

Sussex Research

Syngenetic sand veins and anti-syngenetic sand wedges, Tuktoyaktuk Coastlands, western Arctic Canada

Julian Murton, Mark Bateman

Publication date

01-02-2007

Licence

This work is made available under the **Copyright not evaluated** licence and should only be used in accordance with that licence. For more information on the specific terms, consult the repository record for this item.

Citation for this work (American Psychological Association 7th edition)

Murton, J., & Bateman, M. (2007). *Syngenetic sand veins and anti-syngenetic sand wedges, Tuktoyaktuk Coastlands, western Arctic Canada* (Version 1). University of Sussex.
<https://hdl.handle.net/10779/uos.23312642.v1>

Published in

Permafrost and Periglacial Processes

Link to external publisher version

<https://doi.org/10.1002/ppp.577>

Copyright and reuse:

This work was downloaded from Sussex Research Open (SRO). This document is made available in line with publisher policy and may differ from the published version. Please cite the published version where possible. Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners unless otherwise stated. For more information on this work, SRO or to report an issue, you can contact the repository administrators at sro@sussex.ac.uk. Discover more of the University's research at <https://sussex.figshare.com/>

Syngenetic sand veins and anti-syngenetic sand wedges, Tuktoyaktuk Coastlands, western Arctic Canada

Article (Unspecified)

Citation:

Murton, Julian B. and Bateman, Mark D. (2007) Syngenetic sand veins and anti-syngenetic sand wedges, Tuktoyaktuk Coastlands, western Arctic Canada. *Permafrost and Periglacial Processes*, 18 (1). pp. 33-47. ISSN 1045-6740

This version is available from Sussex Research Online: <http://sro.sussex.ac.uk/1594/>

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:

Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

**Syngenetic sand veins and anti-syngenetic sand wedges, Tuktoyaktuk Coastlands,
western Arctic Canada**

Julian B. Murton¹ and Mark D. Bateman²

¹Department of Geography, University of Sussex, Brighton BN1 9QJ, UK (address for
correspondence) Tel.: +44 1273 678293, Fax: +44 1273 677196, e-mail:

j.b.murton@sussex.ac.uk

²Sheffield Centre for International Drylands Research, Department of Geography, Winter
Street, University of Sheffield, Sheffield S10 2TN, UK

ABSTRACT

Sand-sheet deposits of full-glacial age in the Tuktoyaktuk Coastlands, western Arctic Canada, contain syngenetic sand veins 1–21 cm wide and sometimes exceeding 9 m in height. Their tall and narrow, chimney-like morphology differs from that of known syngenetic ice wedges and indicates an unusually close balance between the rate of sand-sheet aggradation and the frequency of thermal-contraction cracking. The sand sheets also contain rejuvenated (syngenetic) sand wedges that have grown upward from an erosion surface. By contrast, sand sheets of postglacial age contain few or sometimes no intraformational sand veins and wedges, suggesting that the climatic conditions were unfavourable for thermal-contraction cracking. Beneath a postglacial sand sheet near Johnson Bay, sand wedges with unusually wide tops (≤ 3.9 m) extend down from a prominent erosion surface. The wedges grew vertically downward during deflation of the ground surface, and represent anti-syngenetic wedges. The distribution of sand veins and wedges within the sand sheets indicates that the existence of continuous permafrost during sand-sheet aggradation can be inferred confidently only during full-glacial conditions.

INTRODUCTION

Cold-climate sand sheets, especially in central and northwest Europe, have provided valuable palaeoenvironmental information about aeolian, cryogenic and fluvial processes during the Late Quaternary (Koster, 1988, 1995, 2005). This paper discusses whether sedimentary structures within sand sheets from western Arctic Canada record permafrost conditions and, therefore, palaeoclimate, during sand-sheet formation. Its objectives are to (1) describe the abundance, size and morphology of inactive veins and wedges stratigraphically associated with the sand sheets; (2) discuss the relationships between deposition, erosion and thermal-contraction cracking; and (3) compare the structures with those from other contemporary permafrost regions and from former periglacial environments.

STUDY REGION

The study region is in the Tuktoyaktuk Coastlands of western Arctic Canada (Figure 1). The region is within the zone of continuous permafrost. The mean annual air temperature (MAAT) at Tuktoyaktuk is *ca.* -10.5°C , and the mean annual precipitation is 142 mm (water equivalent), of which 67 cm typically falls as snow (Environmental Canada, 1993). Permafrost thicknesses are as much as 750 m beneath northeast Richards Island (Taylor *et al.*, 1996).

The Quaternary history relevant to the present study commenced with deposition of the Kittigazuit Formation, a regionally extensive aeolian sand unit characterized by large dunes (Dallimore *et al.*, 1997) deposited between *ca.* 43,000 and 14,000 yr BP (Bateman and Murton, 2006). The northwest margin of the Laurentide Ice Sheet advanced across the

region, probably between *ca.* 22,000 and 16,000 yr BP. A subsequent glacial readvance (or stillstand) across the southern edges of the Tuktoyaktuk Coastlands and Mackenzie Trough (Sitidgi Stade) dates to *ca.* 15,300 cal. yr BP (Rampton, 1988). A postglacial warm interval lasted from *ca.* 13,500 to 8,400 cal. yr BP (Ritchie, 1984). Mean July air temperatures at *ca.* 10,900 cal. yr BP exceeded modern values by *ca.* 3–5°C (Ritchie, 1984), and between *ca.* 10,100 and 7800 cal. yr BP by *ca.* 1–3°C (MacDonald, 2000). J.R. Mackay (1978) inferred from a regional thaw unconformity that the MAAT during the warm interval remained, nonetheless, several degrees below 0°C. Warmer-than-modern conditions probably lasted until *ca.* 5,150 cal. yr BP, with slow cooling from *ca.* 8,800 cal. yr BP (Ritchie, 1984). The warm interval caused regional thermokarst activity and active-layer deepening (Rampton, 1988; Burn, 1997).

