Ice-wedge growth and casting in a Late Pleistocene, periglacial, fluvial succession at Baston, Lincolnshire

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Abstract: A range of relict, periglacial, ice-wedge cast structures exposed in the working faces of an aggregate quarry are interpreted by reference to analogues in the continuous permafrost of the western Canadian Arctic. Since the host sediments are stable, non-frost-susceptible sandy gravels, cast morphology displays little modification from the original ground ice geometry. Many of the casts are epigenetic and appear to result from the normal single growth and decay cycle, but the remainder are the products of two or more cycles involving rejuvenated ice-wedge growth in previously casted ice wedges. Sedimentological relationships within the latter reveal a complex history of development that is probably a response to both local and regional scale rapid climatic changes. Casts occur at three main horizons, but not exclusively so. The most severe periglacial phase is dated to the Last Glacial Maximum stadial *c.*18-25 ka BP and the youngest to the Loch Lomond Stadial *c.*12 ka BP.

Geological reconstructions of former periglacial environments in the Quaternary, i.e. those that sustained perennially frozen ground or permafrost (Fig. 1), are an important aspect of unravelling the climatic history of the past (Worsley, 2003). The key to this endeavour is the diagnosis of sedimentary structures genetically related to permafrost, and the most ubiquitous of these are ice-wedge casts; they are therefore pseudomorphs. Such casts form when ground ice thaws and is replaced by sediment. Broad estimates of mean annual air temperatures, by reference to the distribution of actively growing ice wedges in contemporary permafrost, yield a maximum of –6° C, but this value is influenced by local environmental factors. Observations in Russia indicate that ice-wedge growth in gravels requires a more severe climate than that needed in finer-grained sediments (Romanovskii, 1985).

***Figure 1**. An actively eroding coastal cliff, 6 m high, on Banks Island, Canada, formed of permafrost bonding unlithified silts, sands and gravels. During rare storms, wave action rapidly removes the slumped thaw sediments (which normally form a low-angle slope down to the beach) and produces a thermally eroded niche that extends some metres beneath the cliff. Toppling failure causes blocks of the permafrost to rotate through 90°. Note the extent of ground ice (mainly ice wedges) exposed in the blocks.*

A persistent problem is the confusion of real ice-wedge casts with forms that are not genetically related to permafrost, mainly because in cross section all are characterised by a host sediment containing a discordant infill with a tapering elongate shape. Johnsson (1959) was the first to discuss true and false ice-wedge casts, and Burbidge *et al* (1987) focussed on the confusion with water-escape structures. In north Norfolk, where ice-wedge casts have been reported in a marine facies, clastic dykes can be demonstrated (Worsley, 1996), although at a nearby site, Fish *et al* (1998) have claimed a 'composite-wedge cast' in a similar 'preglacial' facies, yet a colour photograph of it is indistinguishable from a water-escape feature (Murton 2013, Fig.9). Seismic events can also simulate forms reminiscent of ice-wedge casts (Thorsen *et al*, 1986). Although ice-wedge casts have been identified in Britain for over 150 years, it was many years before comparative studies with ice wedges were made (Worsley, 1999). A pioneering study by Paterson (1940) compared casts near Cambridge with modern ice wedges in Baffin Island. Yet, this direct comparative approach utilising modern analogues has been rarely repeated, and is hindered by the remote locations of modern ice wedges.

The Baston site

Baston Manor Pit [TF126143], an aggregate quarry formerly owned by F.J. Gibbons and Son, lies immediately east of the village of Baston in southwest Lincolnshire (Fig. 2). Reports of splendid ice-wedge cast exposures led to a reconnaissance visit by the writer in March 1980, and numerous monitoring visits were made during the following two decades. As a member of the writer's periglacial group, Mary Seddon worked at Baston in 1981-83, as part of her thesis studies (Seddon, 1984). In 1990, the Baston casts were demonstrated to a global audience during a field excursion for the International Association of Sedimentologists congress, then being held in Nottingham,

The surface geology of the western Fenland margin shows a fringe of Last Glacial Stage (Devensian/ Weichselian) low-angle fans and terraces underlain

***Figure 2**. Part of the Manor Pit at Baston within the context of the Fenland landscape (April 1995). The gravels are being excavated on two levels. An ice-wedge cast is exposed on the far left, descending through the two working levels and into the bedrock clay forming the quarry floor. Behind the two figures, an ice-wedge cast in oblique section is visible in the lower face.*

by sandy gravels with a cover of silt, over Jurassic bedrock. These total 4-5 m thick, and when traced eastwards towards the Wash, descend beneath a cover of Holocene alluvium. In his classic memoir 'Geology of Fenland', Sydney Skertchly (1877, p186) aptly described the lithology as - *It is the usual fen character, consisting chiefly of oolitic limestone, ironstone, flint, with occasional pebbles of older rooks ..... In places it is cemented into compact beds by oxide of iron*. He later commented that the 'iron gravel' occurred as an intensely hard conglomerate needing gunpowder to break it up. Essentially the Baston sequence above bedrock is divisible into three facies units (Table 1). Apart from the upper silt, the facies sequences are characteristic of shifting braided shallow river channels reworking within-channel bars.

