and Inferior Oolite Groups in South Kesteven and the Welland valley present a far more varied relict periglacial landscape, exhibiting well defined dilated joints etched across till-free surfaces of the Blisworth Limestone, Cornbrash, Lower Lincolnshire Limestone and Northampton Sand Formations at heights between 20 and 80 m OD (Fig. 4). Caprock edges are very clearly defined where such competent strata overlie weaker mudstones, resulting in notable gulls and cambers (Fig. 5). Wyatt (1971) observed that Inferior Oolite cambering, by as much as 18 m, occurs between Buckminster and North Witham, Lincs. Dilated joints at Essendine (Fig. 4) are also found in association with stony cellular polygons, imparting a beaded character, thus demonstrating that ice-wedge thermal contraction cracking may have succeeded initial frost wedging. On more sloping terrain elongated stony nets and stripes are visible at Collyweston, Uffington and Wakerley.

Two striking images of potential polygons are found at high elevation at Easton on the Hill (80 m OD) and Wittering (52 m OD) (Fig. 6). These appear to be large primary rectangular polygons, with very well defined wide margins, and diameters of 20–40 m. Some finer secondary subdivision is visible at Wittering. However, the role of ice-wedge thermal contraction here is not clear. They are probably polygonised dilated joints, reflecting (a) orthogonal jointing within the Lower

***Figure 3**. Glapwell: widened linear and rectilinear joints and palaeochannel on Cadeby Formation dolostone.*

Lincolnshire Limestone and (b) irregular block-like jointing (box-stone structure) in the Northampton Sand Formation (Horswill and Horton 1976). Locally, strata dip to the east at between 1° and 5°.

***Figure 4**. Essendine: beaded joints and cellular stone polygons on Blisworth Limestone Formation.*

***Figure 5**. Witham on the Hill: parallel and criss-crossed gulls and cambers on Cornbrash Formation limestone overlying Rutland Formation mudstone (Google Earth).*

***Figure 6**. Wittering: polygonised dilated joints reflecting orthogonal jointing pattern in Lower Lincolnshire Limestone Fm.*

Lincolnshire Wolds (Fig. 13)

A few sites of chalkland non-sorted stripes have been reported from the Lincolnshire Wolds (Evans 1976; Straw 1979) and Bewley (1998) noted well-formed stripes from 1996 aerial photography at Barr Farm, Edlington. Striped patterned ground on bedrock chalk has also been found at Cabourne (Caistor), Benniworth and Haugham. Edlington was targeted in the survey of 2018 satellite images, but without success; clearer images however do exist for January 2007, displaying typical patterning at Hemingby and Baumber (Fig. 13). Dense networks of hummocky ground and closely-spaced non-sorted stripes, similar to those observed in East Anglia (Bateman *et al.* 2014) and Thanet (Murton *et al.* 2003), can be found in at least 20 locations over a 50 km² area north-west of Horncastle. These are located on very chalky till (Calcethorpe Till) rather than directly on bedrock chalk. Stripes are observed to pass off the till surface and onto river terrace sands and gravels of the Hemingby Terrace which contain ice-wedge casts and connect to the Kirkby Moor sandur (Straw 2018).

Trent Valley (Nottingham area) (Fig. 7)

Upstream of the Trent Trench, there are no visible terrace polygons in the middle and upper sections of the Trent (or its tributary valleys) (Fig. 1). The first Trent Valley polygons are encountered near Gotham (Fig. 7), consisting of reticulate and cellular polygons across Gotham Moor (and its extension into the Ruddington, Bradmore and Bunny Moors) at heights around 30 m OD, over an area of 8 km². This is one of only two locations in the region that show polygons associated with known lake deposits. Charsley *et al.* (1990) thought that this was a Holocene lake basin overlying Bunny sands and gravels, partly depressed by underground gypsum dissolution, and accessed from the Trent via the Barton in Fabis gap. The fine mesh pattern, however, suggests a periglacial landscape, with repeated subdivision of polygons denoting both long exposure and very cold conditions. Some cells consist of circular raised walls around small low centres indicating a mature stage of development across a thermokarstic lake bed, perhaps Late Devensian in age.

