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Late-Glacial Dunes, Ventifacts, and Wind Direction in West-Central Maine

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ABSTRACT

A late-glacial complex of eolian deposits, along with wind-modified till clasts and bedrock surfaces, was studied in a 100 km^2 belt along the Kennebec River near Madison, Maine. Of the 64 dunes mapped, most are longitudinal and the remainder are wind-shadow dunes. The eolian sand was derived from a sandy outwash deposit occupying the Kennebec River valley. This report discusses the areal extent, volume, and provenance of the sand, the uniformity of dune type, the orientation of longitudinal dune axes, and azimuths of flutes and cusps on wind-modified bedrock and fixed till-clast surfaces. These data indicate that the complex was formed primarily by west-northwest winds approximately 12,900 to 12,600 yr B.P. while the outwash was actively accumulating and before vegetation became well established in this region.

INTRODUCTION

The purpose of this study is to determine the nature and significance of the eolian features of the Anson quadrangle in west-central Maine: (1) to describe the distribution, morphology, and internal structure of the deposits, (2) to determine their provenance, (3) to describe the type and distribution of wind-modified rock surfaces, (4) to determine the time of formation of the sand deposits and the rock-surface modifications, and (5) to determine the direction of transport of the deposits.

The area of study was chosen because of the relatively wide distribution and good exposure of its eolian deposits, its accessibility, and its recorded glacial stratigraphy. The study area was limited to that part of the upper Kennebec River valley contained within the southern three-quarters of the Anson 15-minute quadrangle (Figs. 1 and 2). Hills in the northwest portion of the quadrangle reach 440 m above sea level and to the south the Kennebec River is approximately 49 m above sea level.

Many geologists, including True and Hitchcock (in Hitchcock, 1861), Stone (1886, 1899), Leavitt and Perkins (1935), Trefethen (1949), Allen (1955), Caldwell (1959, 1965), Hanley (1959), Bloom (1960), and Prescott (1966, 1969), have reported the presence of postglacial eolian deposits and/or ventifacts in localities throughout Maine. Others, including Perkins and Smith (1925), Leavitt and Perkins (1935), Smith (1964), and Borns and Hagar (1965a, 1965b), have reported them in the upper Kennebec River valley (Fig. 1). Some have suggested that the effective wind direction was either west, northwest, or north, but none has placed the period of formation of the eolian deposits and ventifacts into a precise glacial chronology. McKeon (1972) provides a more detailed review of these earlier studies.

LATE-GLACIAL STRATIGRAPHY

The provenance of the eolian deposits and the chronology of the eolian activity in the study area is closely related to the late-glacial stratigraphy of the region. The stratigraphy of the northern part of the Kennebec River valley, as defined by Borns and Hagar (1965a, 1965b), indicates the following sequence of events. As the margin of the last Wisconsin ice sheet retreated northwestward in Maine, the sea transgressed the deglaciated and isostatically depressed region and deposited the clays and

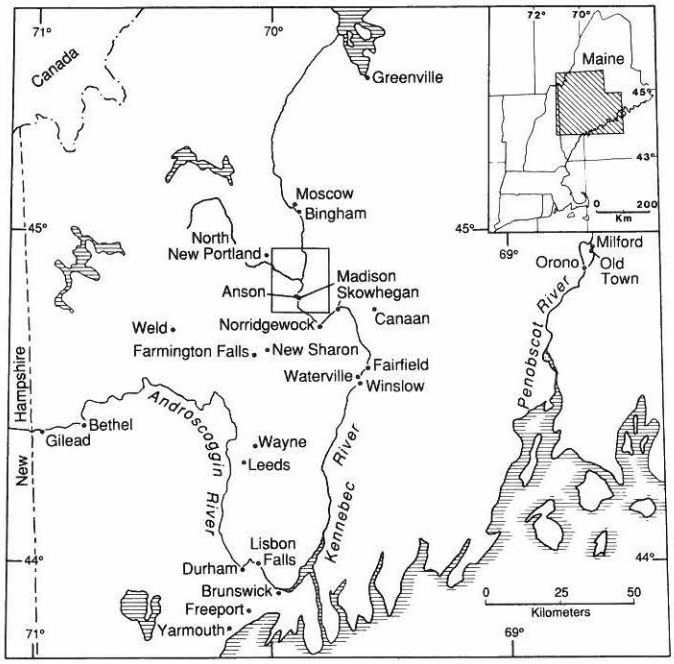

Figure 1. Map showing the location of the study area. Eolian features have been reported in or near all towns shown. For references, see text.

silts of the Presumpscot Formation. Locally, marine fossils found at the base of the Presumpscot Formation near its maximum altitude of 135 m in the Kennebec River valley at Embden Pond (Fig. 2, location 1), yielded a date of 12,930±200 yr B.P. (Y-1477, Borns and Hagar, 1965b). This date is thought to closely approximate the time of maximum marine transgression of the Kennebec River valley. There is some debate about this date since it is reported as 13,020±240 yr B.P. in Stuiver and Borns (1975). [Smith (1985) has noted that this date complicates the ice retreat pattern based on other regional dates and suggests that it may be too old.] As the rate of regional isostatic uplift exceeded the rate of eustatic rise of sea level, sandy outwash of the Embden Formation (Borns and Hagar, 1965b) was transported to the receding shoreline and was deposited gradationally on the Presumpscot Formation. The prograding Embden Formation formed a continuous plain within the Kennebec River valley south approximately to Waterville (Fig. 1). The late glacial sea had regressed at least to the present coast by about 12,300 yr B.P. (Stuiver and Borns, 1968). Since Waterville is halfway between the study area and the present coast, it is estimated that the southern limit of the Embden Formation stood in the sea at Waterville approximately 12,600 yr B.P. By this time the outwash ceased to accumulate, probably because the ice margin had withdrawn to a position north of Greenville where its meltwater streams could no longer discharge sediment into the Kennebec drainage. As uplift continued, both the Embden and Presumpscot Formations were deeply incised by the early Kennebec River. Within this incision, coarse gravels (the "North Anson Formation" of Borns and Hagar, 1965b) were deposited unconformably on the Presumpscot Formation. Presently, the river is cutting these postglacial stream terrace gravels (Fig. 2).

Note that throughout this article "Embden Formation" is used to refer to the coarser upper section of what is presently referred to as the Presumpscot Formation. While the Presumpscot Formation is largely glaciomarine, its upper sediments grade from estuarine to subaerial.

EOLIAN DEPOSITS

Much of the conventional terminology used to describe eolian deposits has been developed from work in modern, warm climate deserts. Although this terminology is used herein, it is recognized that the dune area of this study is small in scale and more rugged in topography when compared to those of the world's modern deserts. Another important distinction is that the eolian deposits of the Anson area were produced in a periglacial environment. The term dune is used for these deposits. Note that Koster (1982), in his report on the eolian deposits of the Netherlands, uses the term dune only if there is a height difference of a least five meters; any eolian ridge less than five meters in height he calls "undulations".

Eolian deposits, first defined on low altitude panchromatic aerial photographs and soil maps, were examined and sampled during the summer of 1971.