The gravels have subsequently been referred to as either Fen-edge Gravels (Horton, 1981) or First Terrace sediments (Booth, 1983; Horton, 1989). They normally lie on a nearly flat unconformity eroded across the underlying Middle Jurassic Oxford Clay Formation (Ancholme Group), which consists of grey blocky mudstones with calcareous concretions (Fig. 3). In the context of the local geomorphology and hydrology, Baston is part of the catchment of the River Glen and it is to that river basin that the sediment source is ascribed. During the Last Glacial Maximum (LGM), Baston was outside the limit of maximum glaciation, which lay at least 25 km to the northeast, close to Boston. So the Baston area was a true periglacial environment. Most of the Fenland area has not been glaciated since before the Last (Ipswichian/Eemian) Interglacial.

A thin sandy silt, which occurs immediately below the ground surface.
A variable, near-horizontal bed of sandy gravels, over a significant para-unconformity above a variously preserved Arctic Structure Soil.
Trough-cross-bedded, clast-rich sands, characterised by planar horizontal and low-angle bedding, with isolated shallow channels infilled by organic rich silts and reworked organic clasts.

***Table 1**. The Quaternary sequence at Baston.*

***Figure 3**. The Baston Pleistocene succession, 4 m thick, above a planar unconformity on the Jurassic Oxford Clay. An ice-wedge cast crosses the unconformity in the shadowed hollow.*

Booth (1983) provided the first published outline of the Baston stratigraphy, and he identified two distinct horizons of ice-wedge casts. Details of the facies exposed at Baston have been described by Seddon (1984) and Briant *et al* (2004b). Photographs of Baston ice-wedge casts, taken by the writer in the 1980s, are featured in the literature (Worsley, 1987; Ballantyne & Harris, 1994; Harris, 1990; Waugh, 1995). Pits excavated in the sandy gravels associated with the Fen margins commonly reveal ice-wedge cast structures (Bell, 1970; Bryant, 1983; Horton, 1989; Davey *et al*, 1991; Straw, 1991; West, 1993a; Keen *et al*, 1999; Briant *et al*, 2004a, 2005). During the growth of the original ice wedges, the alluvial surface must have been stable for at least a millennium, when it is likely that the zone of river activity either shifted to others area on the fan surface or the run-off was severely reduced with most of the fan becoming inactive. An interdisciplinary investigation of the Baston stratigraphy (Briant *et al*, 2004b) had the principle objective of testing the hypothesis that a regional phase of aridity and attendant low fluvial runoff characterised the LGM in Fenland. That focus overlooked the full, permafrost-related, stratigraphic testimony at Baston due to its concentration on the main horizon of ice-wedge casts rather than on the total record present. Accordingly, the current rationale is to identify the full palaeo-permafrost stratigraphy by documenting the kinds of ice-wedge casts and then seeking an understanding of the processes that led to their development. This is aided by recourse to comparisons with the modern environment of continuous permafrost on Banks Island, NWT, Canada (at 72°N, 125°W, with a mean annual temperature of -14°C).

Ice wedges

An ice wedge may be defined as *a massive, generally wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice* (Harris, 1988). Wedges are a form of ground ice within permafrost, and are typically 1-3 m wide and 2-6 m deep (Fig. 4). Their growth is due to recurrent thermal contraction cracking within the permafrost (beneath the active layer) during rapid cooling events and these usually occur as the winter season sets in. Cracks, up to several millimetres wide, extend upwards to the surface where they are subject to infilling by the combined action of snow, hoar frost and meltwater. Most can be classified as *epigenetic*, i.e. they have grown incrementally beneath a stable land surface, but the converse occurs where net sedimentation leads to aggradation of the land surface causing the ice wedges to progressively grow upwards in unison with the rise of the permafrost table – these are termed *syngenetic* ice wedges (Worsley, 1994). Normally, ice wedges do not crop out at the surface because they lie beneath the active layer, the zone of annual freezing and thawing above the permafrost table. However, they do give rise to surface morphological expression as either oriented or random polygons 15–60 m in diameter, commonly with parallel, twin, raised rims where uplift of the host sediment has occurred on either side of the underlying ice wedge during growth (Figs. 4 - 7).