Within the Trent Trench itself, the extensive Holme Pierrepont Terrace appears to lack visible patterned ground for most of its length; two sites north of the Trench, Besthorpe and Broadholme (Fig. 8), do display polygons in this terrace, but this is reckoned to be an early stage in its formation (see later). The oldest surviving terrace in the Trent Trench is the Bassingfield Sands and Gravels, part of a suite of terraces (Beeston, Bassingfield, Scarle and Fulbeck) that postdates the Balderton Terrace but predates the Holme Pierrepont Terrace (Bridgland *et al.* 2014); faint outlines of incomplete polygons are visible on this terrace at Gamston (6 m above floodplain level).

Figure 7*. Gotham Moor: low-centred non-sorted reticulate and cellular nets on lacustrine sediments and Bunny Terrace sands and gravels.*

Trent terraces in the vicinity of the Lincoln Gap (Figs 11 & 12)

The most distinctive patterned ground phenomena revealed in the 2018 satellite imagery are those associated with the terraces of the Lower Trent and Witham valleys upstream of the Lincoln Gap. These relate to at least four terrace aggradations, the Holme Pierrepont, Fulbeck, Balderton and Eagle Moor Terraces, as defined by Bridgland *et al.* (2014). Howard (1995) assigned polygons at Brough to intraformational syngenetic ice wedge casts penetrating the Balderton Terrace (Brandon and Sumbler 1991).

There are many sites across the Balderton Terrace surface – at Aubourn (Fig. 11), Balderton, Barnby, Brough, Carlton le Moorland, Coddington, Langford, Newark, Norton Disney, Stapleford, and Thurlby – at elevations of around 12–18 m OD. With diameters of around 5–10 m, polygons appear to have reached a secondary stage of subdivision, but Aubourn is notable for being more fragmented and reticulate (tertiary stage). Meandering palaeochannels and ridges are found in association with some nets reflecting braided fluvial activity and aggradation that may have truncated sequences. Closer inspection of images immediately north-east of Newark reveals no less than 17 patches of such polygonised ground in an area covering about 40 km²; this high concentration confirms sites are not isolated pockets of thermal contraction, but remnants of a former extensive polygonised floodplain, at least 5 km wide.

At higher elevations (18–32 m OD) the Eagle Moor Terrace (at Eagle Moor, Coddington, Doddington, Skellingthorpe, Swinderby and Whisby) has slightly less well-defined polygons, mostly with diameters of 5 -10 m. Larger primary polygons (30–50 m) however are visible at Skellingthorpe (Fig. 12). This is an important discovery as it coincides with the location of near-surface Skellingthorpe Clay (Jackson 1977; Brandon and Sumbler 1988; Bridgland *et al.* 2014). At Monsons Farm the lower facet of this terrace consists of 2.5 m of sands and gravels overlying 6.5 m of well-laminated red-brown clays and silts (between 9.7 m and 16.2 m OD) which overlie Charmouth Mudstone. In the upper facet of the terrace, Skellingthorpe Clay is proved in boreholes between 5 m and 25 m OD, confirming a substantial thickness (20 m) of glacio-lacustrine sediment. For more details, see Andy Howard's sections (in Bridgland *et al.* 2014, plate 8) and BGS borehole log scans 251409 and 251494. This is a significant sedimentary horizon indicating the earliest drainage through the Lincoln Gap (Bridgland *et al.* 2014, p 308); it probably resulted from glacial ponding ahead of the Wragby Till ice front. Skellingthorpe is thus the second instance of lake-related polygons (with Gotham) found in association with surviving lake deposits.

