Sand wedges in England and arctic Canada

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Abstract: Sand wedges penetrating till were reported from Congleton, England, 50 years ago, but at that time their interpretation was dependent on a single modern analogue in Antarctica. Other sand wedge sites in Britain have been identified; these are mainly associated with a buried land surface (Barham Soil), which ante-dates the arrival of the Anglian ice sheet in southern East Anglia during MOIS 12. In the permafrost of the Canadian Arctic, Banks Island, two generations of mainly epigenetic sand wedges filled by aeolian sand occur. The lower set is intra-formational and truncated by a fluvial para-unconformity, whereas the upper set is buried by a thin bed of fluvio-aeolian coversands. Recent exhumation of an extensive palaeo-deflation surface associated with the tops of the upper horizon of sand wedges has revealed an orthogonal ground pattern. Some second-generation structures penetrate the earlier wedges, giving rise to syngenetic sand wedges. If inactive, the wedges are technically 'ancient' or 'relict' sand wedges, but remain primary sedimentary structures. They generally signify extremely arid, cold, permafrost environments, but locally may co-exist with ice wedges and composite forms.

Fifty years ago, in this journal, the writer presented a paper detailing the stratigraphy of Devensian (Weichselian) permafrost based on the recognition of ice-wedge casts in some eastern Cheshire sand quarries (Worsley, 1966a). Concurrently he described a quarry where sand-filled wedges penetrating a till sheet were exposed at the ground surface, but interpreted these as 'sand wedges' *per se* rather than ice-wedge casts (Worsley, 1966b). A permafrost-related sand wedge is defined as 'a wedge-shaped body of sand produced by filling of a thermal contraction crack with sand either blown in from above or washed down the walls of the crack' (Permafrost Subcommittee, 1988). Hence, the fill of a sand wedge is a primary sedimentary structure and genetically distinct from the secondary fill of an ice-wedge cast or pseudomorph. Both modern ice-wedges and sand wedges develop when annual temperature changes induce thermal contraction cracking of permafrost (mean annual ground temperatures more than 6°C below zero) and hence their antecedents in the rock record have important palaeoclimatic implications.

Figure 1*. Marsh Farm Quarry, Congleton, looking to the northeast in 1964. The main face is in the stratified Chelford Sands Formation. The Stockport Formation till caps the face on the right, and the sand wedges were found penetrating it.*

The Cheshire Plain palaeopermafrost-related sedimentary structures were encountered during an integrated study of the glacigenic landforms, sedimentology and stratigraphy (Worsley, 1967). Later, research was undertaken on former glaciers and permafrost in Britain, and also on contemporary glacier and permafrost environments in several parts of the Arctic. Globally, investigations of cryospheric systems, focussing on the interaction of glaciers and permafrost, have become more widespread in the last two decades (Harris & Murton, 2005). This paper considers sand wedges in England, along with a case study from the continuous permafrost of the high arctic.

Relict sand wedges in Cheshire

In the early 1960s, at the Marsh Farm quarry [SJ 850625] on the southern outskirts of Congleton, a 37m-thick sequence of extremely well-sorted sands was being worked (Fig.1); these sands are part of the Chelford Sand Formation (Worsley, 2015). Prior to sand quarry extensions, the overlying Stockport Formation, consisting of a bed of till <5.3 m thick, was removed. This was done in two stages; first the surface soil was stripped and stockpiled, and then the main till body was excavated and dumped. After stage one, it was evident that some linear sand-filled cracks were present in the till and when examined in section these infills tapered with depth, although most were not deep enough to penetrate into the sand beneath.

In seeking to explain the significance of the sand infills, a literature search showed that the infilled cracks might be 'sand wedges' similar to those reported from extremely arid permafrost areas in Antarctica. Fortunately the quarry owner, Dennis Sheard, was intrigued by this possibility and through his co-operation, the next phase of till removal, in 1964, was undertaken so that the planform of the cracks could be mapped. Thus, rather than mass excavation, horizontal slices of till were successively removed and this unequivocally demonstrated that the wedge fills of pure sand formed an irregular polygonal network (Fig.2),

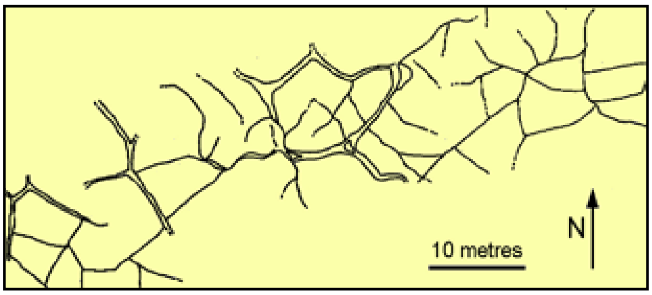

***Figure 2**. Map of sand wedge polygons at the Marsh Farm quarry, revealed when the top soil had been carefully removed. This formed Figure 4 in Worsley, 1966b, where the words "sand wedge" were missing as a prefix to the polygons.*

with the buff-coloured sands contrasting starkly with the red-brown till (Fig.3). A paper describing these 'sand-filled wedge' polygons at Congleton, along with a discussion of their environmental significance, was then prepared.