***Figure 4**. An ice wedge on Banks Island, exposed by rapid coastal erosion following a storm. Note the trough above the top of the ice wedge, and also the base of the contemporary active layer about 25 cm below ground level. The trowel is about 35 cm long.*

***Figure 5**. Air view of ice-wedge polygons in winter on Richards Island in the Mackenzie Delta, Canada. Blowing snow filters down into the open thermal contraction cracks in the ice wedges, thereby incrementally adding to the volume of wedge ice on an annual basis. The polygons are mostly around 30 metres across; snow has drifted from left to right.*

In certain circumstances, generally in more arid locations, the open thermal contraction cracks contain sand as a primary infill, and these grow into so-called sand wedges (Murton *et al.,* 2000). Cyclic repetition of cracking and sand infilling produces a vertically orientated internal lamination to the upper part of the wedge structure, although at depth the individual infills commonly become a series of criss-crossing dykelets. Sand wedges, by their essentially ice-free nature, are not transformed by casting when their host permafrost thaws. Examples have not been identified at Baston.

Figure 6. *Not all rivers flowing over continuous permafrost are braided. In the centre of Banks Island, the Thomson River meanders around classic point bars and an oxbow lake on the left. Right of the active river channel in the foreground, rectilinear ice wedges within the floodplain sediments are revealed by fresh snow that has drifted into the troughs above the wedges.*

Processes of ice-wedge casting

The sedimentology of ice-wedge casts yields valuable insights into the casting processes, although their interpretation needs to be guided by knowledge of modern analogue situations. Nevertheless, it is essential to recall that current Arctic environments have yet to experience significant, widespread permafrost decay on the scale that occurred in Britain at glacial/interglacial and stadial/interstadial transitions (though this is an inevitable consequence of future global warming). Current casting processes in permafrost environments are largely determined by local scale factors.

Figure *7. A net of vegetated low-centre ice-wedge polygons with a typical diameter of c.30 m, on Banks Island. The dish geometry of each polygon encourages the creation of tundra ponds, which are defined by the raised rims adjacent to the bounding ice wedges in the sub-surface. Over time these ponds tend to amalgamate, as at the top right, and flood the sites of the ice wedges. Some ice-wedge troughs have been transgressed by the lakes on the right. As the water warms in the summer months the sub-lake ice wedges within the upper part of the permafrost melt and are casted.*

A key factor in determining whether evidence of former permafrost degradation survives in the geological record is the nature of the host materials, and allied to this is the amount of segregation ice that may have developed. A striking feature of ice-wedge cast distribution in Britain is that their greatest numbers occur in coarse sediments, particularly sandy gravels. These are termed non-frost-susceptible since there is little capillary action sucking unfrozen water to the freezing zone to form segregation ice, hence they are largely stable during thaw. In contrast, silts and clays are frost-susceptible, and during cooling events this range of particle size facilitates the development of segregation ice by the process of cryosuction. When segregation ice melts it gives rise to increased pore water pressures, leading to sediment instability, with gravitational slumping and thaw transformation of the ice making the identification of former ice wedges problematical (Harry & Gozdzik, 1988). Therefore the relative rarity of ice-wedge casts in frost-susceptible

Figure 8. *A small stream on Banks Island is thermally eroding an ice wedge, and the active layer of the overlying tundra mat is in the process of slumping into the deepening cavity, thereby creating a sediment cast of the ice wedge. The surface sediments are inter-bedded, organic-rich silts and sands.*

Figure 9. A coastal cliff exposure of permafrost on Banks Island. An older, dormant ice wedge on the left, has a flat top just over a metre below the land surface (the depth of the active layer when the climate was less severe in the early Holocene). In contrast, on the right a younger ice wedge extends to within 25 cm of the land surface; it is in equilibrium with the harsher, contemporary, climatic regime, which has a thinner active layer.

materials is explained by preservation potential rather than by the former absence of ice wedges. Thermal erosion and thaw influence at least four mechanisms that contribute to the casting process, with the first three operating primarily at a local scale (Table 2).

A major change in perspective when assessing variations in permafrost extent in Britain arose from 1992 onwards when the results from investigations of the GISP and GRIP ice cores from central Greenland became available. These gave new insights into both the rapidity and frequency of climatic change during the 100 ka of the Last Glacial, the so-called 'flickering switch' mechanism showing that climates had been very unstable even within the stadial periods (when had previously been assumed to have been essentially stable). Inevitably, these climatic variations would have first impacted on the thickness of the active layer. A stratigraphically well-constrained example occurs in Banks Island, Canada, where an early Holocene warm phase caused an active layer to thicken by about a metre. This truncated the tops of the ice-wedges producing a *thaw unconformity*. Subsequently, under a deteriorating climate in the mid and late Holocene, the permafrost table and attendant ice wedges have extended upwards to be in equilibrium with a shallower active layer depth of c.0.3 m (Fig. 9; Worsley, 2000, 2014). In northern Québec, the Little Ice Age (Late Neoglacial) event witnessed widespread reactivation of ice wedges followed by deactivation and dormancy that has persisted to the present (Kasper & Allard, 2001).