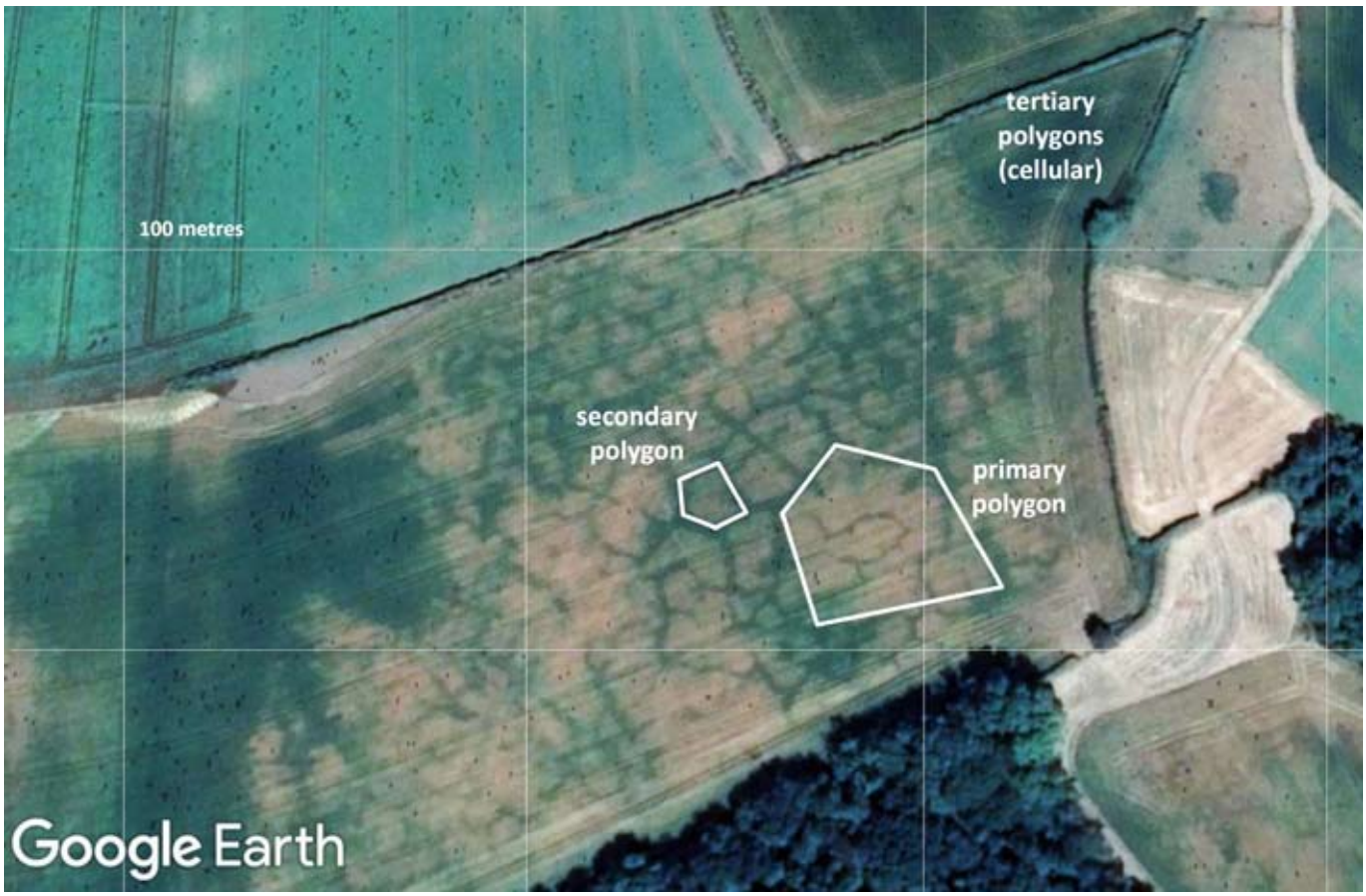

***Figure 8**. Broadholme: high-centred non-sorted primary, secondary and tertiary polygons on early Holme Pierrepont Terrace sands and gravels (HPSG-A).*

In the Witham valley there are a number of potential sites of patterned ground across the surface of the Fulbeck Terrace, between 8 m and 16 m OD, including Brant Broughton, Carlton le Moorland and Stragglethorpe, but patterning is generally incomplete and poorly-defined.

The Devon-Smite valley (Figs 9, 14 & 15)

Within the Devon-Smite catchment (Fig. 14) almost all polygons are found imprinted on bedrock surfaces. It is unlikely that these regular ('honeycomb') polygons were formed directly on bedrock. They are believed to be the truncated roots of ice-wedge casts originating from former cover deposits. Most of these networks are of secondary character, displaying diameters of 10–20 m, and bedrock surfaces are mainly cut across Arden Sandstone (Fig. 9) and Edwalton Formation dolomitic siltstone (skerry). One example however is directly imprinted on terrace gravels at Aslockton. A. S. Howard *et al.* (2009) describe the evidence for this terrace (their Whatton Terrace) in the Devon-Smite valley. However, Bridgland *et al.* (2014, p 105) question its supposed correlation with the Balderton Terrace at Newark. They re-examined locations seen during the BGS resurvey, concluding that most of them were of a residual nature; the gravels, they contend, are too poorly developed to justify the attribution of terrace. Nevertheless, plotted levels of deposits (Fig. 15) are consistently graded downstream and are compatible with the height of the bedrock networks, showing that the roots of former ice wedges could have penetrated the Whatton Terrace surface by up to 5–7 metres. This is a measure of the potential ice wedge depth and the thickness of host cover sediment and active layer that has since been lost to erosion. The case therefore for correlating Whatton Sands and Gravels with those of the Balderton Terrace is not an unreasonable one, and polygonised surfaces were probably generated across its surface.

