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ABSTRACT: Sand-wedge polygons on upland surfaces beneath thin loess in northeastern Nebraska record existence of permafrost around the margin of the Wisconsinan glacier at its maximum advance. Strong unidirectional wind not only kept the upland surfaces free of snow, allowing frost to penetrate deeply and thermal contraction cracks to develop, but also dessicated the surface material so that frost action and sublimation of pore ice could loosen surface material. The strong NW-SE winds deflated soils from upland surfaces, made ventifacts of the cobbles in the lag that remained and created fields of yardangs oriented NW-SE. Sand derived from the soils and underlying till was carried only a short distance to fill the thermal contraction cracks and in some places leave a thin sheet of sand covering the former surface.

INTRODUCTION:

Sand-filled thermal contraction wedges and sand-wedge polygons beneath thin loess have been recognized in several sites in northeastern Nebraska and northwestern Iowa during recent years (Wayne, 1991, Wayne and Guthrie, 1993). First discovered in the highwall of an abandoned gravel pit near Hartington, Nebraska that was being used as a landfill site in 1983, they represent the first unequivocal evidence of the former presence of permafrost near the Wisconsinan ice margin in this state. Since the initial discovery, additional sand-wedge polygons have been observed in the same region when state highways and county roads were being improved and the covering sediments were scraped off. Virtually all of northeastern Nebraska is blanketed by late Wisconsinan Peoria Loess. The loess ranges in thickness from about 1.0 m to more than 10 m and effectively obscures the underlying surface on which the polygons formed. This contrasts with the conditions in Illinois (Johnson, 1990), Indiana (Wayne 1967), and North Dakota (Bluemle and Clayton, 1986), where non-sorted polygons can be recognized by means of airphoto study.

Sand-filled thermal contraction wedges form where permafrost exists and when a rapid drop in temperature after the active layer has refrozen results in thermal contraction cracking. A snow cover more than a few cm thick will insulate the ground so that cracking is unlikely to take place; a snow cover would also prevent saltating grains from falling into the cracks. The sand-filled wedges in northeastern Nebraska, then, must developed when the upland till surfaces were free of snow during winter and after the active layer had become refrozen. For them to be snow-free at that time would require either extremely dry conditions with little snowfall, frequent winds strong enough to sweep the surface free of snow, or both.

The matrix in which the observed sand-filled wedges formed is, with one exception, till. Gravelly sand outwash underlies the till and some of it may have been exposed on slopes, but no outwash plains or valley train deposits exist in the vicinity of the sites were sand wedges are located. This is a region that was not glaciated during the Wisconsinan, and except for a route that carried the overflow from the Missouri River southeastward from the mouth of the Niobrara to the Elkhorn valley when ice blocked it briefly about 23 ka (Wayne, 1985) the region is one of rolling topography with pre-Illinoian till capping the hills. During the late Wisconsinan glaciation, when these periglacial feature probably formed, the Missouri River, which serves as base level for all the streams that drain northeastern Nebraska, flowed at a level 27-30 m higher than it does now; therefore it is unlikely that the present slopes where gravelly sand underlies the capping till were well enough exposed to provide a source for the sand that fills the wedges.

It is my purpose in this report to describe the sand in the northeastern Nebraska wedge fills and to suggest its