Beneath rivers and lakes there is commonly an unfrozen zone or talik within the permafrost. Changes in channel location or lake extension can cause the talik to shift its position, such that any ice wedges that become incorporated within a migrating talik will inevitably decay and cast (Fig. 5). This casting mechanism was first invoked by Bryant (1983).
Tundra ponds within ice-wedge polygons act as heat sinks in the summer with the relatively warm water causing the underlying permafrost table to deepen. Where pond shorelines transgress, adjacent ponds can amalgamate and extend across the ice wedges that had previously defined the pond boundaries, causing at least the upper parts of the ice wedges to degrade (Fig. 7).
The troughs above the ice wedges can be adopted by meltwater drainage systems during the summer, and when this occurs the water can rapidly incise by thermal erosion into the wedge ice below. The adjacent surficial thawed sediments tend to slump into the cavities so created (Fig. 8).
Major climatic amelioration can lead to total permafrost decay and the creation of regional thermokarst.

***Table 2**. The four mechanisms that contribute to the normal process of ice-wedge casting.*

The Baston ice-wedge casts

The casts encountered in the changing quarry exposures may be classified into three general groups based on their characteristics in cross-section. The quarry faces were excavated independently of the casts, so many of the cross-section exposures were not normal to the wedge axes. A striking feature of the Baston ice-wedge casts is the near absence of evidence of fold deformation within the host gravels.

***Figure 10**. A vertical section, c.3 m thick, through part of the Arctic Structure Soil at Baston, where it is unconformably overlain by a thin sequence of horizontally stratified gravels. These involutions are probably related to patterned-ground nets on the ground surface adjacent to the growing ice wedges.*

Single-cycle ice-wedge casts

These casts generally show a simple wedge shape, tapering in width from the top to their lower termination. Normally the tops of the wedge infills lie some 1-2 m below the ground surface at a horizon corresponding to a slight erosional unconformity which causes minor truncation of the original cast structure. Where the erosion is minimal, parts of the soil profile lateral to the wedge tops survives and this palaeosol displays cryogenic disturbance in the form of involutions and clasts with their long axes sub-vertical, forming an Arctic Structure Soil (Fig. 10). In plan form these would have originally been small-scale patterned ground. In addition, the palaeosol is locally a zone of silt enrichment, suggesting the incorporation of loess into the soil profile. Another possible silt source might have been from the waters of proglacial Lake Sparks, at the local LGM ice maximum, if it extended northwards to Baston (West, 1993a, b).

The exposed casts are typically about a metre wide at the top and progressively narrow downwards to an average depth of 3-4 m (Figs. 11, 12, 13). But as the lower parts of the casts commonly penetrate the bedrock surface beneath the gravels, the basal parts are rarely seen. Occasionally however, drainage ditches excavated into the Oxford Clay bedrock forming the

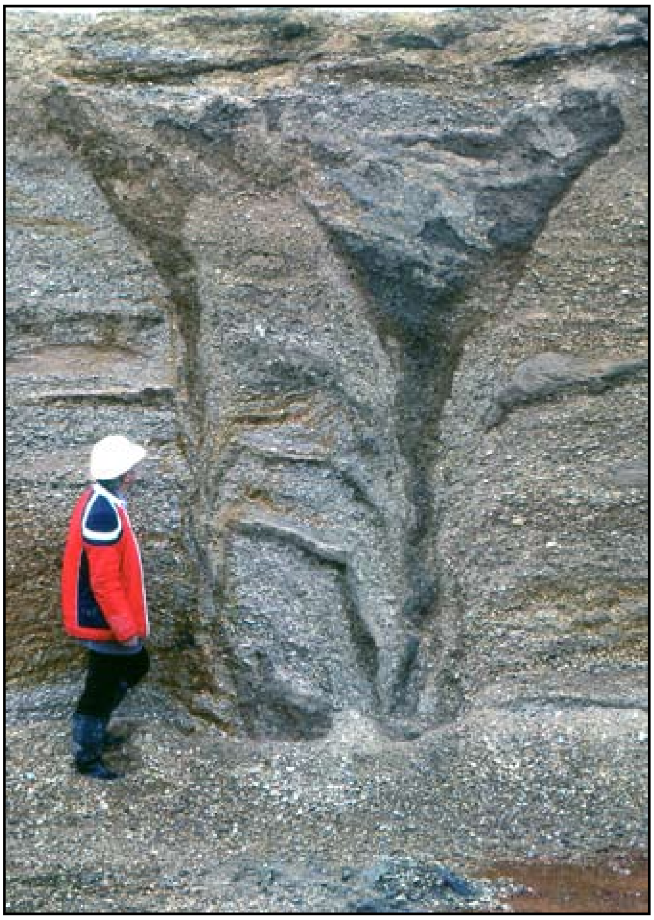

Figure 11. *Two typical ice-wedge casts of single-cycle type descending from the main horizon of development (second generation of growth). The left cast appears to be cut by the fill of the right cast, which would mean that the latter was later.*