The Cropwell Butler Gap (Figs 10, 15 & 16)

Further up-valley the headwaters of the present Devon-Smite arise south of Bingham in the Cropwell Butler Gap. Fig. 16 plots a dozen scattered fragments of polygonised bedrock in this area (Edwalton Formation skerry surfaces) between 26 m and 61 m OD, some with well-defined ice-wedge cast features such as double-ditched margins indicative of mature thermal contraction (Fig. 10). Altitudes are notably higher than those in the Whatton Terrace (Fig. 15), but no supportive depositional record survives at this elevation. Rathbone (1989) noted ice-wedge casts present below Holocene lake bed sediments north of Bingham, but there are no older terraces that could have acted as cover deposits. One possible explanation for this anomaly would be the existence of a former lake basin, with epigenetic ice wedges formed successively on a retreating shoreline.

Figure 9. *Thorpe Lodge: regular, non-sorted, low-centred secondary polygons imprinted on Arden Sandstone Member.*

Figure 10. *Bingham (Spring Farm): regular non-sorted low-centred secondary polygons, imprinted on Edwalton Formation dolomitic siltstone (skerry); inset shows double-ditched polygonal walls.*

At about 40 m OD, the Cropwell Butler Gap col could not have been occupied any later than the Eagle Moor Terrace (see projected downstream gradient, Bridgland *et al.* 2014, plate 4); this is precisely the terrace stage at which the Skellingthorpe Clay was formed. Both Skellingthorpe and Cropwell Butler polygons therefore could have formed under similar conditions, namely, proglacial ponding ahead of an advancing ice barrier.

Figure 11. *Aubourn: regular non-sorted, high-centred reticulate polygons on Balderton Terrace sands and gravels.*

Figure 12. *Skellingthorpe: large primary and secondary polygons imprinted on shallow Eagle Moor Terrace sands and gravels, underlain by 6.5 m of glacio-lacustrine Skellingthorpe Clay at Monsons Farm (note: grid scale is 200 m).*

Figure 13. *Baumber: non-sorted polygonal cells, nets and stripes (convergent and divergent) on very chalky Calcethorpe Till overlying Kimmeridge Clay Formation (2007 image).*