Sand sheets in the Tuktoyaktuk Coastlands crop out along many kilometres of coastal bluffs. The largest sand sheet occurs within an area of *ca.* 2000 km² at the northeastern end of the Tuktoyaktuk Peninsula, near Johnson Bay (Figure 1; Rampton, 1988). The sheet is up to several metres thick and commonly overlies the Cape Dalhousie Sands, which Rampton (1988) attributed to glaciofluvial deposition. Approximately 20 km of coastal bluffs southwest from Johnson Bay were examined at more than 30 stratigraphic sections in 1990, 1993, 2001 and 2005; a representative section is illustrated in Figure 2a. Smaller sand sheets along coastal bluffs around Summer Island, Hadwen Island and adjacent Richards Island were examined in 1989–1991, 1993, 2001 and 2005. The sand sheet at Crumbling Point, northern Summer Island, is illustrated in Figure 2b. Adjacent sections through the same sand sheet at Crumbling Point are shown in Murton *et al.* (1997, fig. 3). Other sections discussed below are from southern Hadwen Island (section 3.10), southwest

Summer Island (section 4.25), and northwest ‘Summer Bay’ (informal name; section 05-01) (Figure 1).

SAND SHEETS

The sand sheets comprise horizontal to undulating bodies of sand with horizontal to gently dipping stratification in which dune deposits with slipfaces are generally absent (Figure 2; cf. Kocurek and Nielson, 1986; Schwan, 1988; Lea, 1990). They occur in several stratigraphic and geomorphic settings: (1) within the Kittigazuit Formation; (2) interbedded with outwash deposits; (3) involuted within supraglacial meltout till; (4) overlying the deposits of drained thermokarst lakes; and (5) inland from the tops of sandy bluffs. The timing of sand-sheet activity, determined by OSL dating of quartz sand grains, is summarized in Table 1. Widespread sand-sheet aggradation occurred between *ca.* 14,000 and 8,000 yr BP, coinciding broadly with the postglacial warm interval and episodic fluvial activity. Today, aggradation is limited to areas near sandy beaches, bluffs and drained lake basins.

SAND VEINS AND WEDGES

The sand sheets examined contain or overlie a variety of inactive sand veins and wedges. Epigenetic ice wedges that penetrate buried sand sheets are not discussed as they extend down from the base of the modern active layer and relate to the modern tundra surface.

(i) Syngenetic Structures

Sand veins and composite veins

Three isolated, sand-filled structures with narrow, chimney-like shapes were examined in sand-sheet deposits at least 10 m thick, within the Kittigazuit Formation on southwest Summer Island and adjacent Richards Island (Figures 3–5). The chimney-like shape refers to the more or less uniform width of the structures with depth; because they lack the downward taper characteristic of wedges, they are termed veins (cf. Murton *et al.*, 2000). The veins were 1–21 cm wide, measured orthogonally to their axial planes. Their sides contained between 1 and 7 horizontal ‘shoulders’ above which the vein narrowed abruptly, usually by a few centimetres (Figure 4b). The height of one vein exceeded 9 m. Internally, the veins were filled with fine sand and silty fine sand, similar to the interstratified sand and silty sand facies of the host sand sheet. The fill contained occasional granules to small pebbles and varied in field appearance from well laminated to structureless within an individual vein. The laminae were vertical to subvertical, often wavy to irregular, and typically a few millimetres thick. One fill contained small cavities, very loose sand and irregular streaks of silty fine sand with a chaotic appearance. Strata in the host sand sheet were mostly undeformed adjacent to the veins, although minor upturning or downturning was locally present.

The veins are interpreted as syngenetic structures, i.e. they have grown vertically with aggradation of the host sand sheet. The vertical lamination is very similar to that reported from other sand veins and wedges along the Beaufort Sea coast (Carter, 1983; Murton, 1996) and more generally within sand wedges of primary infilling (Murton *et al.*, 2000). Where the fill is structureless but firm (i.e. lacking evidence for melt of ice), the sand source was probably texturally and mineralogically very uniform (cf. Murton, 1996). Each shoulder probably marks the former ground surface when the sand sheet experienced a

short phase of non-deposition or erosion. The cavities and irregular streaks within one of the veins probably indicate locations where ice has melted due to inward thaw during recent bluff retreat, and suggest that the vein was originally a composite structure dominated by sand but containing a small amount of ice, probably in the form of ice veins; the unthawed part of this vein is therefore a composite vein. The syngenetic growth indicates that sand was blown across the sand sheets when thermal-contraction cracks were open during winter or spring.

Rejuvenated sand wedges

Two sand wedges with distinctive raised tops above an erosional (bounding) surface (Brookfield, 1977) that truncated aeolian dune deposits and underlay sand-sheet deposits were observed in the Kittigazuit Formation on southern Hadwen Island. The first wedge comprised a downward-tapering body extending 2.15 m beneath the bounding surface, and a raised top with four narrowing shoulders and a central sand vein extending up at least 0.5 m above the bounding surface (Figure 6a). The upper right part of the main wedge, *ca.* 0.2 m high (beneath the highest arrow in Figure 6a), was truncated along the bounding surface. The second wedge was 10.6 m from the first, and related to the same bounding surface. A bundle of sand veins extended up at least 2.8 m above the bounding surface (Figure 6b), but lacked shoulders similar to those of wedge 1 above the bounding surface.