Figure 12. *Two truncated single-cycle ice-wedge casts belonging to the first generation at Baston, lying below the major erosional unconformity. The infill on the left is silt, whereas that on the right is sandy gravel. The lowest part of the left cast could be traced for over 40 m across the quarry floor, and is partly shown in Figure 14.*

Figure 13. *A single-cycle ice-wedge cast exposed in the quarry face where the cast axis is almost parallel with the exposure, which is 4 metres high. The infill is mainly organic-rich silt.*

***Figure 14**. The base of an ice-wedge cast penetrating the Jurassic clay exposed in and beyond a drainage ditch cut into the quarry floor. At this point the fill is much coarser at depth than it is towards the top of the cast exposed in the face 40 m away.*

quarry floor expose the lower parts of the wedges (Fig. 14) and the casts can be seen to extend for over a metre below the main quarry floor. In some cases it has been possible to trace the basal wedge fills where they are exposed as linear casts within the Oxford Clay on the quarry floor. As these correspond to the axial planes of the former ice wedges, they demonstrate a polygonal ground pattern but in a plane at some depth below the original land surface.

Many cast infills display a systematic sedimentary organisation. Typically the interface of the cast with the host gravels shows a thin (5-10 cm thick) clast-rich lining parallel with the cast walls (Fig. 15). The long axes of the clasts lie parallel with the walls; this suggests that during the initial phase of ice-wedge melt the outside of the wedge ice thawed first, and clasts released by the thaw from the host sediment were able to slide down the cavity. It is likely that the permafrost within the ice-poor host sediments, with its lower latent heat potential, melted before the ice wedges, as the latter's higher latent heat would take longer to dissipate. In contrast, the central part of the cast infill is often a massive silt that has clearly been derived by slumping from a source horizon above or adjacent to the ice-wedge cast top. This silt probably accumulated within the surface polygons, and during permafrost degradation was redistributed by meltwater. However, variations in the sediment size within the fills are common, and sands and gravels that are not derived directly from the host sediment were introduced as the wedge tops melted. Commonly, the upper part of the cast fill takes the form of a flat-bottomed channel containing well-sorted, horizontally bedded sandy gravels, suggesting a late phase of high flow regime water movement along the top of the wedge axis. Frequently there is evidence of a phase of ice-wedge growth reactivation within the central cast infill, and normally these smaller infills are relatively coarse-grained.

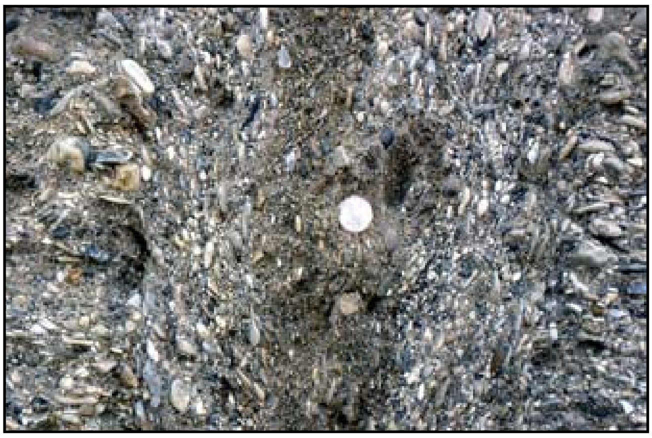

***Figure 15**. The distinctive, vertical clast fabric at the interface between the host sediment and the main cast infill. The host sediment on either side has a clast-supported fabric. Scale is provided by a 50 pence coin, 25 mm in diameter.*

Frost-crack wedges

These are narrow wedge forms without any significant infill other than the down-turning of the adjacent host stratification (Fig. 16). Conventionally these forms probably signify either only short-term surface stability or brief very cold periods of insufficient duration to permit growth of more mature ice wedges. Other factors seen to be operative in permafrost environments, include river channel migration (talik encroachment) and apparent competition (whereby adjacent ice wedges become the dominant sites accommodating thermal contraction). A modern (uncasted) example hosted by sand is illustrated in Figure 17.