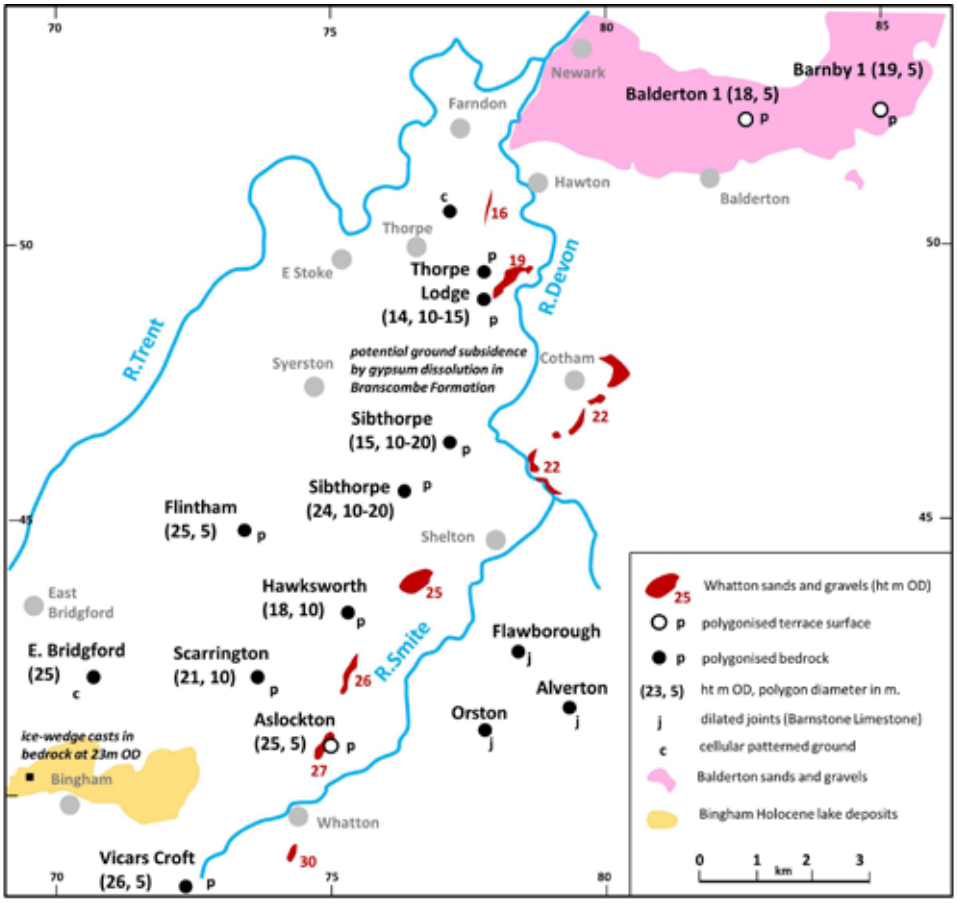

Figure 14. *Devon-Smite valley. Location of polygonised terrace and bedrock surfaces in relation to the Whatton Sands and Gravels (A. S. Howard et al. 2009) and Balderton Sands and Gravels (Bridgland et al. 2014).*

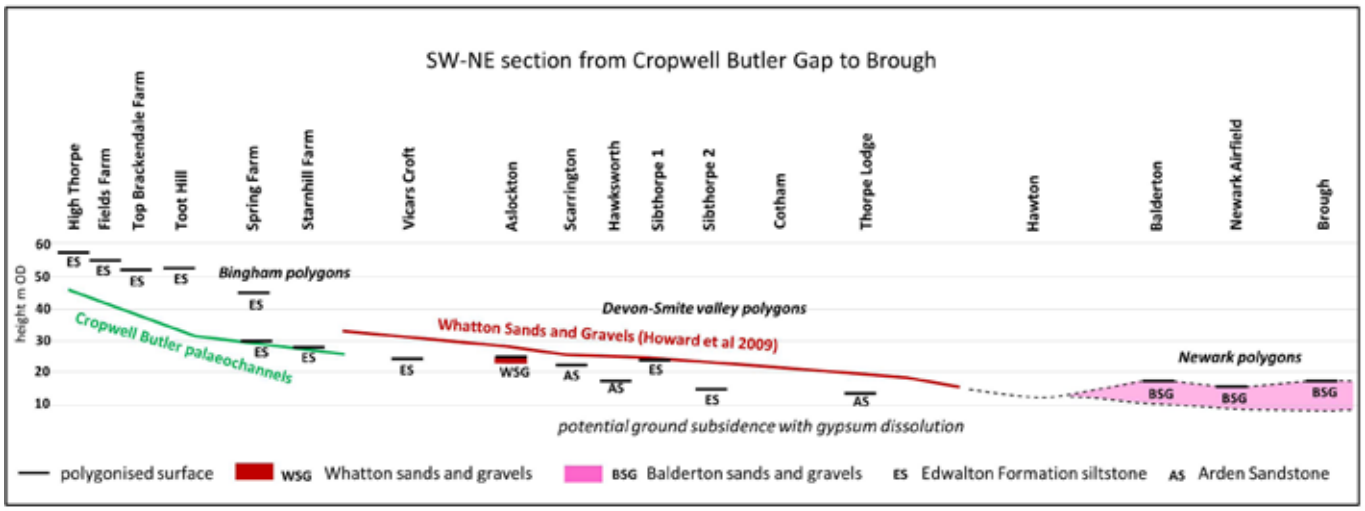

Figure 15. *A 30-km long section from Cropwell Butler to Brough illustrating elevations of polygonised surfaces in relation to the Cropwell Butler Gap, the Whatton Terrace (Devon-Smite valley) and the Balderton Terrace (Newark).*