Both wedges are interpreted as rejuvenated sand wedges. Beneath the bounding surface the lower part of each wedge displays the form characteristic of a downward-tapering epigenetic sand wedge. Wedge 1 has clearly been truncated by aeolian deflation – which formed the bounding surface – because the upper right part of the wedge is only 0.2

m high; originally it was probably at least 1–2 m taller, based on comparison with the numerous epigenetic sand wedges that we have observed in the Summer Island area. Sometime after deflation ceased, sand-sheet aggradation recommenced, rejuvenating both sand wedges. The sand sheet above the bounding surface showed no obvious differences in stratification that might suggest differences in erosion and sedimentation over a lateral distance of 10.6 m. Therefore, the absence of shoulders associated with the sand-vein bundle above wedge 2 indicates that the frequency of cracking and filling was distinctly lower during its rejuvenation phase than that of wedge 1, just 10 m away. In summary, both sand wedges commenced growth as epigenetic or possibly syngenetic structures, were then partially eroded and later resumed growth – at different rates – as syngenetic structures.

(ii) Anti-syngenetic sand wedges

Sand wedges with unusually wide tops extended down below a prominent erosion surface beneath the Johnson Bay sand sheet. The maximum widths of five wedges examined, measured orthogonally to their axial planes, were 2.3, 2.8, 3.1, 3.6 and 3.9 m (Figure 7). The wedges could not be fully excavated because of permafrost and repeated slumping, but the minimum heights exceeded 1–3 m, and some of wedges tended to narrow markedly with depth. Their tops were truncated by a prominent erosion surface, above which a granule-pebble lag contained many wind-polished pebbles. Adjacent to the tops of the wedges, strata in the host sand and gravel were often vertical to overturned. Slumping prevented accurate measurement of the lateral spacing between wedges, but a rough

estimate for the typical spacing is *ca.* 8–20 m. Thus, the wedges form a polygonal network.

This type of wedge is thought to have grown vertically downward during erosion (deflation) of the ground surface, and so is termed ‘anti-syngenetic’, following J.R. Mackay’s (1990) classification of ice wedges. The erosion in this case may have been either progressive (cf. Mackay, 1990) or episodic. Deflation is inferred from the erosion surface, which we have traced for some kilometres beneath the sand sheet. Downward growth of the wedges is inferred from their unusually wide tops (2.3–3.9 m), which are distinctly wider than epigenetic ice wedges in the region (typically $\leq 1\text{--}2$ m wide). J.R. Mackay (2000) reported that anti-syngenetic ice wedges along the western Arctic coast have maximum true widths of commonly a few metres, with the widest >8.4 m – much wider than epigenetic wedges in adjacent flattish areas. He suggested that such widths may develop because less winter snow accumulates on windblown hillslopes than on most flattish areas, and so the hillslopes are probably colder and subject to more frequent cracking. At Johnson Bay snow was absent at the time of crack infilling, otherwise ice wedges or composite wedges, rather than sand wedges, would have formed. The sand wedges at Johnson Bay differ from epigenetic sand wedges within other sandy deposits of the Tuktoyaktuk Coastlands, inasmuch as the latter tend to be distinctly narrower (maximum widths of *ca.* 0.3–1.5 m), they lack the vertical to overturned strata in the adjacent host sand and most taper downward more gradually.

(iii) Epigenetic sand veins and wedges

Sand veins and narrow wedges sometimes occur at one or more stratigraphic levels within sand sheets. In the fluvio-aeolian sand sheet at Crumbling Point, a stratigraphically lower group of sand veins extended down from the base of the sand sheet into the underlying sand (not illustrated), and a higher group occurred intraformationally within the interstratified sand and silty sand facies (*ca.* 3.7 m depth in Figure 2b). Both groups extended down from truncation surfaces and mark episodes of erosion before and during sand-sheet development. OSL age estimates from the overlying sand indicate that the veins are older than *ca.* 14,000 yr BP. Some of the sand veins may have formed more or less at the same time as the large epigenetic sand wedges that penetrate massive ice and icy sediments nearby at Crumbling Point, and which have provided a weighted mean optical age – from feldspar – of 14.0 ± 1.0 ka (Murton *et al.*, 1997).

At the Johnson Bay sand sheet, several sand veins and wedges were observed extending down from the prominent erosion surface at the base of the sheet into underlying sand. They therefore pre-date sand-sheet aggradation (Table 1). By contrast, only two small wedges were observed whose tops were located *within* the sand sheet, 10 and 80 cm above the base. The lower was a sand wedge *ca.* 1.5 m high, and the higher was a composite-wedge pseudomorph *ca.* 2.3 m high; both were no wider than *ca.* 20 cm.

The size and shape of these structures suggest that they are epigenetic, each associated with a specific surface or horizon at the base of or within the sand sheets.

DISCUSSION

These field observations allow inferences to be made about thermal-contraction cracking and sand-wedge growth, and about the palaeoenvironmental significance of sand veins and wedges associated with aeolian sand sheets.