***Figure 16**. A frost crack cast in the lower part of the succession.*

***Figure 17**. An ice wedge arrested at an early stage of growth in a coastal exposure on Banks Island. This has the potential of producing a frost-crack type of cast if the active layer were to deepen following climatic amelioration. Large ice wedges occur nearby. Hammer head is at base of the active layer.*

Multi-cycle ice-wedge casts

This class is of compound form, and its genesis is not yet fully comprehended, although Kasper & Allard (2001) gave some insight into modern ice-wedge growth and morphology in response to climate fluctuations. This class was first recognised at Baston in 1980, and examples have been exposed periodically since then. The casts appear to have been either (a) buried by post-casting sedimentation but then penetrated by later ice wedges descending from a higher stratigraphic level, or (b) pre-existing casts that have been reactivated as ice wedges at the same stratigraphic level. In both cases, the location of a second cycle of thermal contraction cracking appears to have been influenced structurally by the presence of the earlier cast features. These presumably acted as vertical sedimentary discontinuities that created planes of reduced strength within zones of tensile stress imposed by the subsequent cooling. After a second phase of ice-wedge growth, a change in the thermal regime appears to have promoted thaw, when the second-cycle ice wedges decayed and became casts, creating a sedimentary structure that is effectively diachronous. This evidence favours the notion that the initiation of thermal contraction cracking lay *within* the former permafrost, and not within the active layer.

Observations at Baston and other sites were used to develop the notion of 'stratigraphically superimposed casts' and 'complex superposed casts' (Seddon, 1982, 1984; Seddon & Holyoak, 1985). It was postulated that they arose solely from talik migration associated with shifts in the location of river channels. Here the terms 'two-cycle or three-cycle ice-wedge casts' are proposed for the same relationships.

***Figure 18**. The two-cycle ice-wedge cast (on right) that was exposed in a bank about 3 m high in 1995, and is interpreted in Table 3.*

***Table 3**. A possible sequence of events for the two-cycle ice-wedge cast shown in Figure 18.*

1. Aggradation of sands and gravels, probably in a shallow, low-sinuosity river system on a low-profile alluvial fan. In a stabilised part of the alluvial surface, permafrost was established in the alluvium and underlying bedrock. Following repeated thermal contraction, ice wedges increased in size (first cycle) and extended through the full thickness of alluvium with the toes penetrating the Jurassic mudstone beneath. By chance, the exposure demonstrates in two dimensions, the intersection of two linear ice wedges forming elements of a polygonal network.
2. Degradation of the ice wedges by thaw and their subsequent casting. The cause is unknown but, in the context of a widespread local pattern of casting at this horizon, was probably a regional climatic amelioration.
3. Following casting, lateral erosion by river channel migration truncated the upper part of the casted ice-wedge system and also removed any evidence of allied active-layer structures in an associated soil. A planar unconformity now represents this event. Synchronously, further sandy gravels aggraded and buried the surviving lower parts of the ice-wedge infills. Permafrost was possibly absent, at least locally, at this stage.
4. A regional climatic deterioration enabled the re-establishment of permafrost, and second cycle ice-wedge growth commenced within the sediments associated with the new (higher) alluvial surface. The new phase of thermal contraction cracking exploited vertical discontinuities within the newly developed permafrost, with the truncated cast infills in the subsurface facilitating development of new contraction cracks in the pre-existing zones of structural weakness. Hence, at least some of the new ice-wedge growth was focused on sites where they were previously developed.
5. The second cycle of ice-wedge growth extended downwards into one of the first generation infills as well as upwards into the upper aggradation unit. These new ice wedges were also sufficiently deep to penetrate the underlying bedrock.
6. At and just below the land surface adjacent to the second-cycle ice wedges, the associated active-layer processes produced involutions with a reorganised clast fabric having most of the clasts' long axes vertical. However, it is possible that the involutions relate to the subsequent casting event.
7. A second phase of permafrost thaw led to the casting of the second-cycle ice wedges. Again, the regionally extensive evidence for this degradation suggests that the cause was a major climatic amelioration event.
8. Renewed fluvial activity swept across the locality and eroded less than half a metre of the pre-existing surficial succession, hence the infills became slightly truncated and the relict active layers were similarly affected. In association with this fluvial activity, about a metre of sandy gravels aggraded. Finally some half-metre of loessic silt with dispersed clasts was deposited; this latest unit is probably also affected by agricultural activity.

***Figure 19**. The three-cycle casted ice-wedge exposed in 1986; its stages of growth are discussed in the text.*

A relatively simple case example of a *two-cycle ice-wedge cast* structure is interpreted to reconstruct the sequence of environmental changes (Fig. 18). This site was exposed in the mid 1990s close to the processing plant and probably survives today buried beneath fill banked against the former limit of quarrying. A sequence of events may be reconstructed (Table 3).

A variant on this sequence of cast development is shown by a second case example which is on a more complex and massive scale (Fig. 19). Importantly, this cross section is almost normal to the ice wedge axis, hence the widths are not excessively exaggerated. Three separate cycles of ice-wedge growth and decay appear to have been involved.