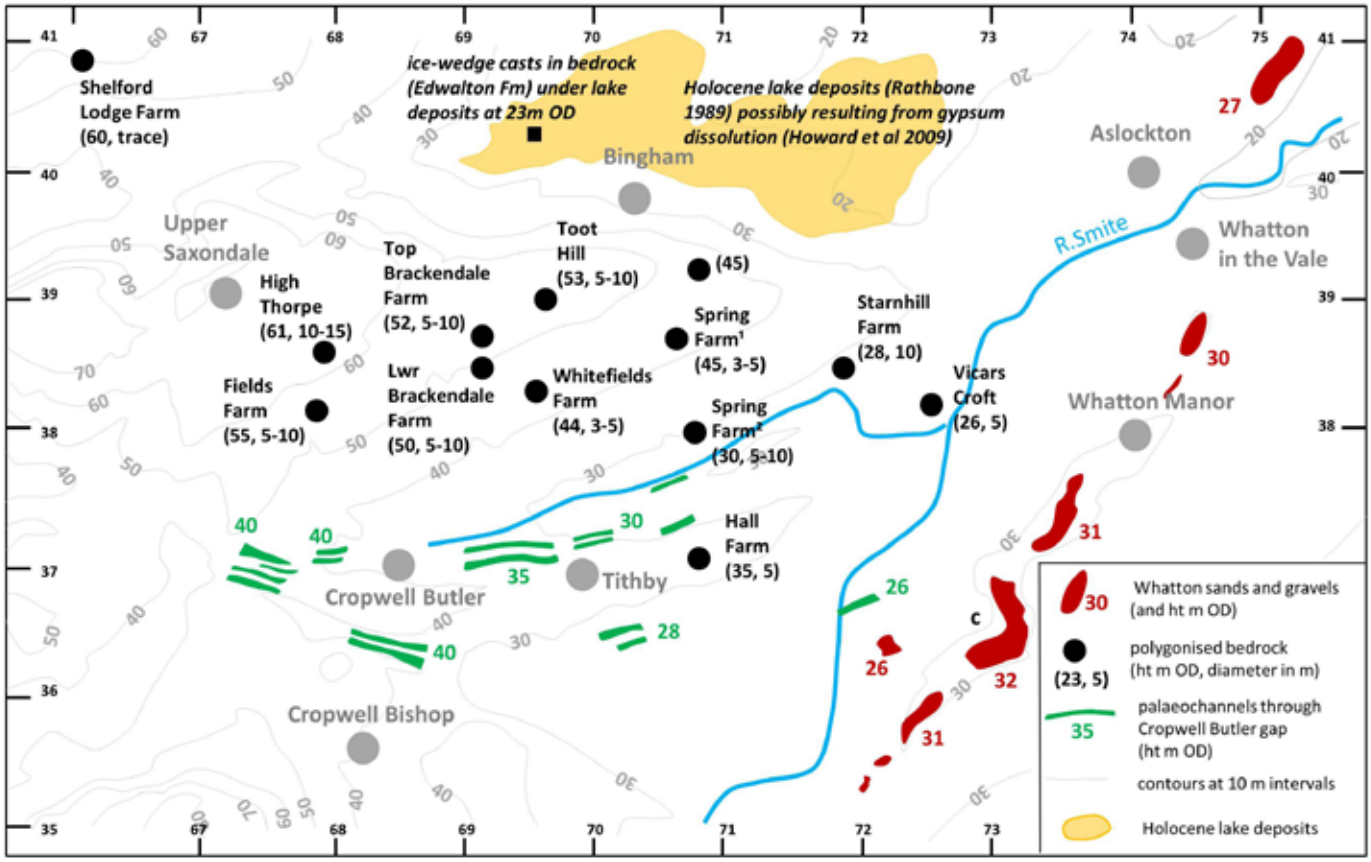

Figure 16. *Cropwell Butler Gap. Sites of polygonised bedrock (Edwalton Formation siltstone or skerry) and palaeochannels visible in 2018 imagery.*