Distribution

The eolian deposits are not distributed randomly throughout the study area. All are found east of the western limit of the Embden Formation as mapped by Borns and Hagar (1965b) within the Kennebec River valley, with the exception of two localities southwest of the confluence of the Carrabassett and the Kennebec Rivers (Fig. 2). Eolian deposits in the Carrabassett River valley are on, or less than 0.5 km south of, the Embden Formation. Of the 64 dunes identified in the study area, 50 are east of the present Kennebec River, and all but three of the remainder are in the Carrabassett River valley. In general, more dunes are to the east than to the west of a chain of hills 100 m in relief that trends north-south between the eastern limit of the Embden Formation and Wesserunsett Lake (Fig. 2). The range in altitude of all dunes is 85-218 m above sea level, and the mean is 138 m above sea level. With respect to the glacial stratigraphy, one dune rests upon the erosional surface of the Presumpscot Formation, nine on the Embden Formation, and one on the postglacial stream terrace gravels. The remaining 53 dunes rest upon till and/or bedrock.

Morphology

There are three basic types of eolian deposits present in the study area: longitudinal dunes, wind-shadow dunes, and blanket

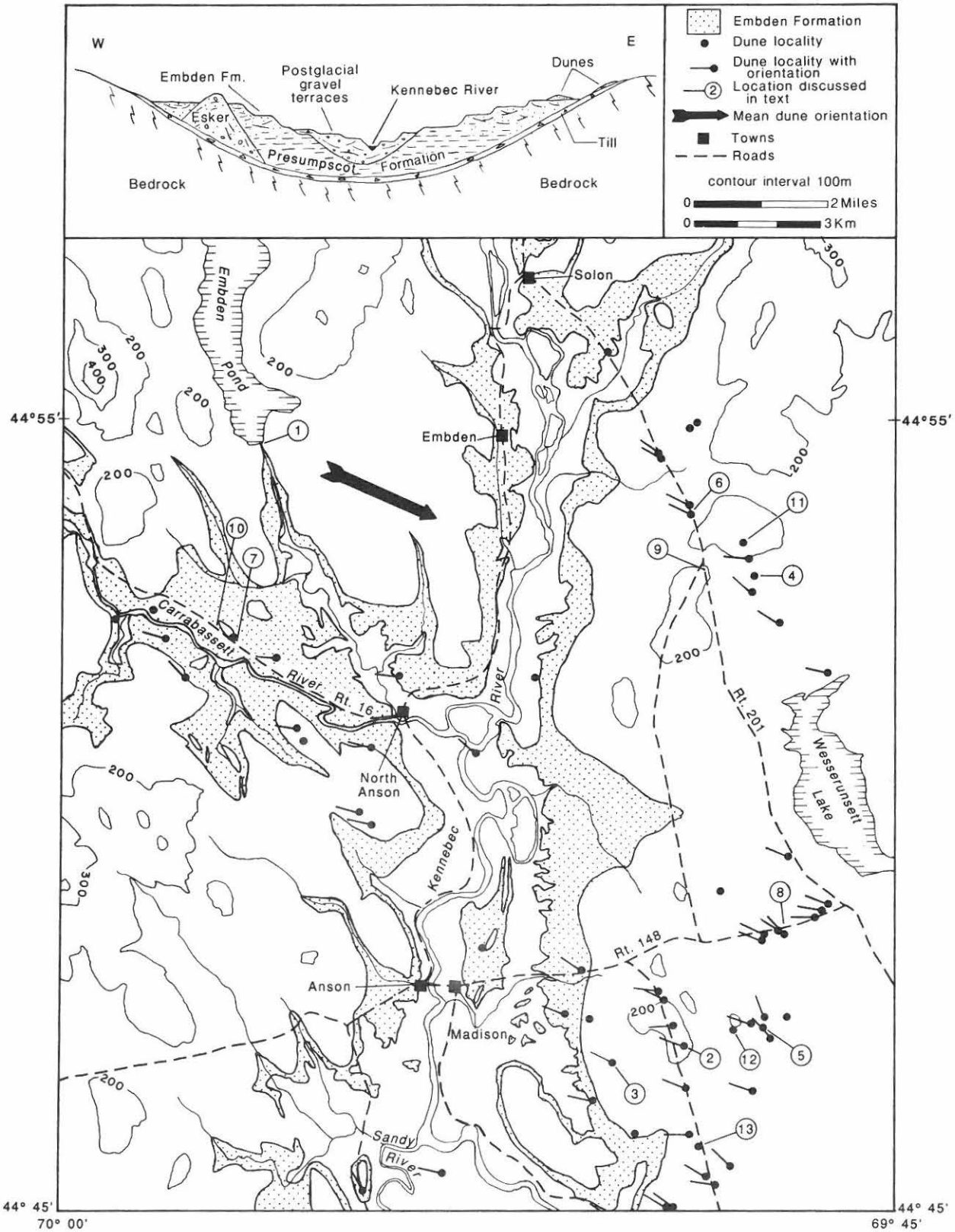

Figure 2. Dune locations and orientations, general topography, location of late-glacial outwash, and generalized cross section of the Kennebec River valley within the study area. (Base map adapted from the 1:62,500 scale Anson quadrangle of the U.S.G.S., and generalized cross section modified from Borns and Hagar, 1965a. The 100 m elevation contour has been omitted for clarity.)

Figure 3. A well formed, stable, and vegetated longitudinal dune trending west-northwest to east-southeast, center to lower left, rests upon the Embden Formation outwash in the Carrabassett River valley 2 km west of North New Portland near Route 145 (Fig. 1). This dune is about 400 m in length and 4 m in width.

Figure 4. An unstable and partially vegetated wind-shadow dune on the southeast flank of Ward Hill (Fig. 2, location 2).

TABLE 1. APPROXIMATE DIMENSIONS IN METERS OF 10 LONGITUDINAL DUNES IN THE ANSON AREA. LISTED IN ORDER OF DECREASING AREA. (-) INDICATES NOT MEASURED.

	Height	Length	Width	Length/Width Ratio
	4	380	35	10.9
	3	165	33	5.0
	7	80	44	1.8
	1	100	16	6.3
	-	100	13	7.7
	2	33	25	1.3
	3	31	16	1.9
	2	33	13	2.5
	2	50	7	7.1
	1	33	6	5.5
Mean	2.8	101	21	5.0

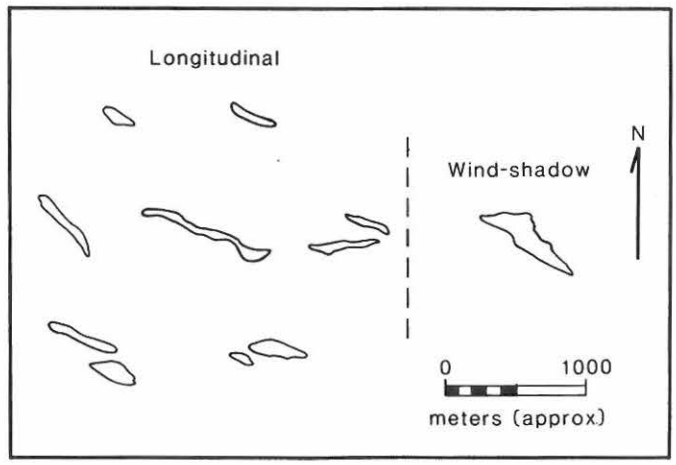

Figure 5. Outline of typical dunes of the study area. Dunes shown here are at the same scale and correct orientation, but they are not in their correct spatial location.

sand. The most useful eolian deposits for interpreting wind direction are longitudinal dunes (Fig. 3). In plan view these dunes vary from linear to sinuous forms with length/width ratios from 11 to 1.3 (Table 1). These sand ridges are generally symmetrical in cross section and have flank slopes dipping 5 to 20°.