***Figure 3**. Surface expression of the sand wedge fills cutting the exposed top of the till at the Marsh Farm quarry.*

When first submitted, the paper was titled 'Sand wedge polygons at Congleton …', and after peer review, the paper was accepted with minimal change and eventually the page proofs arrived for checking. Meanwhile, the journal editor, Anders Rapp of Uppsala University in Sweden, decided to send the manuscript to Troy Péwé, an American geologist with extensive permafrost experience, as he judged (correctly) that Péwé would be interested. Unexpectedly, Péwé rejected the sand wedge interpretation and as a result Rapp mandated that the paper title be changed to the more neutral 'Fossil frost wedge polygons …..'. Péwé asserted that the Congleton structures were ice-wedge casts rather than sand wedges and unusually an 'editorial comment' based on Péwé's opinion was appended the paper rather than issued as a separate discussion. Péwé justified his opinion by claiming *just because fossil ice wedges have sand in them it does not make then sand wedges*; one can agree with that view. However, he inexplicably assumed that the host to the wedges was sand rather than till. He also stated that the presence of slump structures was incompatible with sand wedges, despite the fact that evidence of slumping was restricted to the very top of the fill. Finally (and tellingly) he wrote *it is very difficult to visualise the rigorous climate necessary for sand wedges to have existed in England during the late Pleistocene. I think the climate was marine rather than continental*; presumably he meant maritime, rather than marine. This view was despite global sea level falling by some -125 m during the Last Glacial Maximum, resulting in Britain and its allied continental shelf forming an extension of mainland Europe. It is suggested that this is an example of 'the eye seeing what the mind was looking for'. Cold, arid environments during the Devensian in Cheshire were indicated by the presence of aeolian sands with many ventifacts at several horizons (Thompson & Worsley, 1967). Nevertheless, it was difficult to refute the views of a worker who at the time was the author of the sole description of modern sand wedges (Péwé, 1959). A little later, when challenged directly, Péwé (1967, *pers. comm.*) admitted that he had not realised that the sand fill was not directly derived from the host sediment.

Ice wedge: a massive, generally wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice derived from in-blown snow and hoar frost.

Ice-wedge cast: a filling of sediment in the space formerly occupied by an ice-wedge; it is therefore a pseudomorph, with a wedge of **secondary** filling due to slumping from above as the wedge ice melts.

Sand wedge: a wedge-shaped body of sand produced by the repeated filling of a thermal contraction crack by sand blown into it when it was open; this is characterised by a marked vertical fabric and laminations; the sand is a **primary** filling and is not a replacement structures associated with the melting of ice wedges.

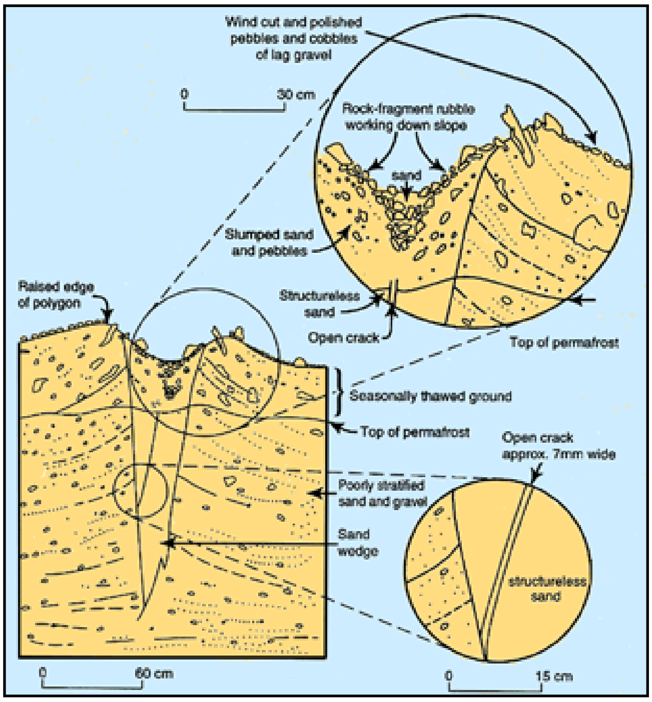

***Figure 4**. Péwé's sketch (1959, Figure 3) of a sand wedge in cross-section, from McMurdo Sound, Antarctica.*

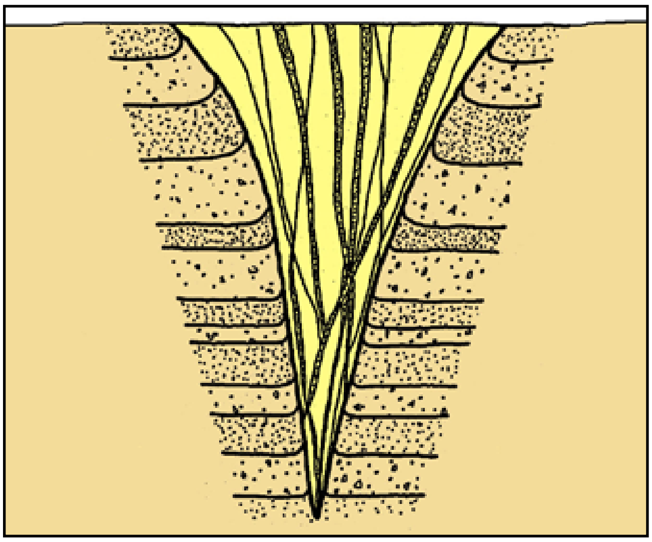

***Figure 5**. Black's diagrammatic model (1976, Figure 9) of a sand wedge in cross-section.*

The editor originally intended to have a separate discussion on the problem of sand wedge identification involving Péwé, Robert Black and Gunnar Johnsson (the Swedish wedge specialist). Unfortunately this did not materialise. It would have been interesting, as there were differences of opinion at that time between the Antarctic field workers Black and Péwé.