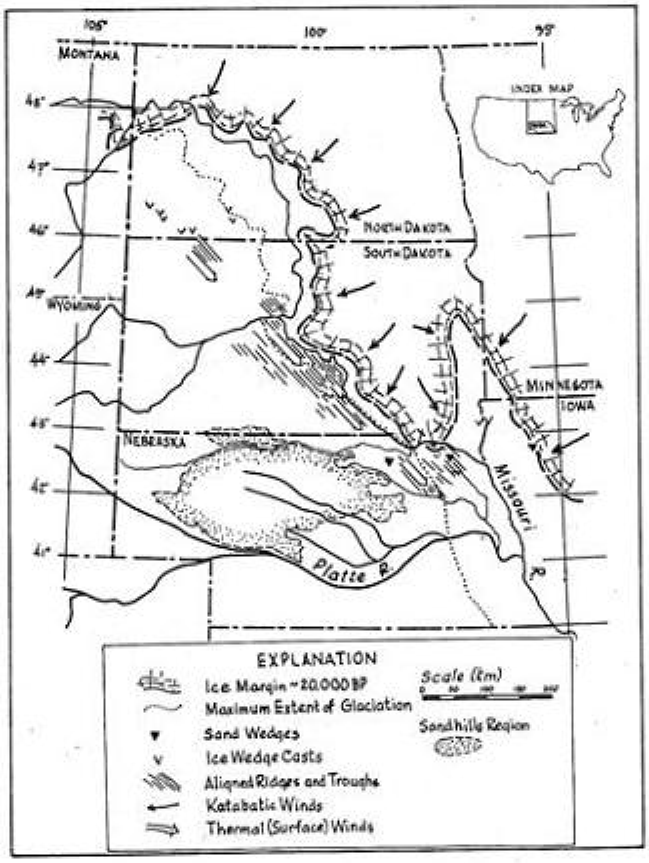

Figure 1. Map showing Wisconsinan ice limit in north central United States about 23,000 yr BP, distribution of yardang-like troughs and ridges, and probable pattern of katabatic and thermal/synoptic winds near the ice margin.

probable source, along with the environmental conditions that accompanied its generation and transport.

CHARACTERISTICS OF THE SAND IN THE WEDGES:

Most of the sand in the wedges consists of quartz grains that are well sorted; median grain size is 0.30 mm (1.74 O), with 67% of the samples falling between 0.70 mm and 0.14 mm (Wayne, 1991). Sphericity of the grains is high, and although a few are highly angular, most of the grains show varying amounts of corner rounding and polishing that is characteristic of abrasion during wind transport. Nearly all grains, though, exhibit conchoidal and stepped fractures that have not been obscured by wind transport. A few, however, are well rounded. In some exposures, a thin layer (about 30 cm) consisting of laminae of medium sand that alternates with laminae of very fine sand and silt overlies the wedges and the matrix in which they formed. Grains in the coarser sand laminae of this sand cover are identical to the sand grains that fill the wedges.

In studying the surface textures of the sand, grains from the wedge filling and overlying sand were compared with sand grains from the till that forms the matrix for the wedges. All samples were treated with sodium hexametaphosphate (Calgon) to flocculate clays, sieved to obtain grain-size distribution, then modal grain sizes were examined under a binocular microscope for roundness and sphericity. Individual grains were picked out of each sample to be mounted on an aluminum plug with double-sided tape, sputter coated with Au, and examined with a scanning electron microscope at magnitudes between 50x and 5000x. Grains were selected from the median grain size of the sand samples and compared with those of similar size from the till.

Single quartz grains constitute 89.8% to 95.6% of the more than 200 grains in each of the samples of sand from the basal and middle parts of the wedge fillings that were examined. In the fine sand range (0.88 mm), the highest percentage of grains is subrounded. Nearly all the well rounded grains, which make up a small part of the sample, show some pitting that surely took place in an earlier transport cycle, either by water, wind or both. Most of the quartz grains in these samples retain some of the fractures that were produced by crushing, although they were rounded and polished somewhat during wind transport before they fell into the thermal contraction fractures. Similar fractures in quartz grains have been used to indicate transport by glacial ice (Krinsley and Doornkamp, 1973), but other studies (Moss, 1966; Moss et al, 1973) suggest that such surface features as stepped and planar structures and conchoidal fractures may represent original microfractures that formed in the grains as a result of stresses that developed during the cooling of the igneous rock from which they were derived. Called deformation sheeting by Moss and Green (1975), these incipient fractures exist as zones or planes of weakness along which breakage takes place during erosion or transport. Highly angular grains may not necessarily be diagnostic of glacial transport (Mazzulo and Magenheimer, 1987); rather, simply liberating the grains from the rock could have produced the surface features. Similar features can also be produced by frost action (Corte and Trombotto, 1984; Lautridou and Seppälä, 1986; Coude-Gaussen and Lautridou, 1987), although movement by wind results in both rounding of sharp edges and sorting by shape. Most of the quartz grains collected from the sand wedges near Hartington probably were derived from igneous and metamorphic rocks of the Canadian Shield. Glacial erosion and transport surely played a part in their surface characteristics, but any grains that weathered free from the parent rock prior to having been transported by glacial ice undoubtedly had been subjected to many freeze-thaw cycles and may have resided in a permafrost environment before the glaciation. Quartz grains from the till of the same sizes as those near the median grain size in the wedges show similar surface textures, but few of them exhibit smoothed and polished edges. The till also contains quartz grains that are rounded and exhibit features inherited for an earlier mode of transport.