Approximately one quarter of all dunes identified are of the wind-shadow type (Fig. 4). These dunes, unlike the relatively uniform longitudinal dunes, are irregular in plan, often with length/width ratios close to 1.0, and have maximum diameters up to 800 m. The volume of the average wind-shadow dune is five to ten times that of the average longitudinal dune. Very few of the wind-shadow dunes have a shape that is an indication of wind direction; however, their location relative to an obstacle is an important indicator of wind direction. Figure 5 shows the outline shape of selected dunes. The wind-shadow dune included in this figure is also shown in Figure 4.

The third type of eolian deposit, the blanket sand, conforms to the underlying topography as a more or less continuous sheet of sand less than one meter thick. Because of its planar form, the blanket sand is not an adequate indicator of wind direction. Furthermore, because they are more susceptible to destruction by erosion and by agricultural tilling, blanket sands have not been preserved as well as the longitudinal and wind-shadow dunes.

There is a fair correlation between type of eolian deposit and local relief. Longitudinal dunes generally are found on the remnants of the Carrabassett and Kennebec River valley out-

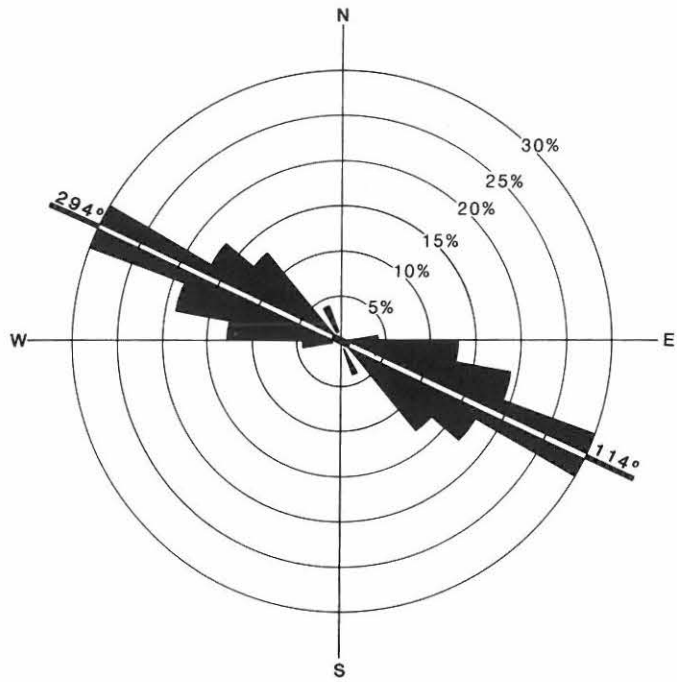

Figure 6. Rose diagram showing the long axis orientation of 47 dunes within the Anson quadrangle. Diagram is based on the summation of 10° class intervals.

wash plains and on the lower portions of the west flanks of the north-south trending chain of hills to the east of the Kennebec River (Fig. 2). While some of the wind-shadow dunes are located on the west slopes, most are on the east slopes of these same hills. Although recognized only in limited exposures, a thin blanket sand appears to have mantled most of the study area to the east of the Embden Formation and hence does not show a topographic preference.

The orientation of the long axis of most longitudinal and a few wind-shadow dunes was recorded to $\pm 2^{o}$; the mean orientation of these 47 dune azimuths is 294-114° with a standard deviation of 17°. The small variance of the distribution, as best shown in a rose diagram (Fig. 6), implies that the dunes were formed by a uni-directional wind rather than bi- or multi-directional winds.

Internal Characteristics

The color, general mineralogy, roundness, and average textural parameters of the dune sands are as follows. Unweathered, dry, and organic-free samples of dune sand range in color from light brownish gray (10 YR 6/2) to light yellowish brown (10 YR 6/4). In general, the sand is composed of a high proportion of quartz with lesser amounts of feldspar and other minerals, including approximately five percent heavy minerals (ρ>2.95). Selected quartz grains in the 1.0 to 2.0 ϕ (0.5 - 0.25 mm) size range were found to be either subrounded or rounded, according to the Russel-Taylor-Pettijohn descriptive classification (Mueller, 1967). The roundness increases with increasing distance east from the Embden Formation. Sand samples weighing 100-150 gm and collected with a 2.5 cm diameter soil auger from the upper meter of 52 of the 64 eolian deposits were sieved mechanically using standard wire mesh sieves, 0.5 - 4.0 ϕ (0.71 mm - 0.0625 mm), at 0.25 ϕ intervals. Cumulative grain size curves were plotted for each sample. Figure 7 shows curves for three representative dunes. The mean textural parameters and descriptive equivalents (Mueller, 1967; Folk, 1968) are shown in Table 2.

The internal sedimentary structure of eolian deposits usually provides a strong indication of the effective wind direction. Exposures suitable for the study of bedding characteristics are few in the study area. However, the deposits can be described as either tabular planar bedded, trough bedded, or structureless. The most prominent bedding type, tabular planar, was observed in exposures of three dunes (Fig. 2, locations 2, 3, and 4). The beds range from 0.5 cm to 2 cm in thickness, are subparallel, laterally persistent for three or four meters, and distinguished on the basis of slight variation in grain size. Unfortunately, bedding of this type is not helpful in determining transport direction. The second type, trough bedding, is a good indicator of transport direction, but it was observed only in the upper one meter of one dune (Fig. 2, location 5), where the long axes of the troughs trend northwest-southeast. The structureless blanket sand, which has an average thickness of 0.5 m, shows ungraded, massive bedding which presents no indication of transport direction. In summary, the internal structures of the eolian deposits in the study area are not reliable indicators of wind direction at the time of deposition.

WIND-MODIFIED ROCK SURFACES

Ventifacts

Ventifacts found in the area vary in size and lithology, but their distinct textural features resemble those of ventifacts from diverse environments as described by others. A few pebbles, smaller than 4 cm in their longest direction, showed extensive modification on all sides, forming triquetrous or "brazil nut" ventifacts, a type common to the loose stones of desert pavements. Sharp (1949) maintained that "many generalizations concerning ventifacts have been made with respect to smaller stones," and that the features of larger ventifacts may differ greatly from those found on smaller ventifacts. In this study only the larger (>8 cm) ventifacts were selected for the purpose of recording the various features resulting from wind abrasion. Most ventifacts were less than 30 cm in length but the largest ventifact found was approximately 1 meter in diameter (Fig. 8d). Most of these ventifacts showed one or more of the following features.