Thermal-Contraction Cracking and Sand-wedge Growth

The syngenetic sand veins differ in size and / or shape from those of syngenetic sand wedges and ice veins and wedges reported in the literature. In particular, their chimney-like shape is unusual. The rare reports of sand wedges that exhibit two or more upward growth phases (syngenetic) – from a sand sheet on northern Hadwen Island (Figure 1) and alluvial-fan deposits on southwest Banks Island (P. Worsley *pers. comm.* 2000) – reveal downward-tapering or irregular structures, often with sand veins branching from their sides and toes (Murton, 1996, fig. 6; Murton *et al.*, 2000). Syngenetic ice wedges tend to have a chevron or nested growth pattern (Yershov, 1998; Melnikov and Spesivtsev, 2000, fig. 4.19) due to variations in the frequency of thermal contraction cracking and the rate of sediment aggradation. Ice wedges tens of metres high have developed in Siberian lowlands where silty sediments – probably of polygenetic origin – have aggraded over many thousands of years (Dostovalov and Popov, 1966; Sher *et al.*, 2005), the largest wedges reported measuring 50–80 m or more high and ≤ 8 –10 m wide (Yershov, 1998). Syngenetic ice wedges ≤ 26 m high and ≤ 2 –3 m wide also occur in windblown silt (loess) in northern Alaska (Carter, 1988). French and Gozdzik (1988) suggested, however, that the majority of syngenetic frost fissures outside of central and northern Siberia are probably smaller than epigenetic ones, with heights of 0.5–2.0 m and maximum widths of 5–20 cm (cf. French *et al.*, 1982). Accordingly, they described them as ‘veins’ rather than ‘wedges’.

Some syngenetic ice wedges of similar height (3.5 to >6 m), although substantially wider ($\leq ca. 1.5\text{--}2.0$ m) than the sand veins described here, occur in Holocene peats and sands in western Siberia, Yakutia and the Trans-Baikal region (Vasil'chuk and Vasil'chuk, 1995). But the ice structures most similar to the sand veins are small, relict syngenetic ice wedges $\leq ca. 3$ m high and a few cm to *ca.* 10 cm wide, partially thawed, on Hooper Island (Figure 1; Mackay, 1976, fig. 3.1), and the narrow syngenetic ice wedges formed by gradual accumulation of peat in ice-wedge troughs and polygon centres (Mackay, 1992a).

The unusual, chimney-like morphology of the syngenetic sand veins indicates a balance between the rate of sand-sheet aggradation and the frequency of thermal-contraction cracking, implying that the veins grew upward more or less continuously during aggradation. This balance is surprising given the variable frequency of thermal-contraction cracking currently observed from snow-covered tundra in the region. Mackay's (1992a) long-term monitoring of ice wedges on Garry Island and at Illisarvik (Figure 1) indicates that cracking frequencies vary substantially among ice wedges at an individual site, from site to site, and from year to year. Had cracking frequencies similarly varied during growth of the Kittigazuit Formation sand veins, the veins would not to be chimney-shaped but would have more ragged, irregular margins or wide shoulders as the vein thickness changed repeatedly and abruptly with depth, like many of the syngenetic ice wedges discussed above. One explanation for the fine balance necessary for growth of chimney-like sand veins is that snow cover was largely absent during their formation, and therefore the relationship between air and ground temperature was closer than beneath modern tundra covered by variable thicknesses of winter snow. In addition, the rate of

sand-sheet aggradation – and presumably the rate of sand supply by deflation upwind – must have been relatively uniform.

A much closer match in size and shape can be drawn between the multiple shoulders of rejuvenated sand wedge 1 (Figure 6a) and those of rejuvenated ice wedges in Arctic North America and Siberia (Péwé, 1962; Mackay, 1974; Harry *et al.*, 1985; Lewkowicz, 1994; Yershov, 1998, fig. 5.6; Kasper and Allard, 2001). This agreement indicates that both ice wedges and sand wedges that began growth as epigenetic structures can later be rejuvenated and grow syngenetically. The multiple shoulders of wedge 1 define a pyramid-like top (i.e. upward narrowing) that is quite different from the chimney-like (i.e. uniform width) shape of the syngenetic sand veins discussed above. The pyramid-like top indicates that upward growth of the wedge occurred in discrete stages rather than continuously. These two growth forms of syngenetic sand veins and wedges define end members of a continuum between episodic growth that produces rejuvenated structures of very uneven (e.g. pyramid-like) width and more or less continuous growth that produces structures of nearly uniform (i.e. chimney-like) width.

The anti-syngenetic sand wedges are similar in size and morphology to anti-syngenetic ice wedges reported by Mackay (1990, 1995, 2000) in the region. The sand wedges differ, however, from the anti-syngenetic ice wedges in that they formed beneath a flat rather than hilly landscape. Deflation removed only a limited amount of sand – much less than the few metres depth of typical epigenetic sand wedges in the region, thus preserving a substantial width of sand wedge beneath the deflation surface and so allowing very wide sand wedges to develop in the partially-truncated wedges. If deflation occurred when the thermal-contraction cracks were open, then the anti-syngenetic sand wedges provide a record of

deflation activity. Aeolian activity subsequently changed from deflation to deposition, as a sand sheet aggraded above the deflation surface, burying the wedges.

The growth of sand wedges is more complex than discussed above. In addition to the aeolian processes that raised or lowered the ground surface by aggradation or deflation, sand-wedge growth itself contributed to surface aggradation. Other things being equal, the ground surface adjoining growing sand wedges rises because of the externally-supplied sand that accumulates within thermal-contraction cracks and therefore adds volume to the permafrost and active layer. This volume addition and consequent surface aggradation results from growth of ice wedges (Mackay, 1992a), sand wedges (Sletten *et al.*, 2003) or composite wedges. Surface aggradation increases with wedge volume, and so will be most pronounced for wide and deep wedges. The widest reported sand wedges, from Antarctica, are 10 m (Berg and Black, 1966) and, in the lower Beacon Valley, “the entire surface is underlain by sand wedge material” and associated with a microrelief of *ca.* 0.8 m between the floors of troughs above cracking sites and the tops of parallel ridges on each side (Sletten *et al.*, 2003, p.6). These authors estimate a spatially-averaged rate of surface aggradation of 0.05 to 0.1 mm yr⁻¹ for this location. By implication, the wide sand wedges near Johnson Bay must also have caused some surface aggradation. But we suggest that deflation exceeded aggradation, planing off any surface microtopography and leading to net downward growth of anti-syngenetic sand wedges.