Pre-Devensian glacial ponding – a possible hypothesis

Langford (2018) identifies ice-contact deltaic deposits at Uffington at a height of 20–30 m OD, and stratified lake sediments at Elton at 28–35 m OD, indicating small proglacial lakes trapped against the Nene-Welland interfluve. These are part of a sequence of ice-marginal features recognised along a north-south corridor connecting Essendine and the East Glen valley (Straw 2020). Skellingthorpe and Cropwell Butler (described above) and Uffington and Elton (Langford 2018) all share this in common: they appear to register a process of glacial ponding by Wragby Till ice, advancing westwards (or perhaps southwards) blocking the exit of eastward-flowing rivers. Straw (2020) speculates that this ice went on to block the Ancaster Gap, while Gibbard *et al.* (2020) propose that the Lincoln Gap was also closed off by advancing ice at this stage. These views are entirely consistent with a glacio-lacustrine

interpretation of the Skellingthorpe Clay and postulated lake bed polygons at Cropwell Butler. The height of potential ponding at Cropwell Butler (61 m OD) raises the level of the glacial barrier considerably.

Chronology of the patterned ground

Bateman *et al.* (2014) identify four main episodes of periglacial activity in East Anglia: 60–55 ka, 35–31 ka, 22–20 ka (Last Glacial Maximum), and 12–11 ka (Younger Dryas). Comprehensive coverage of French periglacial patterned ground (Bertran *et al.* 2013) has also established that large polygons (8–25 m diameter) in the Paris Basin reflect epigenetic ice-wedge casts, and mostly date to 36–25 ka, coinciding with the second episode of Bateman *et al.* (2014). Earliest periglaciation in the East Midlands, however, potentially predates all these Devensian episodes, and should probably be attributed to the late Middle Pleistocene Wolstonian interval (MIS 10–MIS 6, 374–123 ka). The extent and dating of the Wolstonian ice advance however is difficult to establish, and is the subject of ongoing debate (Gibbard *et al.* 2020; Westaway, 2021). Conflicting arguments are complex, but essentially they are contingent on the position taken regarding the timing of glaciation (whether Middle, MIS 8, or Later, MIS 6), and the interpretation of interglacial horizons within the terrace deposits themselves. At present there are no means of directly dating the polygonal horizons. It would certainly be incorrect to assume they are in any way synchronous. The formation of individual terrace surfaces provides the earliest date (*terminus post quem*) at which a given polygon could possibly have been formed. Episodes of periglacial activity are probably polycyclic (Bateman *et al.* 2014; Murton and Ballantyne 2017) and so it is likely that later events could have reopened and re-activated previous lines of weakness. Table 3 attempts to place maximum time constraints on the various periglacial horizons identified.

The Holme Pierrepont Terrace mostly lacks polygonal imprint, a possible artefact of preservation. On the other hand, Howard *et al.* (2011) conclude that there were two phases of aggradation, here termed HPSG-A (lower) and HPSG-B (upper). The lower unit is tentatively dated to 28,800 ± 200 BP (Brown *et al.* 1994) which calibrates to 33,380 ± 370 cal BP (Westaway *et al.* 2015), while the upper falls between 12,900 ± 180 and 13,050 ± 180 cal BP, meaning that the two phases occurred (A) towards the end of MIS 3 (MIS 2 commencing at 29 ka) and (B) the close of MIS 2. Bridgland *et al.* (2014, p 108) also show that the terrace appears to bifurcate at Spalford; from there, HPSG-A passes north-eastwards into the Lincoln Gap following the old route established during Eagle Moor and Balderton stages, while HPSG-B is aligned north to the Humber. Polygons are thus segregated, found on the older HPSG-A surface (Broadholme, Fig. 8), but not on the younger HPSG-B, reflecting its more recent Lateglacial origin.

Widened joints, gulls and cambers within Permian and Jurassic outcrops are difficult to date and may have had distant origins, but the co-existence of joints and cells (beaded joints) is a significant observation, confirming periglacial origin, probably of Late Devensian age. Similarly, the non-sorted stripes on Calcethorpe Till and the Hemingby Terrace are superficial structures unlikely to have survived the Last Glacial Maximum, so may be as recent as the Younger Dryas. Indeed, stripes at Caistor are closely associated with Lateglacial coversand sequences (Bateman *et al.* 2000).