Péwé's *diagrammatic sketch* of an Antarctic 'sand wedge' in poorly stratified sand and gravel subsequently became the main model for interpreting the structures (Fig. 4); it was prominently featured (as Figure 4.5) in Ballantyne & Harris's (1994) influential textbook. An alternative model was suggested by Black (1976), which emphasised the vertical lamination structure of the sand fill (Fig. 5), and was featured in the revised edition of Washburn's classic geocryology textbook (1979). After gaining field experience of continuous permafrost terrain, the writer became suspicious of aspects of Péwé's model. Below the active layer (zone of annual freezing and thawing), ice-bonded permafrost behaves in a similar manner to concrete while it remains frozen. Normally only steep, naturally undercut slopes offer the potential of observing ground surface polygonal patterns at depth and the case study to be presented below demonstrates this situation. Péwé did not explain how his 'type example' was exposed in section; the component below the active layer may have been, at least in part, based on inference. A recent study of Antarctic sand wedges had to employ a gasoline-powered *concrete* breaker to excavate the wedges (Bockheim *et al,* 2009).

Other British 'sand wedges'

Away from Congleton, relict sand wedges are rarely known from Pleistocene successions in Britain. Possibly the earliest record was that of Straw (1963), who during a 1962 visit by the Yorkshire Geological Society to Crosby Warren ironstone mine near Scunthorpe in Lincolnshire, observed 'sand-wedges' penetrating a head (weathered unstratified 'porridge' of small platy fragments) derived from Lower Liassic clays (Coleby Mudstone Formation). These consisted of 'larger irregular masses of sand that tapered wedge-like into the shale'. Thin veins of sand <25 mm wide split off from the main masses of sand. Originally they were considered to be ice-wedge casts although this was not specifically stated in the paper, but later they were reinterpreted as true sand wedges (Straw, 2016, *pers. comm.*), a conclusion supported by the local presence of coversands. Close by at Yarborough quarry, a similar succession was exposed in the period 1997-2000 (Murton *et al* 2001). Several sand wedges just less than a metre deep and 0.2 m wide penetrated the head. Significantly, elements of the fills displayed 'isolated sand veins and bundles of vertical sand laminae in otherwise structureless pebbly sands' suggesting that, at least in part, the fills were also sand wedges *sensu stricto*.

Most known sand wedges are associated with a buried land surface (Barham Soil) which immediately antedates the Anglian ice sheet in East Anglia (Allen, 1984; Rose *et al.,* 1985). The parent material is the ancestral Thames Kesgrave Formation and the known structures are mainly concentrated in the area to the north of Chelmsford (Fig. 6). The soil was originally referred to as the 'Barham Arctic Structure Soil' but as it became better understood (it has components produced by temperate as well as cold climate pedogenesis), this term was considered to be too restrictive and was abandoned. Nevertheless the last phase of soil development, with allied coversand, polished flint pebbles and loess deposition, was in an extreme cold environment, and

***Figure 6**. Barham Soil in a quarry at Bloomfield (north of Chelmsford) in the mid 1970s. Anglian chalky till forms the upper half of the face, above the palaeosol that is present in the upper part of the underlying Kesgrave Sands and Gravels (forming the lower half of the face, behind the people). The palaeosol is penetrated by sand wedge structures (above each of the blue spots).*

***Figure** 7. Barham Arctic Structure Soil at Great Blakenham in the Gipping valley developed on Creeting Beds (now thought to be part of the Norwich Crag Formation). The sand wedge has subsequently been deformed by the passage of the Anglian ice-sheet, and the base of the till sheet cuts across the top of the wedge infill. Trowel for scale.*

this occurred immediately prior to burial by till. Thus these sand wedges were the last component of the Barham Soil to form, although the evidence provided by ice-wedge casts at the same horizon suggests that synchronous ice-wedge growth may have occurred in some of the more poorly drained areas.

In some respects the East Anglian sand wedges are enigmatic both in size and morphology. They are only 0.5–2.0 m deep and 0.05–0.75 wide at the top, and many have been sheared and laterally displaced as a consequence of subglacial deformation (Fig. 7). The fills are of fine to medium sands but with occasional wind-polished flint pebbles. However, instances of vertical lamination (with laminae 2–5 mm thick) are known, and cross-cutting relationships are described (although these are not clearly evident in Figure 9.7b of Rose *et al.,* 1985). Laminations are particularly diagnostic of the sand wedges on Banks Island (see below). Undoubtedly sand wedges are present in East Anglia, but it may be that some of the smaller examples are related to desiccation processes rather than thermal contraction in permafrost.