First, after a sediment aggradation phase, the earliest cycle of ice-wedge growth ended with the generation of a large cast with an outer zone of collapsed gravels around a core of massive silt with some dispersed clasts (the top of the surviving cast lies 0.5 m above the spade handle in Figure 19). There is no evidence, such as a palaeosol profile, to enable an assessment of the thickness of material removed when the cast was truncated by fluvial erosion. Nevertheless, the second aggradation phase at this site deposited some 1.5 m of sandy gravels when it is likely that some of the first-cycle ice wedge in the subsurface had not melted. As with the earlier phase, this subsequent cycle of deposition, was again truncated by further fluvial erosion, which on this occasion did not fully remove the near-surface soil profile since parts of it can be identified.

Second, another ice wedge developed and was then casted by an infill of massive silt, with the lower part penetrating into the first formed cast. The source of the silt is enigmatic. Possibly any residual ice, surviving from the first-phase ice wedge, finally melted at this stage.

Third, during another phase of permafrost, a small ice wedge grew within the infill sediment of mainly sorted gravels of the second-phase cast with its toe below the quarry-floor level, probably in bedrock. This ice wedge was largely casted prior to the final fluvial event across the locality, which produced a basal unconformity that sags within the zone of earlier casting. This may, in part, be a function of erosion, but subsidence shown by the stratification suggests that at least an element of the apparent channelling was due to further syndepositional subsidence consequent to residual ice melt within the now multi-stage cast.

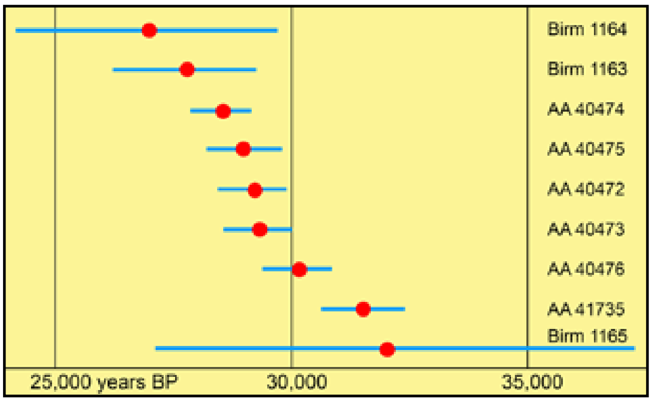

Figure 20*. Laboratory sample numbers and radiocarbon age estimates (with error bars of 2σ that indicate 95% probability) for plant debris within the main sandy gravels at Baston. These help define a period when organic-rich sediments were accumulating prior to the LGM.*

Dating of the materials

Three principal stratigraphic horizons can be identified, each with sedimentary structures indicating significant ice-wedge growth and decay, and linked throughout the exposures to near-horizontal erosional para-unconformities. The cast structures may be assigned to one of early, middle or late phases of permafrost development, each accompanied by sufficient landscape stability to permit ice-wedge growth. Biostratigraphical and radiometric methods help constrain the casting chronology, but cannot determine the durations of ice-wedge growth or the time lapse prior to decay, since ice wedges can become dormant so long as the permafrost can be sustained. Four phases of active patterned-ground formation have been defined with OSL (optically stimulated luminescence) data at around 11-12, 20-22, 31-35 and 55-60 ka in central East Anglia (Bateman *et al*, 2014). The earliest recorded Baston permafrost event might correlate with one of the two older phases.

Seddon (1984) obtained three radiocarbon age estimates on plant macrofossil material derived from organic clasts within the main Baston sandy gravel succession. These were established by classic gas proportional counting at the Department of Geology, University of Birmingham. Briant *et al* (2004b) supplemented these results with those from similar material sent for accelerator mass spectrometry (AMS) assays to the NERC Radiocarbon Dating Laboratory in East Kilbride (in co-operation with the University of Arizona). There is consistency in all the nine radiocarbon age estimates (Fig. 20), indicating that the Baston middle and upper permafrost events occurred after *c.*25 ka BP. The earlier event cannot be constrained by these data. The latter workers also undertook OSL measurements on quartz grains, which corresponded broadly to the chronology established using radiocarbon dating, though there were some discrepancies.

Two age estimates arising from the OSL technique that are particularly important are from samples within the upper aggradation (facies G1-2), which post-dates the main LGM horizon of ice-wedge casts. They relate to samples G140 and G182 respectively from logs C and S in which the palaeosol horizon with its arctic-structure soil can be recognised. Both samples are from facies Gl-2, above the palaeosol. In Briant *et al* (2004b) these are stated to have yielded age estimates of 11.34 and 12.85 ka at the Cambridge laboratory. Briant & Bateman (2009) focussed on comparing the radiocarbon and OSL methods, and sample G182 was again assayed for OSL but this time at Sheffield, where an age of 11.20 ka BP was obtained. A radiocarbon sample G183 taken adjacent to G182 gave an age estimate of 11.55

ka BP and when calibrated this becomes *c.*13.4 cal ka BP. Assuming that these dates are meaningful (the two independent techniques are in general agreement), they signify a Loch Lomond Stadial age for the final phase of gravel aggradation at Baston.