Polished Surfaces. A few quartz clasts are highly polished to a waxy luster (Figure 8a). The quartz grains of some coarse-

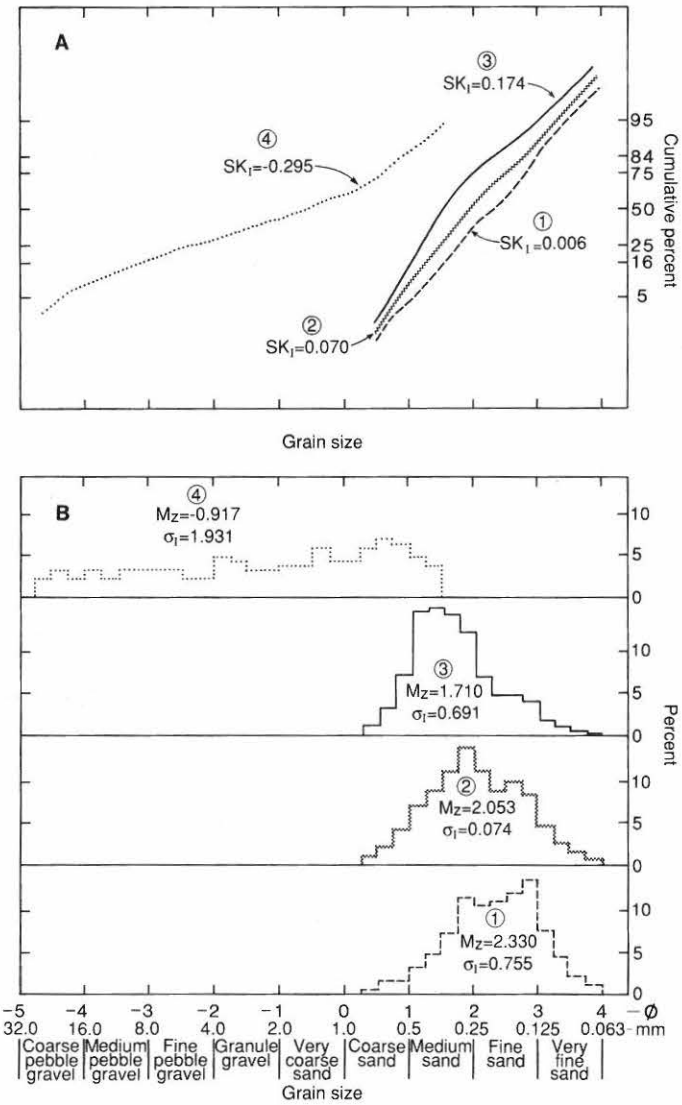

Figure 7. Grain size distribution curves and textural parameters for three representative dune sand samples from the Anson quadrangle. Sample 1 is approximately one standard deviation finer in mean size than the mean of all dunes. Sample 2 is closest in mean size to the mean of all dunes. Sample 3 is approximately one standard deviation coarser in mean size than the mean of all dunes. M_Z is mean grain size. σ_I is inclusive graphic standard deviation, SK_I is inclusive graphic skewness. Sample 4 is representative of the outwash of the Embden Formation. (a) Log probability scale, (b) Histograms in percent in each 0.25 ø class interval. Both samples 1 and 2 are described as moderately sorted, fine-grained sands that have symmetrically skewed platykurtic distributions. Sample 3 is described as a moderately well-sorted, medium-grained sand that is fine skewed and mesokurtic.

grained (>3 mm) granites and quartz veins in other clasts are similarly polished.

Smoothed Surfaces. Most fine-grained (<3 mm) ventifacts are smoothed, not polished, to a dull finish on some cusp, flute, and pit-hollow surfaces.

TABLE 2. MEAN TEXTURAL PARAMETERS AND DESCRIPTIVE EQUIVALENTS FOR ALL 52 DUNE SAND SAMPLES ANALYZED.

	Mean grain size ø	Sorting σ_I	Skewness Sk_I	Kurtosis K_G
Mean	2.048	0.757	0.105	1.024
Description	fine grained	moderately sorted	fine skewed	platykurtic
Std. Dev.	0.310	0.107	0.118	0.137
Median	1.928	0.813	0.082	0.886
Minimum	1.233	0.544	-0.212	0.474
Maximum	2.623	1.081	0.375	1.298

Facets. Less than one out of ten wind-modified clasts have facets. Of these, most clasts have only one or two facets, which are usually flat or slightly concave and only rarely display sharp interfacial edges.

Differentially Abraded Surfaces. Veins, phenocrysts, and laminae commonly project above the general rock surface (Fig. 8b and 8c). Usually these features are found best developed on one side of the clast, which was generally inclined from the local horizontal surface by 30 to 60°.

Fluted Surfaces. Many of the clasts display flutes, or subparallel, discontinuous, shallow grooves on surfaces inclined less than 30° with the present horizontal.

Pitted Surfaces. These surfaces of alternating smoothed hollows and more resistant raised areas are common among coarse-grained (>3 mm) granites. The pitted surfaces are developed through accelerated abrasion of feldspar grains (Fig. 8d).

Ventifacts with these features were found at many localities within the Carrabassett River valley and in the hills to the east of the Embden Formation in the Kennebec River valley. All ventifacts found in this study area are modified till clasts located at the contact of the Late Wisconsin till and the overlying eolian sand. Close inspection of the sand/till interface at one section (Fig. 2, location 3) shows that approximately 50 percent of the till clasts, most of which are fixed rigidly in the upper till surface, display one or more of the ventifact features as described above. There is no indication of migration by frost action of the till clasts into the sand. Examination of a small pit, dug in the till to a depth of approximately 0.6 m, suggests that the distribution of clasts is homogeneous near the surface. Thus, whereas many clasts at the surface showed signs of modification by wind-driven sand, no distinct surface concentration of clasts similar to a deflation surface was observed.

In desert environments the features of wind abrasion listed above typically may be found on all sides of non-fixed ventifacts, but in the Anson area they are found only on the north-to-west face and/or on the top of the fixed ventifacts. Some of these features, especially the fluted surfaces, are indicative of effective