Features described as 'sand wedges' were recorded at two construction sites in Wimbledon, London (Hutchinson, 2010). These lay between two solifluction sheets each 1.2 m thick, overlying London Clay bedrock. These wedges were small, <50 mm wide and <1.5 m deep, and were partially deformed by shear. At one site, minor polygons 1.0–1.5 m across were evident. On-site dating was not possible but by comparison with other localities (none with sand wedges), Hutchinson argued for a late Loch Lomond stadial date (c.11.5 ka) for wedge formation. In view of the size of the features in conjunction with the clay-rich nature of the head's parent material, it is suggested that a desiccation origin might be a more plausible mechanism of formation rather than thermal contraction of permafrost.

Sand wedges at Angus Lake, Canada

Deep within the Canadian Arctic, Banks Island [at 72°N 125°W] has mean annual ground temperatures below −10°C and hence is firmly within the zone of continuous permafrost. It has a meagre 90 mm of annual precipitation, making it an extremely arid environment (Heginbottom, 1995). Thickness of the modern active layer is largely determined by thermal conductivity of the surficial materials, and generally falls into the 0.2–1.0 m range.

At the western extremity of Banks Island, and therefore on the western margin of Canada's Arctic Archipelago, Sachs Harbour (Ikaahuk) is a small Inuit community at the mouth of the Sachs River. A significant outcrop of sand wedges occurs in the Sachs River lowlands (Fig.8). The latter were glaciated during the Last Glacial Maximum (Vincent, 1983; England *et al*., 2009). Active aeolian sand sheets are ubiquitous within them (Good & Bryant, 1986; Worsley 2014a), and equifinal pingos are common (Gurney & Worsley, 1998).

The Sachs River estuary planform is beaded due to a series of thaw lakes having been progressively incorporated by a combination of lake extension, river channel migration and sea level rise. A potential future lake capture may occur when a narrow strip of land lying only 1500 m inland from the current delta is breached by either the migration of the main Sachs River channel or possibly by lake over-topping (Mackay, 1992). The lake concerned is Angus Lake (Picnic Lake on the 1:50,000 map sheet 97G/15), which extends for about 2000 by 600 metres. The slopes leading down to the lake shores are at a low angle with the sole exception of a cliffed embayment in the southwestern sector of the lakeshore. The sand wedge study site lies on top of the cliff in the middle of the bay (Fig. 9); to each side, retrogressive thaw slides at the bay margins are periodically active and have resulted in much reduced slopes (Worsley, 1999).

***Figure 8.** Arrowed location of the sand wedges on the southern shore of Angus Lake, Sachs River Lowlands, Banks Island, western Canadian Arctic (terrain after Google Earth).*

Geomorphology and stratigraphy

The area immediately around Angus Lake is underlain primarily by an unconsolidated sand succession. To the south, across the Sachs River, these sands can be seen in places to overlie unconformably an irregular till surface that locally appear as a moraine ridge. Outcrops in the central part of the Angus Lake embayment expose <21 m of well-sorted sand that is bonded by interstitial ground ice. At the time of the fieldwork, the upper part of the free face had a slope of 42°, which was covered by an unstable, thawing active layer. Sand talus with an angle of repose of 35° obscured parts of the lower cliff. Laterally from the cliff, the sands were seen to lap onto and interdigitate with thin flow tills tracable to buried, debris-rich, massive ice.

The sands are generally medium to coarse, with rare granule-rich horizons, and with low-angle, planar stratification present throughout the sequence. From a distance this stood out due to wind etching emphasising the slight textural differences in the constituent sand beds. SEM examination of single grains revealed surface features characteristic of a fluviatile rather than an aeolian origin. Although texturally uniform, the sand succession could be subdivided on the basis of colour into two units. The lower sand unit (>15 m thick) constitutes the bulk of the cliff sequence and is yellowish brown (10YR 5/4), whereas the upper sand unit is dark greyish brown (2.5Y 4/2) and attains only 3–4 m in thickness. A para-unconformity forms the contact between the two units, and sedimentary structures within the lower unit are truncated by the base of the upper. This sequence forms part of a sand sheet formation which is widespread in the Sachs River Lowlands.

Figure 9*. An oblique air view, looking south, of the sand wedges site on the top of the 20 m high cliff on the shoreline of Angus Lake. The deflated area on the right (lighter tone) displays exhumed, rectilinear, patterned ground that is the surface expression of the sand wedges. The step separating the deflated area from the uneven ground to the left corresponds to the outcrop of the palaeosol.*

Figure 10*. Shallow troughs that mark the tops of sand wedges. The surface is covered by a traction carpet of granules that filter into the thermal contraction cracks during the winter months. Ventifacts are ubiquitous. Trowel for scale*

The cliff top corresponds to a near-horizontal deflation surface (sloping 1° to the NW), concordant with the underlying stratification. The limits of the deflated surface were marked by a low step that corresponded to an eroding `Orthic Turbic Cryosol' (palaeosol) some 1 m thick. This was extensively developed throughout the area and forms a marker horizon. Above the buried soil a thin loamy fine sand forms an aeolian cover, <2 m thick, with localised, stabilised dunes centred on single specimens of shrub willow (*Salix alexensis*). On the deflated surface, very shallow troughs were just discernible and these formed an orthogonal ground pattern (Fig.10). A scattering of mainly pebble-sized ventifact clasts, with salt crusts on their undersides, covered the deflation surface. This exhumed horizon, classified as a palaeo `Regosolic Static Cryosol', could be traced beneath the palaeosol. The Sachs River Lowlands sands have been mapped as of 'deltaic, eolian and fluviatile origin' (Vincent, 1983). In the immediate area of Angus Lake these were identified as 'sediments deltaique', but the sedimentary structures are here interpreted as being either of glaciofluvial or fluvial origin.