FACTORS FAVORING LOCAL TILL AS THE SAND SOURCE:

Unlike northern Europe, where sandurs and sandy sediments on the North Sea were exposed during Pleistocene glaciations to serve as a sand source for the sand-filled thermal contraction wedges and sand sheets ("coversands"), no sand plains or outwash regions existed in northeastern Nebraska from which the sand that fills the wedges of that region could have been derived. The nearest outwash surfaces were along the Missouri River, which flowed through a trench 35 km to the northeast. With no nearby sand source evident, it became necessary to examine the only other material present that might have served as a source for the wind-driven sand: the till that capped most of the nearby upland surfaces and now lies beneath a thin layer, generally less than 1-2 m thick, of late Wisconsinan loess.

Similarity of the sand grains recovered from the uppermost till of the area with the grains of similar size in the wedges, coupled with the paucity of outwash sediments nearby and the need to have sand available to be blown across a snow-free upland surface after the active layer had become completely frozen make it seem likely that the sand must have been deflated from the till that caps the upland surfaces. (Major arguments against till as a significant source for wind-transported sediment include that it is a cohesive, non-granular diamicton that would have been snow-covered or frozen during late fall, winter, and early spring and wet or covered with enough vegetation to inhibit deflation (Condra et al, 1947; Flint, 1971, p. 254; Embleton and King, 1975, p. 185). The tills of eastern Nebraska are fine grained; generally 70-80% is silt and clay and less than 30% is sand. McKenna-Neuman and Gilbert (1986) observed that summer winds generate little sand movement on a moist Baffin Island sandur, and even though winter winds are much stronger, deflation is inhibited by snow cover and ground ice in southwestern Greenland, but that in March, with a 10 to 20-cm thick cover of snow, a few places where exposed sand had lost its ice content through sublimation and underwent deflation. Law and van Dijk (1994), in their review of sublimation as a geomorphic process, pointed out studies that indicated greater sublimation rates from frozen clayey sediments that from frozen sand.

For a till to undergo deflation, it would have to be free of both vegetation and snow cover during at least part of the winter, when strong winds are most frequent. Nevertheless, several features in northeastern Nebraska tend to corroborate the idea that the major source of sand in the sand wedges and cover sand was the till that caps the upland in the area. Except in a few protected places, such as toe slopes in some narrow valleys, pre-Wisconsinan soil profiles are missing from nearly all upland surfaces in northeastern Nebraska, as is the Gilman Canyon bed, a pre-Peoria Loess aeolian deposit (Wayne, 1991; Mason, 2001). The tills are old–pre-Illinoian in age–yet an accumulation of the Late Wisconsinan Peoria Loess overlies virtually unweathered till in most exposures. In many places pebbles and cobbles in the lag between the till and loess have facets and shallow flutes characteristic of ventifacts.

All of the ventifacts observed indicate a wind direction of N 45^{o} W. Jorgensen (1988) described a similar deflation surface in Denmark. Christiansen and Svennson (1998(used ventifacts to determine paleo-wind directions in Denmark, finding that katabatic winds were effective near the ice margin, but that thermally controlled zonal winds persisted beyond that.