Recent work at Farndon Fields has identified polygonal frost cracking some 0.3 m across, where ice-vein sand casts are infilled by overlying coversands dated by OSL to 11.76 ± 0.79 ka (Garton *et al.* 2020, table 1). Similar sand veins of Younger Dryas age are reported from Westwoodside and Yarborough (Bateman *et al.* 2001; Murton *et al.* 2001), but no polygonal ground expression for these veins is visible on satellite

Polygonal horizons	Earliest date (*tpq*)	MIS	ka BP
Lake deposits overlying Bunny Terrace	Late Devensian (LGM)	2	14 - 29
Early Holme Pierrepont Terrace (HPSG-A)	Late Devensian (LGM)	2/3 transition	
Bassingfield Terrace and Fulbeck Terrace	Early-Mid Devensian	3 – 5d	29 - 109
Hemingby Terrace	Pre-Devensian	Late 6 or 8	(6) 123 - 191 or (8) 243 - 300
Whatton Terrace and Balderton Terrace	Pre-Devensian	Late 6 or 8	
Wragby Till and Calcethorpe Till	Pre-Devensian	6 or 8	
Eagle Moor Terrace and Skellingthorpe Clay	Pre-Devensian	Early 6 or 8	

***Table 3**. Proposed earliest date constraints (terminus post quem) for polygonal horizons. The tpq is oldest (earliest) date for an event determined by the youngest affected layer below the horizon (pre-polygon). LGM is Last Glacial Maximum.*

imagery. The most parsimonious explanation for this is that conditions were insufficiently cold in the Younger Dryas to have generated multiple and deep ice wedges, compared with the extreme cold of a longer Last Glacial Maximum.

Conclusions

1. Satellite imagery from July 2018 can be easily accessed online, and has been usefully employed to identify deep subsoil patterned ground not usually visible in crop markings. Timing of these patterns appears to relate to former ice-marginal periglacial activity.

2. Central areas of the East Midlands (Lower Trent, Vale of Belvoir, Witham valley, Lincoln Gap) have retained evidence of regular mature polygons, thought to have formed during the late Middle Pleistocene (or later). These are imprinted on older river terrace remnants such as those of the Eagle Moor, Balderton, Fulbeck and Bassingfield terraces. Patterned ground of Late Devensian age appears only on the lower phase of the Holme Pierrepont Terrace (HPSG-A).

3. Certain terraced areas are devoid of polygonal patterning by reason of erosion or deep burial, but in the case of the upper Holme Pierrepont terrace (HPSG-B) it is likely that shorter duration and less intensity of periglacial activity during the Lateglacial may explain its absence as clear crop marks. Small cryoturbation structures (including ice-vein sand casts) have been located at Farndon Fields (Younger Dryas) but lack any obvious polygonal expression at ground level.

4. Permian dolostone outcrops in the west of the region display relatively simple dilated joints, but polygonised in a few places, probably reflecting frost wedging on orthogonal joint sets rather than ice-wedge thermal contraction.

5. Jurassic limestone and sandstone outcrops in the south-east present a far more varied relict periglacial landscape, with dilated joints, gulls, cambers, scatters of cellular hillslope polygons and stone stripes, all of uncertain age. In places, cells and joints combine to form beaded joints showing that ice-wedge thermal contraction may have succeeded frost wedging.

6. Typical hummocky and striped chalkland patterning is present in the Lincolnshire Wolds north-west of Horncastle, but formed on very chalky Calcethorpe Till rather than bedrock chalk; stripes are observed to pass downslope and across the Hemingby Terrace.

7. Mature regular polygons are imprinted in bedrock sandstone and siltstone in the Devon-Smite valley, and are thought to be the truncated roots of ice-wedge casts. They probably relate to pre-Devensian periglacial conditions associated with the Whatton Terrace, at a level graded to the Balderton Terrace.

8. Two locations have been located where polygonal patterning is found in association with known lake deposits: Skellingthorpe and Gotham.

9. High-level bedrock polygons have been located within the Cropwell Butler Gap and may be the result of a former drained lake basin. Together with sites of established lake sediments at lower levels (Skellingthorpe, Uffington, Elton), an hypothesis of multiple glacial ponding ahead of advancing late Middle Pleistocene ice is proposed, with significant implications for palaeodrainage reconstruction.

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Ice Age Insights is a community archaeology group, formed in 2016, and a charity aiming to promote the investigation of Palaeolithic archaeology and geology in the East Midlands through the "Ice Age Journeys" project (registered charity number 1169575, website: IceAgeInsights.org.)