Sand wedge sedimentology

Along the precipitous cliff top, a series of 51 funnel-shaped, small, gulley-like features extended for a distance of 270 m, with an average spacing of 5.26 m. Some of these corresponded to shallow troughs forming part of the patterned ground on the deflated surface. Excavation showed that the gullies corresponded to the tops of sand wedges. These stood out because of the contrasts in colour and grain size, but particularly in the difference of almost 90° between the orientation of the dipping stratification of the wedge interior and that of the host sediment.

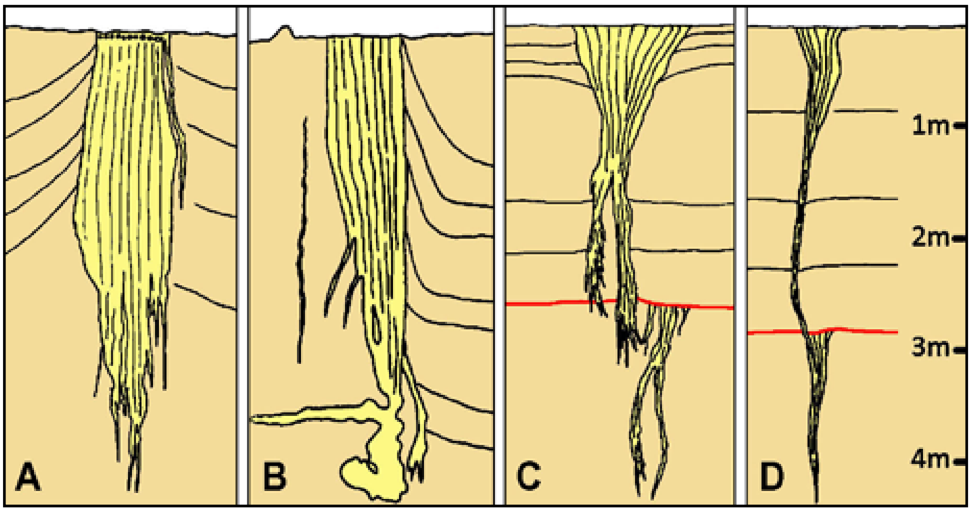

***Figure 11**. Four sand wedges in cross section, show the diversity of forms. **A**: a complete wedge down from an exhumed land surface; it is wider at depth, the toe splits into fingers, and host sands are upturned. **B**: a complete wedge, with an irregular toe (with unknown origins), and host beds are only upturned on the right. **C**: two generations of sand wedges separated by the para-unconformity marked in red, the lower wedge is truncated, and host sands are not deformed. **D**: similar to C but narrower, less mature, and with no branching; the toe of the upper wedge enters the earlier wedge structure.*

Within the cliff, sand wedges cropped out at two different horizons. The upper set, were directly associated with the deflated horizon defining the top of the upper sand unit and were clearly epigenetic, whereas the lower set lay immediately below the para-unconformity between two sand units at a depth of 3–4 m beneath the upper set top. As the latter sand wedges were all truncated by the unconformity, only the lower parts were preserved and these extended for at least 2 m. Some of the upper-set sand wedges were deep enough to extend through the upper sand unit to penetrate the lower sand unit (Fig.11).

The upper sand wedge set

These wedges ranged in width from barely perceptible vertical cracks to broadly wedge shaped features <1.2 m wide and <3.75 m deep. Although normally the wedges narrowed with depth, some became more bulbous, and one wedge widened from 0.8 to 1.3 m (Fig.12). By chance, the cross sections were normal to the trend of the shallow surface troughs extending away from the cliff edge. No longitudinal sections of sand wedges were identified in the cliff face. Not all of the wedge features could be linked to a trough on the deflation surface, suggesting that either the wedges did not always have a corresponding trough, or more than one generation of sand wedges existed at the same horizon with only the younger ones having a trough. If the latter situation were the case, then the hiatus represented by the unconformity is lengthened, with the earlier wedge tops subject to slight erosion that obliterated the troughs before the younger phase of growth.

Average spacing of the wedges was some 5 m, with a range of 1–18 m. If more than one generation was present then the patterned-ground cell size would be exaggerated. A variety of cross-sectional forms were present, varying from simple narrow vertical cracks through classical V forms to more bulbous forms. No sand wedge could be examined in absolute vertical section because of the generally convex nature of the active-layer thaw front parallel with the upper part of the cliff top slope (Fig.13). Thus, the norm for completely exposed sand wedges was for them to crop out in oblique section. As a result, the three dimensional character and orientation of the fills could be more confidently assessed. This situation contrasts with the two dimensional exposures resulting from vigorous erosion such as occurs at coastal and river sections (Murton, 1996).