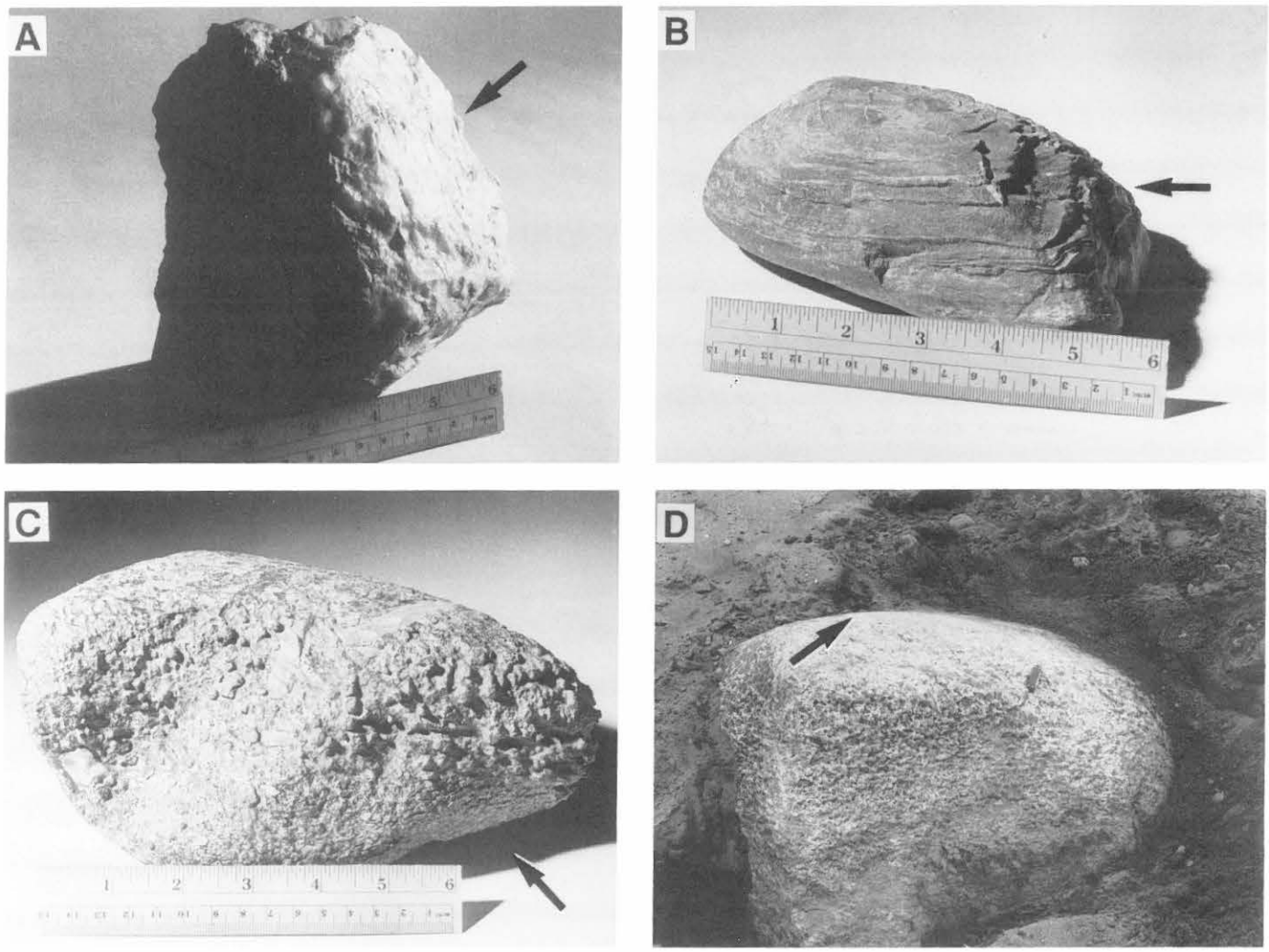

Figure 8. Ventifacts from the study area. Arrows indicate effective wind direction. (a) Highly polished quartz clast from till surface near location 6 (Fig. 2). (b-d) Differentially abraded till-clast ventifacts. (b) Quartz veins and laminae stand out on the right side, all other sides are not wind worn. (c) Resistant garnets protrude on front faces. Top surface is slightly fluted, all other sides are not wind worn. (d) Pitted granite boulder excavated from dune sand at location 6 (Fig. 2). Pocketknife provides scale.

wind direction. Measurements were made of directional features of fixed, till-clast ventifacts at three sites (Table 3).

Bedrock Surfaces

At three other sites, bedrock outcrop surfaces display wind abrasion features similar to those observed on some ventifacts. Directional trends of these features were also measured at each site (Table 3). The most modified outcrop is fine-grained, glacially smoothed, graywacke metasandstone of the Silurian Sangerville Formation (Pankiwskyj, 1979), located on the gentle northwest-facing slope of a broad hill mantled by till and eolian sand (Fig. 2, location 8). Its surface displays both numerous open-ended, one to two centimeter long flutes superposed on glacial striations and shallow grooves (Fig. 9a) and fan-like, two to three centimeter long cusps (Fig. 9b). Both flutes and cusps were found on the top and northwest side of the low outcrop, but not on the southeast side. The alignment of the trough-like flutes provides the trend of formation while the laterally asymmetrical pointed cusps, and the selective distribution on the outcrop surface of both flutes and cusps, provides the direction of formation (Table 3).

DISCUSSION

Much of the traditional literature on the geomorphology and sedimentology of eolian deposits deals with the sands and related features of modern deserts. Thanks to researchers like Niessen and Koster (1984), who assembled an annotated bibliography of periglacial sand dunes and eolian sand sheets, deposits such as those found in the Anson area now can be interpreted with more appropriate analogues.

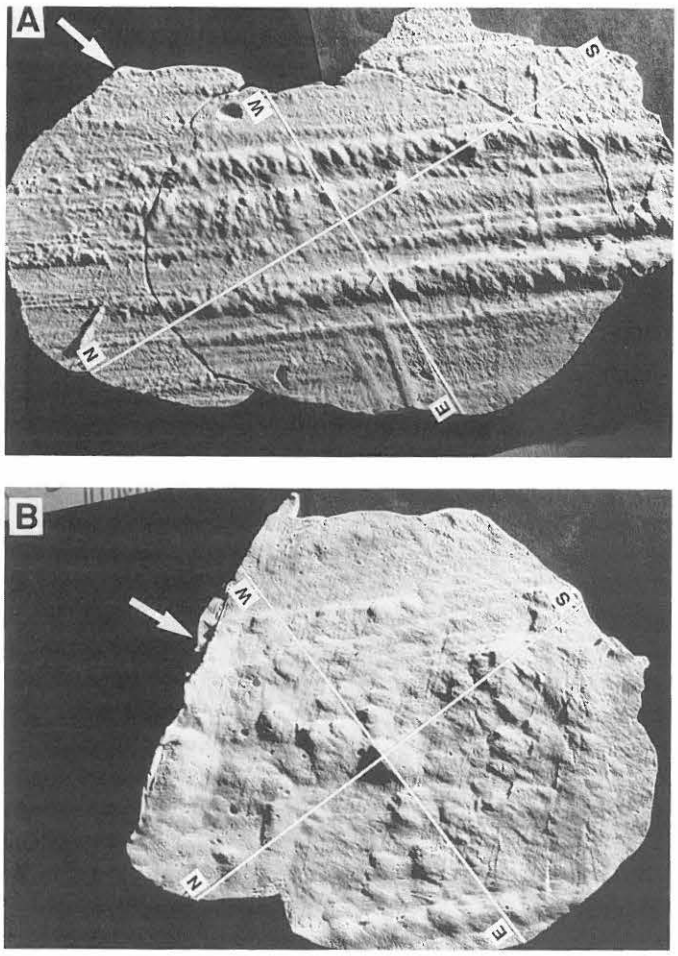

Figure 9. Plaster impressions of wind-modified bedrock surfaces at location 8 (Fig. 2), photographed with low angle illumination. At the outcrop these features are difficult to photograph. Arrow indicates effective wind direction. (a) Note flutes (WNW-ESE) are developed within glacial striations (NNW-SSE). Cast is 0.4 m in length. (b) Cusps, with vertices pointing upwind. Cast is 0.25 m in length.

TABLE 3. AZIMUTHS OF DIRECTIONAL FEATURES ON WIND-MODIFIED ROCK SURFACES.
Features measured include cusps, flutes, interfacial ridges, and normals to facets.