That a soil profile once existed on the till of the upland cannot be doubted. A Sangamon paleosol is preserved beneath thicker Wisconsinan loesses on toe slope positions in a ravine near this site; a radiocarbon date for the top of the Gilman Canyon bed, which underlies the Peoria Loess, is 23,000 yr BP. The Sangamon-Yarmouth profile that developed farther from the zone of sand wedges and ventifacts is distinctive; it has a brown, clay-rich B-horizon with a blocky structure. Beneath the solum the till has semi-vertical joints with a strongly oxidized borders; sheets or nodules of $CaCO_3$ are present in some of these joints to a depth of about 2 m beneath the surface. At the Hartington site, joints in the till have zones of oxidation along them and, near the top of the till, small nodules of $CaCO_3$ are present along a few of the joints. The Peoria Loess there is thin, however, and the Gilman Canyon bed is missing. An uncorrected ^{14}C date on land snails collected about 30 cm above the bse of the loess at the Hartington site is (Wayne, 1991) 18,390+/-70 yrs BP (Beta 165818).

Still another geomorphic feature of the region provides evidence that wind erosion was extensive around the margin of the Late Wisconsinan ice margin. Northeastern Nebraska is characterized by bands of ridge and trough topography that is aligned N45°W (Wayne, 1991). This distinctively fluted topography is present in a strip about 50 km wide that extends along the limit reached by the Wisconsinan glacier (Figure 1), from western Iowa (Hallberg, 1979) to north of Pierre, South Dakota (Wayne and Guthrie, 1993). Through much of this region of aligned ridges and troughs, the troughs are not occupied by streams, although many of them along the Missouri River in the vicinity of Pierre and Chamberlin, South Dakota do have streams in them. This distinctive topography, described and referred to ad fields of yardangs (Wayne, 1991), was offered as partial evidence for the existence of frequent strong winds from the northwest, parallel to the ice margin, during the glacial maximum. Such strong winds would readily have kept most of the upland surfaces blown free of snow, which would then have collected on the lee (southeast-facing) slopes and the valleys, protecting them from the deflation and severe freezing that took place on the wind-swept upland.

PERIGLACIAL WIND PATTERNS AND DEFLATION:

The northwest-southeast-trending yardang-like flutings through northeastern Nebraska and central South Dakota outside the limit of the Wisconsinan glacier, along with the absence of the pre-Wisconsinan soil profiles across the uplands and a ventifact lag on the till surface, are ample evidence for strong NE-SW winds along the ice margin. A mechanism by which this might take place, though, has not been described.

Deflation requires a surface with little vegetation on which the particle are loose, so that they can be placed in motion by the wind. Very strong wind in necessary to remove fine grained material, unless something, such as saltating sand grains moving across the silt and clay, dislodges it through the thin dead air space that exists at the surface. A frozen till surface would not have loose particles that could be deflated, but if the pore ice that binds the particles at the surface were to be sublimated, strong winds would be able to remove the loosened particles.

Katabatic winds are common along margins of glaciers (Liljequist, 1974),. Such winds are very cold when they begin to drain across the ice surface, but they become warmer as they descend toward the glacier margin, and they are dry. Although they are limited to the lower part of the atmosphere and rarely extend far beyond the ice margin, these dry winds will contribute to desiccating conditions near the ice margin.

Thorson and Bender (1985) postulated katabatic winds from glaciers that had sufficient velocity to deflate surface materials in the foothills of the Alaska Range, and the katabatic wind flow off the Antarctic ice sheet includes extremely strong winds (Parish and Bromwich, 1991). Whether katabatic winds descending from the Wisconsinan glacier that covered eastern South Dakota and reached the north edge of Nebraska could have maintained a velocity adequate to deflate soils as far as 50 km from the ice margin is unlikely. The deflation in northeastern Nebraska resulted from strong northwesterly winds rather than katabatic ones, which would have flowed from the northeast, although the dry katabatic wind would have had a desiccating effect on the land surface along the ice margin. Moving air of low humidity would result in sublimation of pore ice in the surface layer of frozen soil and/or till (McKenna-Neuman, 1990). Sublimation of the pore ice would result in loosening the grains of the fine grained sediment/soil so that strong NW-SE wind could deflate the dry, loose soil from crowns of hills that had been blown free of snow.