Palaeoenvironmental Significance

Differences in the occurrence of sand veins within the sand sheets of full-glacial and postglacial age in the Tuktoyaktuk Coastlands are attributed to palaeoclimatic differences.

The tall syngenetic sand veins were observed only in thick sand-sheet deposits of the Kittigazuit Formation. The Kittigazuit Formation sand sheet aggraded during full-glacial climatic conditions, whereas the Johnson Bay and Crumbling Point sand sheets formed mainly during the climatic amelioration associated with the postglacial warm interval (Bateman and Murton, 2006). Although aeolian sedimentation was regionally continuous during both full-glacial conditions and the postglacial warm interval (Table 1), intraformational sand veins or wedges are rare to absent within the postglacial sand sheets examined. We suggest that the warm interval did not favour thermal contraction cracking within the sand sheets. We discount differences in sediment texture because an interstratified sand and silty sand facies is present in both full-glacial and postglacial sand sheets, and the ice contents are not visibly different. The cessation, or only rare occurrence, of thermal-contraction cracking in the postglacial sand sheets supports J.R. Mackay's (1992b, p. 11) suggestion that "ice-wedge growth was probably greatly reduced if it did not cease" between about 13,000 and 8,000 yr BP.

Differences in the infilling of veins and wedges within the thick sand sheets of the Canadian Arctic Coastal Plain and those of southwestern Alaska also reveal climatic differences. To our knowledge, cold-climate sand sheets 10 m or more thick have been detailed only from the Kittigazuit Formation in northwest Canada and from the Nushagak, Holitna and Upper Kuskokwim lowlands of southwestern Alaska (Lea, 1990, 1996), although others may occur in central Alaska (Lea and Waythomas, 1990). Lea (1990) reported that ice-wedge pseudomorphs are widespread within the sand sheets of presumed full-glacial (DuvannyYar interval; Lea and Waythomas, 1990) age in southwestern Alaska, especially at fine-grained horizons in sand-dominated sections. He inferred that

ice wedges formed during periods of reduced aeolian deposition and relative landscape stability, under conditions of continuous permafrost. By contrast, the dominant primary (i.e. original) infilling of the Kittigazuit Formation veins is aeolian sand, and their chimney-like shape implies more or less continuous growth. The different primary infills indicate that snow cover was substantially greater during wedge formation in the sub-Arctic Alaskan sand sheets than the Arctic Canadian ones. Such differences are consistent with the geographic location of the SW Alaskan sand sheets closer to a moisture source (North Pacific Ocean) and the Arctic Coastal Plain sand sheets being in a rainshadow of moisture sources in the Gulf of Alaska and the Bering Sea (Hopkins, 1982; Dinter *et al.*, 1990), with pervasive sea-ice cover on the Beaufort Sea combined with a very low glacio-eustatic sea level minimizing moisture supply from the north (Bateman and Murton, 2006).

To our knowledge, relict sand veins and wedges of similar size and morphology to those discussed above have not been reported from Pleistocene sand-sheet deposits in Europe or elsewhere. Although relict sand veins ('frost cracks' in the European Pleistocene literature) occur in coversand deposits in northwest and central Europe (e.g. Dylik and Maarleveld, 1967; Van der Hammen *et al.*, 1967; Kasse, 1997) the veins are usually no taller than *ca.* 1 m, and often taper gradually downward rather than having a uniform, chimney-like morphology. Relict sand wedges and composite-wedge pseudomorphs have frequently been described from Europe (e.g. Worsley, 1966; Gozdzik, 1986; Kolstrup, 1986, 1987, 1993; Kasse and Vandenberghe, 1998; Ghysels and Heyse, 2006), but their maximum true widths are usually less than *ca.* 1.5 m, distinctly less than the anti-syngenetic sand wedges near Johnson Bay. Despite the differences in size between

the Canadian and European structures – which may reflect colder Arctic conditions and the great thickness of the Kittigazuit Formation sand sheets – the abundant evidence for aggradation and deflation (e.g. pebble lags) preserved in the European coversand deposits suggests that syngenetic and anti-syngenetic wedges may be more common here than previously thought. One might speculate that composite-wedge pseudomorphs or relict sand wedges that extend down from surfaces underlain by permafrost and subaerially exposed to periglacial conditions for long periods of time (cf. Kolstrup, 2004) may have been subject to deflation and some anti-syngenetic growth.

The structures most similar to the syngenetic sand veins described above are pseudomorphs of syngenetic ice veins or narrow ice wedges formed in fluvial pebbly sand in eastern England (Bateman *et al.*, 2001, fig. 49), and in fluvio-aeolian sands and silty sands in the eastern Netherlands and adjacent Germany (Vandenberghe and Van Huissteden, 1988). The latter, for example, are up to 4.5 m tall, and have a vertically-laminated core several centimetres wide that is surrounded by numerous normal faults. The wedges have a cone-in-cone structure that is attributed to episodic deposition of fluvio-aeolian sands and burial of the ice wedge, causing a new ice wedge to develop above, but extending down into, the buried ice wedge. This episodic growth contrasts with the more or less continuous upward growth and therefore more uniform width of the sand veins formed by aggradation of the Kittigazuit sand sheets.