Location (Figure 2)	Type of Surface	Number Measured	Mean Azimuth, by location (± 2°)
3	Till Clasts	6	286°
6	Till Clast	1	304°
7	Till Clast	1	282°
8	Bedrock	130	294°
9	Bedrock	5	305°
10	Bedrock	40	310°
Mean of 6 locations			297°

Dune Orientation and Wind Direction

Dunes in the study area are classified as either longitudinal or wind-shadow according to their morphology and distribution. Effective winds are the sand-moving winds; the term effective wind direction is used here to refer to these winds. The writer contends that the effective wind direction parallels the mean orientation of the long axes of the dunes (Fig. 6). Since the majority of long-axis orientations measured were from longitudinal dunes, the assumed direct relation between longitudinal dune-axis orientation and wind direction must be verified. Verstappen (1968) reviewed several theories on the genesis of longitudinal dunes and found that "all the theories have in common the belief that a marked dominance of one wind direction is essential to their formation." Smith (1949) also noted that the elongation of longitudinal dunes represents the alignment of former winds, but warned that there is not universal agreement in this theory. For example, Bagnold (1942) and McKee (1966, 1979) believe that longitudinal dunes are oriented along the vector of two slightly divergent wind directions. Nevertheless, there is general agreement that the orientation of longitudinal dunes approximately parallels effective wind direction.

It is emphasized that most of the Anson area dunes are similar in shape and grain size, and dissimilar in size and extent, to classical longitudinal dunes. Folk (1971a), in reference to the longitudinal dunes of "vast inland deserts," listed their consistent parallelism over large areas, uniform lateral spacing, and occasionally bifurcating form, as features of this dune type. Cooper (1958) reviewed the literature on inland longitudinal dunes and described some dunes that are as much as 100 m high and continuous for 100 km. In summary, almost all research on inland longitudinal dunes has been carried out in deserts where the individual dunes are typically 10 to 50 times larger than those of the Anson area. Nevertheless, the subparallel orientation, lateral symmetry, and linearity of the dunes of the study area warrant a longitudinal classification; hence, the mean orientation of these dunes defines the trend of the effective wind.

Wind-Modified Rock Surfaces and Wind Direction

The morphology and distribution of facets, pits and cusps on ventifacts has long been recognized as being directly associated with wind direction (e.g. Sharp, 1964). Observations of modern ventifacts enabled Thiesmeyer and Digman (1942) to assert that "the longitudinal dimension of these (ventifact) furrows is generally parallel to wind direction." Within the Anson quadrangle, this relationship is also apparent since the average trend of directional features on the ventifacts (Table 3) agrees with the mean dune orientation to within 3° (Fig. 6).

Careful measurement of the azimuth of the surface features of a till-clast ventifact should provide the effective wind direction, but it must also be established that the till-clast has not been displaced by frost action since eolian modification. It was

observed that only a few small (<8 cm) ventifacts were not fixed in the till surface at most localities. Thus, it is assumed that the majority are *in situ*. Even if some of the till-clasts had been moved post-ventifaction by frost action, the measurements may still be significant, for Harris (1969) found that while the plunge of a till clast may be affected by freeze-thaw, its trend is not.

The flutes and cusps found on bedrock surfaces in the study area are similar but less well developed than those reported by Denny (1941), Segerstrom (1962), Minard (1966), and Thornbury (1969). Table 3 shows that the orientation of wind-modified rock surface features on bedrock closely approximates that of similar features on till-clasts. Clearly, wind-modified bedrock surfaces rather than clast surfaces are preferred as fixed indicators of wind direction, yet accounts in the literature of the use of wind-modified bedrock surfaces as indicators of wind direction are comparatively few. In New England there are two reports on the use of bedrock outcrops in Massachusetts to determine late-glacial wind directions (Hartshorn, 1961; Koteff, 1964).

Provenance of Eolian Deposits

There are only three possible sources of the eolian deposits of the study area: the Presumpscot Formation (a marine silt and clay), the Late Wisconsin till, and the Embden Formation (a sandy outwash). The Presumpscot Formation clearly was not the primary source of the eolian sands for the following reasons: (1) its grain-size distribution in weight percent for sand/silt/clay is approximately 7/39/54 (Caldwell, 1959), which shows first, that too few sand size particles are present to yield such sizable eolian deposits and second, that because of the high clay content it is highly resistant to eolian erosion; (2) only one of the 64 mapped dunes rests upon its erosional surface; and (3) its surface exposure often is very limited in areas west-northwest of the dunes, especially in the Carrabassett River valley. In some cases till has been reported as a source for eolian sands (Flint, 1971; Embleton and King, 1968). If till was the primary source of the eolian deposits in the study area, then the deposits should be found on both sides of the Kennebec River valley, rather than just on the east side, and signs of deflation such as a till-clast pavement should exist at the upper till surface. Mechanical grain-size analysis of one till sample from this area showed that it is 42 percent sand (0 - 4 ϕ or 1.0 - 0.625 mm). This grain-size range includes approximately 93 percent of all eolian sand particles analyzed. Eolian deposits, including both dunes and blanket sands, cover an area east of the Kennebec River valley, within the Anson quadrangle, of approximately 100 km^2 and average at least one half meter in thickness. Thus, the minimum total volume of all eolian deposits is about 5×10^7 m^3. If the till was the primary source of these sands, then the till surface over the same area would have had to deflate, on the average, by 1.2 m to produce this volume. Not only is such extensive deflation highly unlikely, but no evidence indicating any deflation was found.

Of the three possible sources, only the Embden Formation could provide a sufficient amount of sediment of the necessary grain-size distribution to form the eolian deposits of the study area. Furthermore, other workers have reported on the derivation of similar glacio-eolian deposits from adjacent valley outwash plains both as inferred for Pleistocene age deposits (e.g. Fernald, 1960) and as observed for Holocene deposits (e.g. Black, 1951 and Péwé, 1975).

Interpretations Based on Textural Parameters

Comparison of textural parameters, computed from the cumulative grain-size curves, indicates not only the similar nature of the many sand samples from the study area, but also supports the basic assumption that the sands are of eolian origin.

The mean size of the eolian deposits of the study area (2.048ϕ or 0.242 mm) indicates clearly that these deposits cannot be interpreted as loess deposits, which are primarily silt- and clay-size deposits (mean size 0.06 to 0.02 mm) and which are transported in suspension over long distances (Reineck and Singh, 1980). The term cover sand may be appropriate for the Anson area eolian sands, since they do drape an irregular topography as in some parts of the Netherlands (Ruegg, 1983) and their suggested niveo-eolian origin (De Jong, 1967) fits the assumed periglacial depositional environment. However, the Anson sands are slightly coarser in mean size than the cover sands described either in Denmark (Kolstrup and Jorgensen, 1982) or in the Netherlands (Ruegg, 1983).

Ahlbrandt (1979) published plots of textural parameters for 506 eolian sand samples from five continents. A comparison of the mean values obtained for the Anson area (Table 2) with Ahlbrandt's plots shows that while the Anson eolian sands are coarser and more poorly sorted than the 291 coastal dune sand samples, they fall very close to the mean of the 175 inland dune sand samples in all four textural parameters (grain size, sorting, skewness, and kurtosis).