***Figure 12**. A complete second-generation sand wedge, with a lighter fill within a darker host rock. The view is steeply upwards, and is somewhat distorted due to closeness to the cliff face. Scale bar 20 cm. The layering that appears to cross the host and the wedge is an artefact of cutting the face back with a small trowel.*

Sedimentary criteria common to most wedges were:-

1. Internally the sediment was characterised by fine laminations consisting of bundles of individual sand veins. These ranged from fine to coarse sand, although that of a given bundle tended to maintain a consistent grain size.

2. Some lamination bundles crossed one another.

3. Many bundles leave the main wedge body to penetrate the host sediment to create apophyses, analogous to the branches frequently found with igneous dykes. This relationship was especially prominent towards the toes of the wedges. Indeed, the latter were normally very irregular, consisting of a large number of individual veins entering into the host sediment. Some of the veins disappeared into the section only to reappear lower down. Excavation showed that these breaks in continuity were not an artifact of the two dimensional exposure, but were real discontinuities in the veins.

4. The stratification in the host sands was normally up-turned at the interface with the main wedge infill. The amount of up-turn was variable; commonly it was in the order of a few dm, but it reached 75 cm at one site. Where developed, the up-turning was not necessarily present on the opposite marginal interface. Down-turning, especially towards the top of the host-fill contact, was present at a few sites.

5. Although inclusions of the host material did occur within the wedge infill, they were uncommon. Such instances appear to have arisen where a particularly numerous set of apophyses had isolated part of the host mass and incorporated it within the fill (Fig. 10 B).

6. Where the top parts of the wedge infills were preserved, they contained a range of particle sizes including abundant pebble-sized clastic material. Evidence for wind faceting of the clasts was ubiquitous.

The lower wedge set

The sand wedges of the lower set were all incomplete, having been truncated by erosion prior to the accumulation of the upper grey sands; hence they did not retain the element described in #5 above. A typical example (Fig. 14) had the granule-rich, basal, upper sands lying with a sharp planar contact on the surviving wedge fill. The main surviving fill is 90 cm deep, and consists of a distinctly coarser grain size in comparison with that of the host. However, there are numerous sand veins extending root-like beyond the main fill limits, and some of these attain a depth of over 30 cm below the main toe. Also some of the veins appear as isolated segments.

This example illustrates another relationship, that of second cycle penetration. If the wedges in the lower set are regarded as first generation, and the second set as second generation, then in this instance the lowest part of a second-generation wedge can be seen penetrating the para-unconformity for some 50 cm into a truncated first-generation wedge infill close to the right hand margin. It is marked by a rather subtle decrease in grain size.

Figure 13. *An excavation into a sand wedge on the talus slope, with the unthawed permafrost of the lower part contrasting with the thawed sand that clearly shows the internal laminations in the upper half. Scale bar 20 cm.*

Thermal contraction structures, whether they are ice, composite or sand wedges can be classified into three types: epigenetic, syngenetic and anti-syngenetic (Mackay, 1990), with the former typifying growth beneath stable ground surfaces. The second-generation sand wedges at Angus Lake generally fall into this epigenetic category. In contrast, syngenetic features are associated with net sediment aggradation and anti-syngenetic with erosional slopes. With syngenetic wedges, the theory is that pre-existing thermal contraction features grow upwards in unison with the sedimentation rate. This results in later growth progressing from a stratigraphically higher position.

Ice wedges have been described as syngenetic when they possess a wedge-within-wedge structure (Mackay, (1992). The literature on sand wedges is more ambiguous, although Murton (1996) describes some aggradation of the surface from which sand wedges are growing without using the term syngenetic. Where the second-generation sand wedges enter the first-generation structures a syngenetic feature is created in effect. The complicating factor at Angus Lake is the fact that the earlier structures are truncated whereas the conventional syngenetic model assumes that the net aggradation occurs without any erosion. Nevertheless, some of the lower sand wedges are at least partially syngenetic.