CONCLUSIONS

The existence of continuous permafrost conditions during aggradation of aeolian sand sheets at least several metres thick is inferred from chimney-like syngenetic sand veins

and rejuvenated (syngenetic) sand wedges within the Kittigazuit Formation. Continuous permafrost conditions cannot be inferred confidently from sand sheets formed during the postglacial warm interval because sections often lack, or contain relatively few, elementary sand veins or wedges. We urge caution in interpreting permafrost conditions from relict cold-climate sand sheets that contain only small or few sand veins and wedges, as is common in the Late Pleistocene coversand deposits in Europe; but without more data on the size and growth rate of active sand veins and wedges, it is difficult to specify precise sizes. Likewise, the absence of veins or wedges in glacial age sand sheets does not rule out the former occurrence of permafrost.

ACKNOWLEDGEMENTS

Funding for this research was provided by the Royal Society, the British Society for Geomorphology (formerly BGRG) and the Quaternary Research Association. Della Murton, Enoch Pokiak and Fred Wolki assisted with fieldwork, and Hazel Lintott with cartography. Logistical support for fieldwork was provided by the Aurora Research Institute (Inuvik) and the Polar Continental Shelf Project. The paper has benefited from constructive comments from Professor H.M. French, Dr G. Ghysels and Professor Toni Lewkowicz.

REFERENCES

Bateman MD, Murton JB. 2006. Late Pleistocene glacial and periglacial aeolian activity in the Tuktoyaktuk Coastlands, NWT, Canada. *Quaternary Science Reviews*, in press.

- Bateman MD, Buckland PC, Carpenter R, Davies S, Frederick CD, Gearey B, Murton JB, Whitehouse NJ. 2001. Cove Farm Quarry, Westwoodside. In *The Quaternary of East Yorkshire and North Lincolnshire. Field Guide*. Bateman MD, Buckland PC, Frederick CD, Whitehouse NJ (eds). Quaternary Research Association, London; 141–160.
- Berg TE, Black RF. 1966. Preliminary measurements of growth of non-sorted polygons, Victoria Land, Antarctica. In *Antarctic Soils and Soil-Forming Processes*. Tedrow JCF. (ed). American Geophysical Union Antarctic Research Series, Vol. 8; 61–108.
- Brookfield ME. 1977. The origin of bounding surfaces in ancient aeolian sandstones. *Sedimentology* **24**: 303–332.
- Carter LD. 1983. Fossil sand wedges on the Alaskan Arctic Coastal Plain and their paleoenvironmental significance. In *Permafrost, Fourth International Conference, Proceedings*. National Academy Press: Washington, D.C.; 109–114.
- Carter LD. 1988. Loess and deep thermokarst basins in Arctic Alaska. In *Permafrost: Proceedings, 5th International Conference on Permafrost*. 2–5 August 1988, Trondheim, Norway, Vol. 1. Tapir Publishers: Trondheim; 706–711.
- Dallimore SR, Wolfe SA, Matthews JV. Jr. Vincent J-S. 1997. Mid-Wisconsinan eolian deposits of the Kittigazuit Formation, Tuktoyaktuk Coastlands, Northwest Territories, Canada. *Canadian Journal of Earth Sciences* **34**: 1421–1441.
- Dinter DA, Carter DL, Brigham-Grette J. 1990. Late Cenozoic geological evolution of the Alaskan North Slope and adjacent continental shelves. In *The Arctic Ocean Region. The Geology of North America* vol. L, Grantz A, Johnson L, Sweeney JF (eds). Geological Society of America, Boulder, Colorado; 459–490.

- Dostovalov BN, Popov AI. 1966. Polygonal systems of ice-wedges and conditions of their development. In *Permafrost International Conference, Proceedings*. Lafayette, Indiana, 11–15 November 1963. National Academy of Sciences – National Research Council publication 1287; Washington D.C.; 102–105.
- Dylik J, Maarleveld GC. 1967. Frost cracks, frost fissures and related polygons. *Mededelingen van de Geologische Stichting, Nieuwe Serie* **18**: 7–21.
- Environment Canada, 1993. *Canadian climate normals, 1961–1990, Yukon and Northwest Territories*. Canadian Climate Program, Environment Canada, Ottawa, Ontario; 37.
- French HM, Gozdzik JS. 1988. Pleistocene epigenetic and syngenetic frost fissures, Belchatów, Poland. *Canadian Journal of Earth Sciences* **12**: 2017–2027.
- French HM, Harry, DG, Clark, MJ. 1982. Ground-ice stratigraphy and late-Quaternary events, south-west Banks Island, Canadian Arctic. In *The R.J.E. Brown Memorial Volume, Proceedings of the Fourth Canadian Permafrost Conference*. National Research Council of Canada: Ottawa; 81–90.
- Ghysels G, Heyse I. 2006. Composite-wedge pseudomorphs in Flanders, Belgium. *Permafrost and Periglacial Processes* **17**: 145–161. DOI: 10.1002/ppp.552
- Gozdzik JS. 1986. Structures de fentes à remplissage primaire sableux du Vistulien en Pologne et leur importance paléogéographique. *Biuletyn Peryglacjalny* **31**: 71–105.
- Harry DG, French HM, Pollard WH. 1985. Ice wedges and permafrost conditions near King Point, Beaufort Sea coast, Yukon Territory. In *Current Research, Part A, Paper 85-1A*. Geological Survey of Canada: Ottawa; 111–116.
- Hopkins DL. 1982. Aspects of the Paleogeography of Beringia during the late Pleistocene.