Friedman (1961) and Moiola and Weiser (1968) submit that a beach sand can be distinguished from a dune sand by plotting mean grain size versus skewness. A plot of this type suggests that the deposits sampled in the Anson quadrangle are indeed dune sands and not beach or water-worked sands (Fig. 10a). Friedman (1961) and Moiola and Weiser (1968) agree that dune sands may not be as readily distinguished from river sands as from beach sands, but they found that a combination plot of mean size and standard deviation best separates the two environments (Figure 10b).

More recent work has shown that such graphical comparison of textural parameters does not always adequately permit determination of a given sand sample's depositional environment whether it be alluvial, littoral, or eolian. Ahlbrandt and Fryberger (1981) suggest that textural data are useful primarily as complementary evidence for an eolian interpretation. The assumed eolian origin for the sands of the Anson area is not

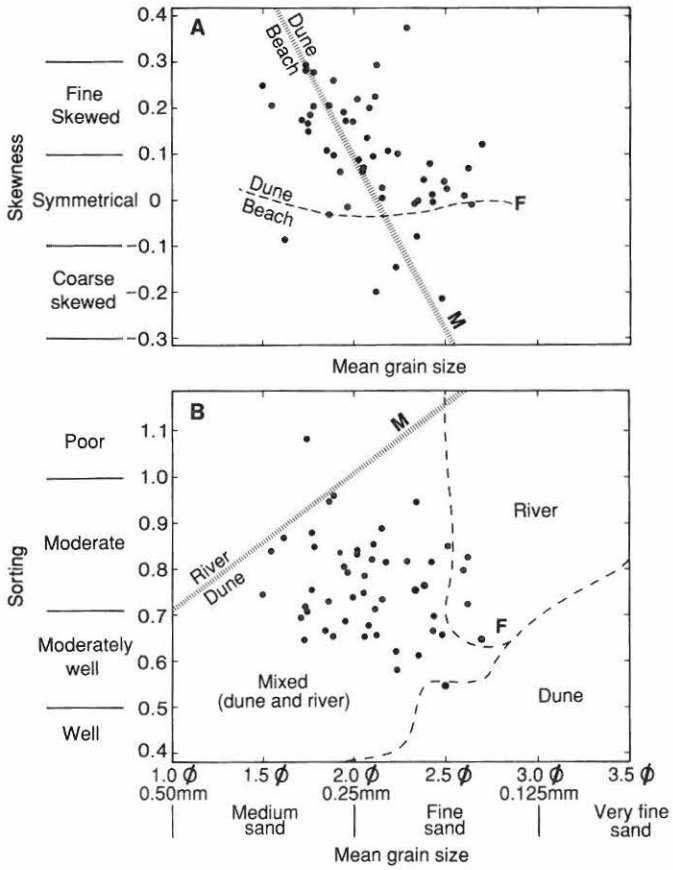

Figure 10. Combination plots of textural parameters of dune sand samples with implied environmental boundaries by others (F=Friedman, 1961, M=Moiola and Weiser, 1968). (a) Inclusive graphic skewness versus mean grain size. (b) Inclusive graphic standard deviation (sorting) versus mean grain size.

discounted when their textural parameters are compared with published data.

The eolian sand's textural parameters could be expected to change with increasing transport in the direction defined by the mean orientation of the longitudinal dune axes and consistent positioning of the wind-modified rock surfaces. Figure 2 shows that sands of dune localities to the southeast of the Carrabassett River valley apparently have been transported up to 3 km farther from the eastern limit of the Embden Formation than the sands of dune localities to the north and south.

Plots of textural parameters versus transport distance, measured east-southeast of the Embden Formation (Fig. 11), show only poor correlations between: (1) decreasing mean size and increasing transport distance, (2) decreasing standard deviation, or improved sorting, and increasing transport distance, and (3) increasing kurtosis and increasing transport distance. Only skewness, which increases slightly with increasing transport distance, shows a relatively significant change as the result of eolian transport of up to 6 km.

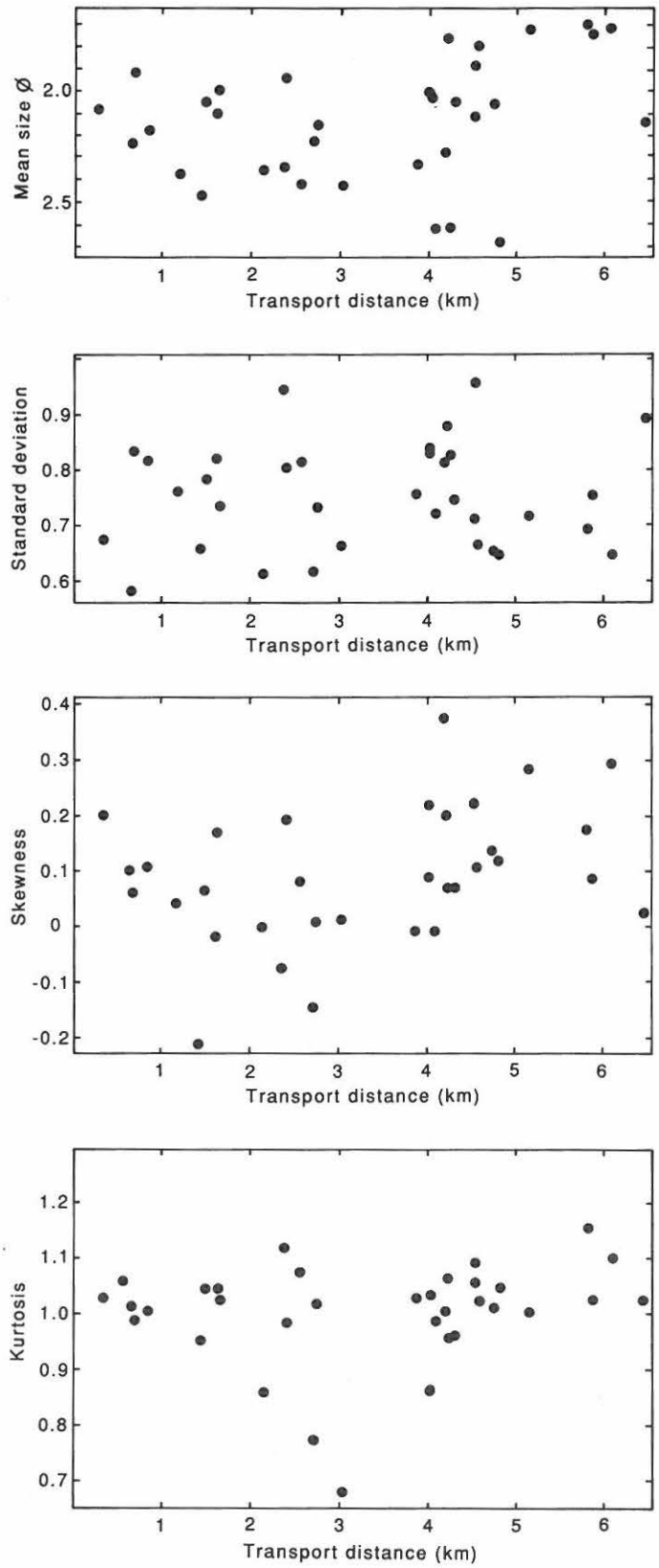

Figure 11. Plots of the four textural parameters of dune sand samples versus transport distance from the eastern limit of the outwash source.