Ashwell (1966) pointed out that katabatic flow of air descending from the small icecap Langjøkull took place mostly at night when minimum wind speeds were recorded. He also noted that the main strong winds in Iceland parallel the wave circulation and that the winds are deflected around the margins of the ice cap. A similar situation may have existed around the southwestern side of the Laurentide ice sheet; wind-speed maxima evidently were those that followed long wave circulation patterns from northwest to southeast.

Wind-erosional features of the ice-marginal region of Nebraska corroborate earlier studies that presented the effects of the Late Wisconsinan circulation over North America (Wells, 1983). Tracks of cyclonic low pressure areas have been postulated to follow the margin of the Laurentide ice sheet across the Great Plains (Lamb and Woodruffe, 2970; Liljequist, 1974; Wells, 1983), sometimes crossing the outer part of the ice, other times being forced farther to the south. Cyclonic disturbances that crossed the Cordilleran glaciers and continued southeastward parallel to but south of the ice margin more likely would have generated an airflow dominated by southeasterly winds along the edge of the glacier–the reverse of the winds that formed the features observed there.

In their modeling of the climate during the Late Wisconsinan maximum, Kutzbach and Wright, (1986) explained that the high altitude wind current, the jet stream, split around the North American ice sheet, which served as a barrier. One branch went around the north side and the other followed the southern edge of the Laurentide glacier, accompanied by very strong surface winds. The two branches joined again on the northeast coast of the continent.

Over and along the edge if the Laurentide ice sheet, temperatures were significantly lower than the present ones in the area. Farther away, however, the temperature difference was much less. The thermally controlled winds flowed roughly parallel with the ice margin and became very strong (Kutzbach and Wright, 1986, p. 158). Temperatures in the reentrant between the Laurentide and the Cordilleran glaciers would have been low over a broad area, but the zone of cold narrowed toward the southeast, thus forcing the thermal wind into a narrower band and increasing its velocity (Gates, 1976). Cold anticyclonic winds draining across the glacier would have become more dry as they approached the edge of the ice, but in their descent should also have warmed at the dry adiabatic rate. If they started at -30°C at an altitude of about 2500 m, they would have warmed to about -15° C on reaching the ice margin and spreading across the land adjacent to the glacier. These northeasterly katabatic winds wee shallow, though, and probably did not reach great enough velocities to cause any erosion or ventifact formation. They were greatly overpowered by the much stronger thermal winds from the northwest that paralleled the ice margin.

SUMMARY:

Sand wedges developed in northeastern Nebraska during the Wisconsinan maximum, 23-20 ka, when upland till surfaces were free of snow during the fall or winter, after the active layer had become refrozen. For them to be snow-free at that time would have required either very dry conditions, frequent winds strong enough to sweep the surface clear of snow, or both. No sandurs or valley trains exist upwind from the area where wedges have been observed, so no obvious source except till is present for the sand that was blown across the thermal contraction cracks. Absence of a pre-Wisconsinan soil profile across the upland surfaces, lag of ventifacts, and broad areas of NW-SE fluting (yardangs) in northeastern Nebraska are indicative that a significant deflation of the surface has taken place. The presence of a few $CaCO_3$ nodules in till joints near the surface at Hartington indicates that nearly 2 m of material has been removed. Katabatic winds draining southeastward off the Laurentide glacier undoubtedly helped desiccate the surface and sublime the interstitial ice of the soil so that strong northwesterly wind currents were able to deflate the soil and underlying till. Deflation of the till, which is >70% silt and clay and <30% sand, would have yielded the sand that was blown across the surface, accumulating in the cracks. With a relatively short transport distance, some rounding and polishing of angular sand grains took place, but textures inherited from prior environments, including glacial and periglacial activity, remain recognizable.

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