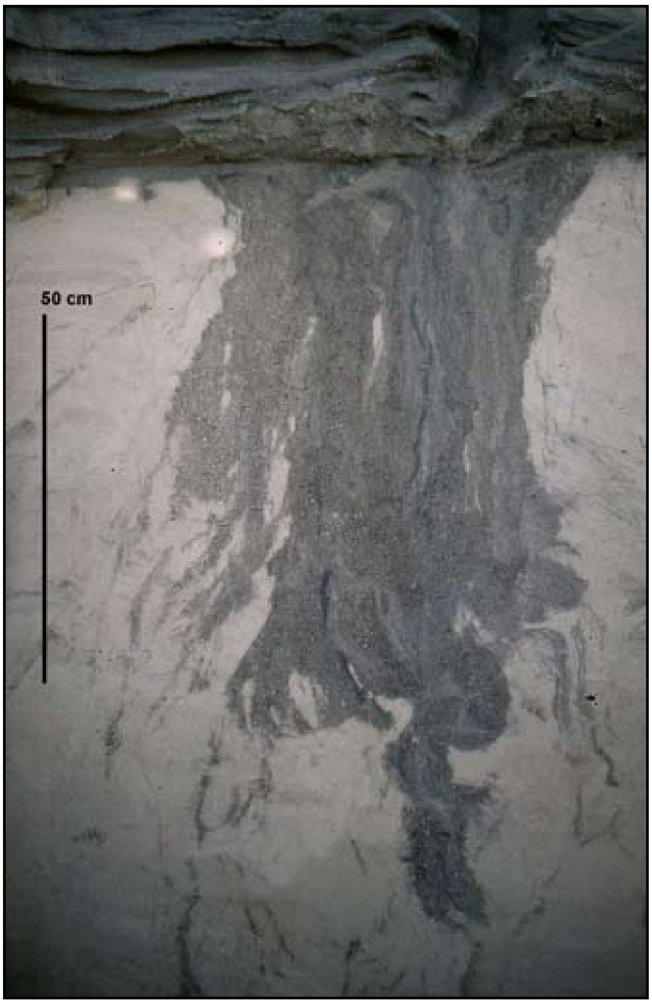

***Figure 14**. A truncated first-generation sand wedge, with a colour contrast at the para-unconformity at the base of the horizontally stratified, upper sand unit.*

The coincidence in position of the two generations of growth may well be fortuitous, but several examples were revealed in the excavations. Where a similar stratigraphic development of two-generations (two-cycle) casted `ice wedges' are known in Late Pleistocene fluvial gravels at Baston in Lincolnshire, it is significant that many of the second-generation structures are located above the first, and indeed the upper features commonly penetrate the lower (Worsley, 2014b).

The active headwall of the thaw slide to the northeast of the main section at Angus Lake revealed the presence of sand wedges some 3 m deep penetrating the buried, debris-rich, massive ice (Worsley, 1999). These sand wedges had a simple V-shape in outline, and had internal vertical lamination (Figs.15 & 16). No apophyses were observed, and a similar absence was noted in sand wedges penetrating massive ice at Crumbling Point in the Mackenzie Delta on the Canadian mainland (Murton, 1996). The age relationship of the sand wedges in the massive ice to the two sand wedge sets in the sand sequence was not established, and they could be temporally related to either. However, their tops corresponded to the base of the palaeoactive layer that is dated as early Holocene (Worsley, 2000).

Sand wedge growth

Increments of sand wedge growth are related to infilling by sand grains of open thermal contraction cracks. These cracks arise from winter cooling of the ground (not necessarily every year) and are initiated at the permafrost table; they then propagate both upwards through the newly refrozen active layer and downwards into the permafrost. The mineral sediment entering the open contraction cracks produces a single sand vein that normally corresponds to a single winter (Péwé, 1959,1962; Black & Berg, 1964; Berg & Black, 1966; Murton *et al.,* 2000).

Importantly, the specific character of the sand grains that fall into the cracks is determined by the kind of sand available at the time, *i.e.* during the winter and at the ground surface. At Angus Lake, the first-generation wedge fills consist of coarse sand similar if not identical to that of the upper sand unit, so their dark sand fill contrasts with a lighter coloured host. The

***Figure 15**. A sand wedge hosted by buried, massive, glacial ice that is believed to be relict from the LGM event. Below the spade the ice foliation is upturned against the border of the wedge. The top of the wedge is overlain by a solifluction diamict (derived from till), and its base corresponds to that of a former active layer (early Holocene) that was deeper than the contemporary one.*

Figure 16. Laminations associated the sand wedge in massive ice (seen in Figure 15). Also present are veins of ground ice, which (if hosted by sediment rather than ice) would likely lead to the destruction of the laminations during degradation of the permafrost; this would result in a homogeneous sand infill.

opposite relationship applies to the second generation where the infills are much lighter in colour than the host and match that of the lower sand unit. These relationships suggest that two contrasting sand sources were successively tapped, and that each in turn was able to be transported over the other to the open cracks. Further, this differentiation persisted during the entire infilling cycle. As wedge width is crudely a function of time, wedges with a width of the order of a metre are at least several centuries old; hence the separation of sand sources must have persisted for a significant period.

A youngest age limit for the upper sand wedge set at Angus Lake can be constrained stratigraphically as they could be seen to be directly related to the unconformity that was in the process of exhumation; hence they antedate the overlying palaeosol. This palaeosol has striking parallels with one overlying sand wedges on the Alaskan coastal plain (Carter, 1984; 1993). The ^{14}C data indicate that it developed in the interval 11–12 ka and was abruptly buried at 11 ka. The lower set is obviously older. It is also possible that the upper sand wedge set was reactivated, with renewed growth, when exposed at the ground surface. Unlike ice wedges, no casting is involved when sand wedges are subject to major climatic change, so reactivation during a subsequent climatic deterioration remains a possibility provided the wedges remain at the surface or are exhumed (as is the case at Angus Lake). Testing this scenario at Angus Lake would involve winter monitoring or possibly O.S.L. dating. Despite this, the bulk of the wedge fills are older than the palaeosol. It has been suggested (Hopkins, 1982) that dormant sand wedges be referred to as 'ancient', although an alternate term is 'extinct' (Péwé, 1973), but clearly both are unsuitable if later reactivation is possible.