Two factors may explain the apparent insensitivity of the textural parameters of the Anson sands to change with increasing transport -- too short a transport and/or imprecise sampling. Folk (1971b) has shown that there are consistent and significant differences in the textural parameters of sands of one dune sub-environment and those of the next (i.e. dune crests versus dune flanks) for the longitudinal dunes of the Simpson Desert, Australia. Generally, longitudinal dunes were sampled in this study at mid-length of their long axes near the dune crest, and wind-shadow dunes were sampled near their geometric center. The auger sampling technique used in this study samples several beds and thus smooths inter-bed textural variations and also may sample more than one dune sub-environment (Ahlbrandt and Fryberger, 1981).

Figure 12. Buried soil horizon exposed in a 6 m high section of a wind-shadow dune (Fig. 2, location 5). A radiocarbon date of charred wood fragments (arrow) immediately above the soil surface implies that this soil surface was buried by dune activity about 1700 AD.

Chronology of Eolian Activity

No datable material was found at the till surface below the eolian sands during the field study, so an absolute chronology of eolian activity within the study area cannot be established. However, the dates of eolian activity can be based on indirect evidence. The Embden Formation, the outwash which was the primary source of the eolian deposits, prograded into the regressing late-glacial sea in the Kennebec River valley near North Anson no earlier than approximately 12,900 yr B.P. (Borns and Hagar, 1965b). By about 12,600 yr B.P. the outwash had stopped accumulating and the early Kennebec River had begun to incise the outwash plain. It was during this interval that conditions were probably most favorable for eolian activity because of the availability of sediment.

Flint (1971) briefly summed up the periglacial eolian history typical of many areas:

> Most of the ancient dunes recorded in the literature of the Pleistocene were built in the lee of outwash bodies.... Some accumulated during outwash aggradation, probably during deglaciation; others did not form until postglacial dissection of the outwash had begun. Later both source and dunes became fully clothed with vegetation and dune building came to an end.

If dunes of the study area were built after the dissection of the Embden Formation, then the outwash plain surface might show evidence of deflation. Since no such pavement was found, it is suggested that the eolian sediments were derived from the outwash primarily while it was accumulating or approximately 12,900-12,600 B.P.

Modern and Historical Eolian Activity. An obvious indicator of modern eolian activity in the Anson area is the active, partially vegetation-free surface of some dunes. The stable dunes usually are covered by a thick humus layer and occasional pine trees. Other indicators of modern activity include the burial of wire fences and the migration of dune sand into wooded areas and across road segments (Fig. 2, locations 11, 12, and 13 respectively). Evidence of limited historical eolian activity is provided by a radiocarbon date, 245 ± 60 yr B.P., or A.D. 1705, (SI-970), of a 2 cm-thick bed of charred wood chips in the uppermost layer of a soil profile developed on and buried by the sand of a single wind-shadow dune (Fig. 12).

Modern Wind Directions. The only official weather bureau station within the study area, at Madison (Fig. 2), provided a 25 year record for prevailing wind direction, by compass octants, showing the average annual wind direction as northwest (Martin, 1930). A summary of the May-to-October daily wind records of four stations of the Maine State Forestry Department, located at Canaan, Moscow, New Sharon, and Weld (all within 35 km of the study area), shows that most winds of 6 m/sec and greater velocity are from the northwest. Thus the modern mean annual direction, to the nearest compass octant, of winds capable of presently transporting the sand in the study area is also northwest. The modern and historical eolian activity is nevertheless considered to be a limited eolian activity rather than a complete erosion and redeposition of the late-glacial deposits.

It is most likely that the late-glacial influx of vegetation severely limited eolian activity. The general vegetation cover of the immediate region of the study area was generally treeless tundra from the recession of the sea (about 13,000 yr B.P.). By about 11,000 yr B.P., trees were sparsely scattered about to create a mixed woodland landscape (Bonnichsen et al., 1985). The oldest bog-bottom date in the region, from below the vegetation zone in a core from Muddy Pond near Waterville, is 12,350 ± 300 yr B.P. (Davis, 1969). There is no proof that there was a period of significant eolian activity at any other time during either the late-glacial or Holocene period in this area. If there was significant eolian activity during the Holocene, then the distinct longitudinal dunes would have to have been built in conflict with the thick forest cover that, as shown by pollen diagrams, was present throughout the Holocene. Alternatively, a regional fire could have removed the forest cover and allowed

the deposits to reactivate. However, no extensive evidence of either buried trees or organic matter, such as a soil developed on till, was found beneath the eolian sand in dune sections.

An additional piece of evidence, the absence of weathering, shows that the period of eolian activity is basically late-glacial. No exposed weathering rind was found where flutes and cusps cut bedrock striations, indicating that the bedrock was not subjected to a significant amount of weathering between retreat of the overlying ice sheet and the deposition of the overlying eolian sand.

It is instructive to compare the proposed length of this period of primary eolian activity of approximately 300 years with the length of time required to form ventifacts. Hickox (1959) found that it was possible to form small ventifacts in 10 years; however, Sharp (1964) found that medium-coarse grained granitic to dioritic clasts showed no wear in 10 years by a sand with a mean size between 2 and 1 ϕ (0.25 and 0.4 mm) in a region where the wind velocity was greater than 6 m/sec for 17 percent of the time. Kuenen (1960) has shown in laboratory experiments that with a constant wind force of 11 m/sec and sand of 2 to 1.75 ϕ (0.25 to 0.30 mm) grain size, it takes 24,000 hours to effect a six percent weight loss on a quartzite ventifact. At present the Anson area has winds of this velocity less than one percent of the time from May to October. At this rate it should take about 550 years to form such a ventifact under present wind conditions in the Anson area. However, the ventifacts of the study area were not modified to such a well developed state as those of Kuenen. A qualitative appraisal of this evidence, then, indicates that it is possible that ventifacts found in the Anson area formed in the proposed 300 year period.

The maximum intensity of eolian activity during this interval was probably in the late summer and early autumn months when the ground surface was unfrozen, relatively dry, and free of snow (Embleton and King, 1968). It was not necessary that the climate be strictly arid, but only that the upper surface of the outwash plain be relatively dry. However, the eolian activity may not have been restricted to just the summer and autumn months. The blanket sand present may be analogous to the "cover sands" described in the low countries of northwestern Europe, where they are interpreted as niveo-eolian in origin (West, 1968; Flint, 1971). If similar conditions existed in the study area, then substantial amounts of sand may have been transported in the winter months, too, and hence the west-northwest wind direction reported herein may be more than a seasonal one.

CONCLUSIONS

The data and observations as reviewed here lead to the following conclusions for the Anson quadrangle of the upper Kennebec River valley in west-central Maine: (1) the late-glacial outwash, the Embden Formation, was the primary source of the eolian sands; (2) orientation of dune axes, azimuths of directional features on wind-modified till-clast and bedrock surfaces, and geographic distribution of eolian deposits are indicative of a west-northwest effective wind direction; (3) a period of major eolian activity occurred about 12,900 to 12,600 yr B.P.; and (4) the effective late-glacial winds during this period were from approximately the same direction as at present, that is, west-northwest.

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