Briant *et al* (2004b) state that *disturbance features were not seen within facies Gl-2 between 1998 and 2003*, which implies that no cast structures indicative of permafrost within this facies were identified. Critically, they noted that Seddon (1984) had recorded one frost crack extending from the top, i.e. it passed through facies Gl-2, but they did not comment further. This statement requires amplification since it underplays the significance of Seddon's observation. The frost crack concerned is actually a large ice-wedge cast, *c.*2.4 m wide at the top (this is probably exaggerated by an oblique cross section) and at least 3.5 m deep (it enters the Oxford Clay at the base of the section). Reference to Seddon (1984, Fig. 5.13 Section A) shows the geometry very clearly, and it is unquestionably younger than the main horizon of the preserved structure soil. She noted that the upper 0.8 m of the wedge infill consisted of gravels, and interpreted these as having been slumped and faulted into their position following melt of residual ice in the lower part of the developing cast structure, with or without infilling of a temporary void. In addition, she noted a thin wedge of sediment within the main cast infill, extending down from the surface to a depth of some 2 m; this feature she reasonably suggested was a late-stage, reactivated ice wedge that was subsequently casted.

Fortunately, other directly comparable ice-wedge casts have been recorded at Baston by the writer in the same stratigraphic context and it can be confirmed that other ice-wedge casts do extend downwards from the top of the uppermost gravel bed (Fig. 21). This evidence supports the contention that some ice wedges at Baston grew in the Loch Lomond Stadial (Younger Dryas). Collaboration of the fact that the youngest generation of ice-wedge casts extend through the uppermost gravel unit from close to the current ground surface comes from in the Maxey Quarry, some 7 km south of Baston (Davey *et al*, 1991, Fig. 55). In the upper part of the sequence that is directly comparable to the Baston site, a 'regenerative ice-wedge cast (two phases of growth)' is recorded in their schematic composite stratigraphy. They also portray one of their 'younger generation of ice-wedge casts' extending upwards from the main, buried land surface through about a metre of horizontally-bedded gravels to the modern ground surface. Further afield, in the Gipping Valley of Suffolk, Rose (1993) reported a single ice-wedge cast in sub-floodplain gravels that both palaeontological and radiometric criteria can probably assign to the Loch Lomond Stadial, further strengthening the case for permafrost at that time.

***Figure 21**. A third-generation cast of probable Loch Lomond Stadial age. The simple, classic-type ice-wedge cast extends downwards through the final gravel aggradation phase. The organic-rich palaeosol (just above the top of the spade handle) may have developed in a short-lived shallow pond associated with the LGM depositional hiatus recognisable on either side of the cast.*

The permafrost chronology at Baston

The permafrost record at Baston is a complex one and is possibly the most detailed yet deciphered from the later part of the Last Glacial (Devensian) at a single site in Britain. The sedimentological character of the casts suggests a fluctuating climatic regime as the cycles of ice-wedge growth, cast infilling and fluvial sedimentation progressed. This was probably accompanied by variations in active-layer thickness, which in turn determined the availability and kind of sediment supply into the thawing wedges. A particularly striking characteristic is the widespread occurrence of channels containing well-bedded gravels in the upper parts of the cast infill, suggesting that significant flows of meltwater run-off were routed along the ice-wedge troughs during the final phase of permafrost ground-ice decay.

The balance of probability is that the entire gravel sequence lying on the Oxford Clay is of Last Glacial age (*c.*11.5–115 ka BP). At least three major phases of ice-wedge growth are evident. The two earlier phases appear to have produced ice wedges of similar magnitude, suggesting stadials with similar climatic severity and duration. Finally, the third phase demonstrates that the climate of the Loch Lomond Stadial (11.5-12.7 ka BP) was exceptionally severe in the Fenland region. Superimposed on this main pattern, are shorter phases of ice-wedge growth typified by the frost-crack casts and by the evidence for a regenerated phase of ice-wedge growth within the main cast structures. Overall, the recurrent phases of permafrost are likely to have been orchestrated by a highly variable palaeoclimate of the kind deduced from the Greenland ice-core data.

The possibility that parts of the basal succession may pre-date the Last Interglacial cannot be rejected. At Maxey, an organic-rich lens of Last Interglacial aged occurs within a gravel-dominated sequence where the organics were absent, implying a single, cold-stage aggradation cycle. Ice-wedge casts both pre-date and post-date the interglacial bed (Worsley 1987).

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