Conditions conducive to sand-wedge development prevail today in the Sachs River lowlands with their severe temperature regime, windy and open landscapes, lack of vegetation, abundant sand supply and low snowfall. The flat, sand ground is scored by networks of shallow troughs analogous to those on the exhumed surface beside the lake. Only limited excavation was possible because of the shallow thaw front, but the exposed fills of the troughs were reminiscent of the upper horizon of sand wedge fills, and the probability is that active growth of sand wedges is widespread. In the Mackenzie delta, ice wedges, and to a lesser extent sandy ice wedges, currently appear to be the norm, and only in exceptional circumstances will sand wedges grow, *e.g.* immediately after the sudden drainage of sand-floored lakes.

Environmental history

Following deglaciation, a sand-dominated succession accumulated largely by fluvial processes but with an aeolian component, and at Angus Lake this buried most of a ridge cored by relict ice. The prevailing climate was not dissimilar to the modern one and continuous permafrost was present. During a phase of stability, sand wedges grew, and their widths suggest that this state probably lasted for at least several centuries. Under an arid climatic regime an aeolian traction carpet moved coarse sand across the surface, and, especially during the winter months, filled open thermal contraction cracks with the sand. Annual increments of this material led to the growth of the sand wedge fills. A major change in the sedimentary system led to an erosional phase and the upper part of the sand succession was removed. If, as is likely, the sand wedges grew to the same depths as did the later ones, then some 2–3 m of sand was removed, leaving only the toes of the first-generation sand wedges preserved beneath the subsequent para-unconformity. The erosional phase then ceased and sand supplied from a slightly different source led to further aggradation, but primarily as an aeolian sand sheet with a minor fluvial input introducing some small clasts. This depositional phase eventually terminated and a stable land surface was again established, but unlike the earlier one this surface was later to be buried intact. On this surface a second generation of sand wedges grew after the permafrost had aggraded upwards.

The wedges were part of an orthogonal ground pattern developed on a regosol. Wind abrasion was widespread and the clasts were abraded to produce a carpet of ventifacts. Some of the ventifacts found their way into the troughs above the growing sand wedges but the restricted width of the open thermal contraction cracks in winter prevented them from sinking below the active layer. As in the first phase, the sand wedges grew incrementally following each winter's thermal contraction. Some sand wedges grew to a size and depth that enabled them to extend down below the buried para-unconformity into the sand-wedge fills of the first generation. At least several centuries of stability and

***Figure** 17. View south from the crest of the Sachs Ridge across Angus Lake and the Sachs River Lowlands. The group of sand wedges lies at the top of the cliff on the far side of the lake. Just beyond, the Sachs River flows from left to right, and active, aeolian, sand sheets extend from its far bank. The distant horizon is formed by the Beaufort Sea.*

progressive growth are indicated by the size of the sand wedges. Eventually the deflation surface was buried by a thin coversand. A further palaeosol developed and sealed the sand wedges, probably during the early Holocene. At this stage, the sand wedges were inactive. Thermokarst processes led to the formation of the Angus thaw lake, and in combination with significant fluvial incision by the Sachs River, the present day landscape was created (Fig.17). More recently, the lowlands have been subject to wind deflation once more and the main palaeosol has been stripped to exhume the second-generation sand-wedge ground pattern in many areas. Some reactivation of the recently exposed upper horizon of the sand wedges is likely to have occurred since exhumation.

Reflections

The use of polar analogues in the interpretation of fossil features in currently temperate areas faces a serious difficulty. This revolves around latitudinal contrasts, which inevitably produce a different solar regime; a higher angle sun, even in the depth of winter, would likely have induced a shallow, diurnal active layer over any permafrost that might have developed. During the summer months the active layer would have deepened to values significantly in excess of the 0.15 – 0.50 m typical of the high Arctic.

It is remarkable how after five decades, the data base for modern sand wedges remains so limited. This is probably influenced by logistical problems of reaching them for study. As understanding has slowly improved, it is now clear that the dry valleys of the McMurdo Sound region of Antarctica are most unusual, since to a large degree they present fossilised terrains. The polygonal networks underlain by sand wedges fall into three age groupings, at about 117, 200 and >1100 ka (Bockheim *et al*., 2009). Such a long timescale cannot realistically apply to the now-temperate landscapes in the northern part of the northern hemisphere. Although fundamental physical processes related to the behaviour of permafrost are universal, caution is advisable when Antarctic evidence is utilised to interpret palaeo-permafrost evidence in regions subject to multiple glacial/temperate cycles. Arctic analogue data are preferable.

In this paper, sand wedges and ice-wedge casts have been treated as distinct entities. In the real world, these primary and secondary sedimentary structures are not so simply classified, because intergrades exist. These should be termed *composite* wedges and one British example has been identified by Fish *et al* (1998) on the north Norfolk coast. In theory, a change in precipitation, from a moist to an arid permafrost environment, can lead to pre-existing ice wedges switching to growth as sand wedge, and vice versa. Further, active ice wedges and sand wedges can be found within only a few kilometres of each other, as is the case on Banks Island. Normally, in now-temperate areas ice-wedge casts are regarded as evidence for climatic warming, but even within areas of continuous permafrost ice wedges can degrade to form casts. River channel migration or lake extension can cause permafrost to degrade and develop localised taliks (thawed zones). Such possibilities need careful field assessment when casts are encountered in both permafrost and now-temperate regions (Worsley, 1987). What can be concluded with some confidence is that sand wedges are indicative of aridity, and if correctly identified they are valuable palaeoclimatic indicators.

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