In *Paleoecology of Beringia*. Hopkins DL, Matthews JV Jr, Schweger CE, Young SB (eds). Academic Press: New York; 3–28.

Kasper JN, Allard M. 2001. Late-Holocene climatic changes as detected by the growth and decay of ice wedges on the southern shore of Hudson Strait, northern Québec, Canada. *The Holocene* **11**: 563–577.

Kasse C, Vandenberghe J. 1998. Topographic and drainage control on Weichselian ice-wedge and sand-wedge formation. Venebrügge, German-Dutch border. *Permafrost and Periglacial Processes* **9**: 95–106.

Kocurek G, Nielson J. 1986. Conditions favourable for the formation of warm-climate aeolian sand sheets. *Sedimentology* **33**: 795–816.

Kolstrup E. 1986. Reappraisal of the Upper Weichselian periglacial environment from Danish Frost wedge casts. *Palaeogeography, Palaeoclimatology, Palaeoecology* **56**: 237–249.

Kolstrup E. 1987. Frost wedge casts in western Jutland and their possible implications for European periglacial research. *Zeitschrift für Geomorphologie N.F.* **31**: 449–461.

Kolstrup E. 1993. Complex frost wedge casts as indicators of ice age environmental change. *Würzburger Geographische Arbeiten* **87**: 269–282.

Kolstrup E. 2004. Stratigraphic and environmental implications of a large ice-wedge cast at Tjæreborg, Denmark. *Permafrost and Periglacial Processes* **15**: 31–40. DOI: 10.1002/ppp.479

Koster EA. 1988. Ancient and modern cold-climate aeolian sand deposits. *Journal of Quaternary Science* **3**: 69–83.

- Koster EA. 1995. Progress in cold-climate aeolian research. *Quaestiones Geographicae (Poznan) Special Issue* **4**: 139–160.
- Koster EA. 2005. Recent advances in luminescence dating of Late Pleistocene (cold-climate) aeolian sand and loess deposits in Western Europe. *Permafrost and Periglacial Processes* **16**: 131–143.
- Lea PD. 1990. Pleistocene periglacial eolian deposits in southwestern Alaska: sedimentary facies and depositional processes. *Journal of Sedimentary Petrology* **60**: 582–591.
- Lea PD. 1996. Vertebrate tracks in Pleistocene eolian sand-sheet deposits of Alaska. *Quaternary Research* **45**: 226–240.
- Lea PD, Waythomas CF. 1990. Late-Pleistocene eolian sand sheets in Alaska. *Quaternary Research* **34**: 269–281.
- Lewkowicz AG. 1994. Ice-wedge rejuvenation, Fosheim Peninsula, Ellesmere Island, Canada. *Permafrost and Periglacial Processes* **5**: 251–268.
- MacDonald GM. 2000. Postglacial vegetation change. In *The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change*, Dyke LD, Brooks GR (eds). Geological Survey of Canada, Bulletin 547; 57–63.
- Mackay JR. 1974. Ice-wedge cracks, Garry Island, Northwest Territories. *Canadian Journal of Earth Sciences* **11**: 1366–1383.
- Mackay JR. 1976. Pleistocene permafrost, Hooper Island, Northwest Territories. In *Current Research, Part A, Paper 76-1A*. Geological Survey of Canada: Ottawa; 17–18.

- Mackay JR. 1978. Freshwater shelled invertebrate indicators of paleoclimate in northwestern Canada during late glacial times: Discussion. *Canadian Journal of Earth Sciences* **15**: 461–462.
- Mackay JR. 1990. Some observations on the growth and deformation of epigenetic, syngenetic and anti-syngenetic ice wedges. *Permafrost and Periglacial Processes* **1**: 15–29.
- Mackay JR. 1992a. The frequency of ice-wedge cracking (1967–1987) at Garry Island, western Arctic coast, Canada. *Canadian Journal of Earth Sciences* **29**: 236–248.
- Mackay JR. 1992b. Lake stability in an ice-rich permafrost environment: examples from the western Arctic coast. In *Aquatic Ecosystems in Semi-arid Regions: Implications for Resource Management*, N.H.R.I. Symposium Series 7, Robarts RD, Bothwell ML (eds). Environment Canada: Saskatoon; 1–26.
- Mackay JR. 1995. Ice wedges on hillslopes and landform evolution in the late Quaternary, western Arctic coast, Canada. *Canadian Journal of Earth Sciences* **32**: 1093–1105.
- Mackay JR. 2000. Thermally induced movements in ice-wedge polygons, western arctic coast: a long-term study. *Géographie physique et Quaternaire* **54**: 41–68.
- Melnikov VP, Spesivtsev VI. 2000. *Cryogenic Formations in the Earth's Lithosphere* (graphic version). Konishchev VN (ed.). Siberian Branch of the Russian Academy of Sciences: Novosibirsk Scientific Publishing Centre of the UIGGM, Siberian Branch of the RAS, Publishing House, Siberian Branch of the RAS.
- Murton JB. 1996. Morphology and paleoenvironmental significance of Quaternary sand veins, sand wedges, and composite wedges, Tuktoyaktuk Coastlands, Western Arctic Canada. *Journal of Sedimentary Research* **66**: 17–25.

- Murton JB, French HM, Lamothe M. 1997. Late Wisconsinan erosion and aeolian deposition, Summer and Hadwen Islands, Mackenzie Delta area, western Canadian Arctic: optical dating and implications for glacial chronology. *Canadian Journal of Earth Sciences* **34**: 190–199.
- Murton JB, Worsley P, Gozdzik J. 2000. Sand veins and wedges in cold aeolian environments. *Quaternary Science Reviews* **19**: 899–922.
- Péwé TL. 1962. Ice wedges in permafrost, Lower Yukon River area near Galena, Alaska. *Biuletyn Peryglacjalny* **11**: 65–76.
- Rampton VN. 1988. *Quaternary Geology of the Tuktoyaktuk Coastlands, Northwest Territories*. Geological Survey of Canada, Memoir 423.
- Ritchie JC. 1984. *Past and Present Vegetation of the Far Northwest of Canada*. University of Toronto Press: Toronto; 155.
- Sher AV, Kuzmina SA, Kuznetsova TV, Sulerzhitsky LD. 2005. New insights into the Weichselian environment and climate of the East Siberian Arctic, derived from fossil insects, plants and mammals. *Quaternary Science Reviews* **24**: 533–569.
- Sletten RS, Hallet B, Fletcher RC. 2003. Resurfacing time of terrestrial surfaces by the formation and maturation of polygonal patterned ground. *Journal of Geophysical Research* **108** (E4), 8044, doi:10.1029/2002JE001914,2003; GDS 25-1-10
- Taylor AE, Dallimore SR, Judge AS. 1996. Late Quaternary history of the Mackenzie-Beaufort region, Arctic Canada, from modelling of permafrost temperatures. 2. The Mackenzie Delta - Tuktoyaktuk Coastlands. *Canadian Journal of Earth Sciences* **33**: 62–71.
- Vandenberghe J, Van Huissteden J. 1988. Fluvio-aeolian interaction in a region of

- continuous permafrost. In *Permafrost: Proceedings, 5th International Conference on Permafrost*. 2–5 August 1988, Trondheim, Norway, Vol. 1. Tapir Publishers: Trondheim; 876–881.
- Van der Hammen T, Maarleveld GC, Vogel JC, Zagwijn WH. 1967. Stratigraphy, climatic succession and radiocarbon dating of the last glacial in the Netherlands. *Geologie en Mijnbouw* **46**: 79–95.
- Vasil'chuk YK, Vasil'chuk AC. Ice-wedge formation in northern Asia during the Holocene. *Permafrost and Periglacial Processes* **6**: 273–279.
- Worsley P. 1966. Fossil frost wedge polygons at Congleton, Cheshire, England. *Geografiska Annaler* **48A**: 211–219.
- Yershov ED. 1998. *General Geocryology*. Cambridge University Press: Cambridge; 323–325.

TABLE

Table 1. Phases of Late Quaternary sand-sheet activity in the Tuktoyaktuk Coastlands

FIGURE CAPTIONS

Figure 1 Location map of the Tuktoyaktuk Coastlands. Ice limits of the Toker Point Stade and Sitidgi Stade are according to Rampton (1988). Dark shaded area shows the approximate extent of the Johnson Bay sand sheet at the northeastern end of the Tuktoyaktuk Peninsula, according to Rampton (1988, Map 1647A).

Figure 2 Sedimentary logs through the aeolian sand sheet at section 2.9, southwest of Johnson Bay (a); and through the fluvio-aeolian sand sheet at section 3.11,

Crumbling Point, northern Summer Island (b). Modified from Bateman and Murton (2006). Grain-size classes are field estimates.

Figure 3. Syngenetic sand vein in thick sand-sheet deposits of the Kittigazuit Formation, section 05-01, northwest ‘Summer Bay’, August 2005. The section through the vein is steeply dipping and viewed upwards from the beach below, with the effect that the base of the vein appears relatively larger than the top, and the person in the foreground appears giant-like. The approximate outline of the sand vein is sketched in (a).

Figure 4. (a) Syngenetic sand vein in thick sand-sheet deposits of the Kittigazuit Formation near the vein in Figure 3, August 2001. The lower metre of the vein penetrates a cross set that represents dune deposits, the top of which is truncated by a horizontal bounding surface just above the 8 m depth mark. A small truncated sand wedge occurs to the left of the toe of the sand vein. (b) Detail of upper 4 m of the vein. Horizontal arrows inscribed in the sand in (a) and (b) mark ‘shoulders’ of the sand vein. 1 m-depth increments shown. The section comprises a series of steep faces separated by horizontal steps.

Figure 5. (a) Syngenetic sand vein in Kittigazuit Formation sand sheet, southwest Summer Island. (b) Detail of vein fill and shoulder between 300 and 350 cm depth marks. The section comprises a series of vertical faces separated by horizontal steps. Trowel and spade for scale in (a), trowel in (b). The colour differences within the fill are similar to those in other sand wedges in the region and probably represent variations in the sand deposited in the original thermal-contraction cracks. The origin of the normal fault to the right of the vein is not known.

Figure 6. Rejuvenated (syngenetic) sand wedges 10.6 m apart whose tops rise above a bounding surface that truncates dune deposits and underlies sand-sheet deposits, Kittigazuit Formation, southern Hadwen Island. (a) multi-stage (pyramid-like) top, and (b) single bundle of sand veins above bounding surface. Trowel for scale in (a), trowel and spade in (b).

Figure 7. Anti-syngenetic sand wedges underlying a prominent erosion surface beneath the Johnson Bay sand sheet. (a) 3.9 m-wide wedge, section 6, July 2001. (b) 3.6 m-wide wedge, section 05-02, August 2005. Holes in (b) are sample locations for luminescence dating. Note the vertical to overturned strata in the host Cape Dalhousie Sands, which include layers of upturned gravel. Distinct bundles of different coloured sand veins are visible within the fill of both wedges. Both sections are located within a few hundred metres of each other, marked by the star beside section 05-02 in Figure 1.