Aeolian sandstones in the Copper Harbor Formation, Late Proterozoic, Lake Superior basin

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Sandstones with cross-sets up to 1.5 m thick occur within the Copper Harbor Formation, most prominently at Five Mile Point. In contrast to intercalated sandstones with smaller scale cross-stratification or horizontal lamination, pebbles are very scarce in the large-scale cross-stratified sandstones and, where present, are restricted to set bases. The large-scale cross-stratified sandstones are better sorted than intercalated sandstones and show a mean palaeocurrent direction at 90° to the mean for the interbedded sandstones.

The large-scale cross-stratified sandstones are interpreted as the product of fields of small transverse aeolian dunes that formed on dry parts of alluvial fans bordering the Keweenawan rift. The aeolian palaeocurrent mean is along the rift valley, and tentatively may be interpreted as the result of topographically constrained palaeo-tradewinds.

Des lits de grès à stratification oblique, d'épaisseur jusqu'à 1,5 m, apparaissent dans la Formation de Copper Harbor, plus éminemment à Five Mile Point. Au contraire des grès intercalés avec une stratification oblique à plus petite échelle ou avec lamination horizontale, les petits cailloux sont très rares dans les grès à stratification oblique de plus grande échelle, et lorsque présents, ils sont confinés aux lits de fond. Les grès à stratification oblique à grande échelle sont mieux triés que les grès intercalés, et leur direction moyenne des paléocourants est à 90° de la direction moyenne des grès interstratifiés.

Les grès à stratification oblique à grande échelle sont interprétés comme le résultat de champs de petites dunes éoliennes transversales édifiées sur les parties asséchées d'éventails d'alluvion en bordure du rift de Keweenawan. La moyenne des paléocourants éoliens suit la vallée du rift, et elle peut être considérée comme la résultante de paléo-vents alizés de direction déterminée par le relief.

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Introduction

The coarse conglomerates and sandstones of the Copper Harbor Formation in the Lake Superior Basin (Fig. 1) have been interpreted as the product of deposition on large, fluvially dominated alluvial fans bordering a Keweenawan rift valley (Elmore 1981, 1984; Daniels 1982; Taylor 1987). Desiccation features such as cracked, mud-draped surfaces are abundant in the Copper Harbor Formation, and in the absence of plants in Proterozoic times, it seems highly probable that large areas of the fluvially deposited Keweenawan alluvial fans would have been susceptible to aeolian reworking. This paper presents the results of a detailed study of outcrops at Five Mile Point (for location see Fig. 1) which indicates that some of the sandstones there are of aeolian origin. Evidence for aeolian activity elsewhere in the Copper Harbor Formation is also considered.

Only a small part of the Keweenawan sandstones shows evidence for aeolian deposition, and the units showing this evidence are not extensively exposed. These facts, and the long (though not particularly severe) history of diagenesis these rocks have undergone, may explain why features diagnostic of eolian origin are not more clearly displayed and have not been reported by previous investigators.

Macroscopic features of the large-scale cross-stratified sandstones

Sandstones at Five Mile Point fall into two categories: pebbly sandstones with upper flow regime flat-bed or small-scale trough cross-stratification (sets to about 40 cm); and sandstones with large-scale cross-stratification, with pebbles almost entirely absent and, where present, restricted to the bases of sets. The two categories of sandstone are closely intercalated (as shown by the section in Fig. 3). Sets of large-scale cross-strata range up to 1.5 m in thickness (Fig. 2). Traces of foresets and set boundaries on bedding planes are generally straight or slightly sinuous, although large troughs are present in places. Foreset bases are almost asymptotic to set boundaries. Foresets and set boundaries to different sets commonly meet one another at low angles, so it can be difficult to distinguish different sets where the outcrop is small.

Interpretation

The lack of pebbles and the scale of the cross-strata suggest an aeolian origin for the large-scale cross-stratified sandstones. A search for other structures diagnostic of eolian origin (e.g., Hunter 1977) was unsuccessful: if these features were originally present, they have probably been destroyed during diagenesis (the sandstones have not been significantly metamorphosed). Rare pebbles in the eolian units were well rounded, but typical ventifacts were not observed. Though the sedimentary structures alone are not sufficient to conclusively identify the sandstones as aeolian, the interpretation is confirmed by the grain-size and palaeocurrent data (see below). The cross-strata suggest deposition by aeolian dunes with straight or slightly sinuous crest lines, perhaps similar to the transverse dunes observed on glacial outwash fans by Hine and Boothroyd (1978). The consistency of palaeocurrent measurements (see below) also suggests a transverse type of dune. The size of the cross-sets and the close intercalation with fluvial sandstones may indicate that the fields of aeolian dunes did not persist long enough for very large dunes to form.

Microscopic features of the large-scale cross-stratified sandstones

Sorting

Eight samples were point counted for grain size in thin section. The apparent long and short clast axes were measured

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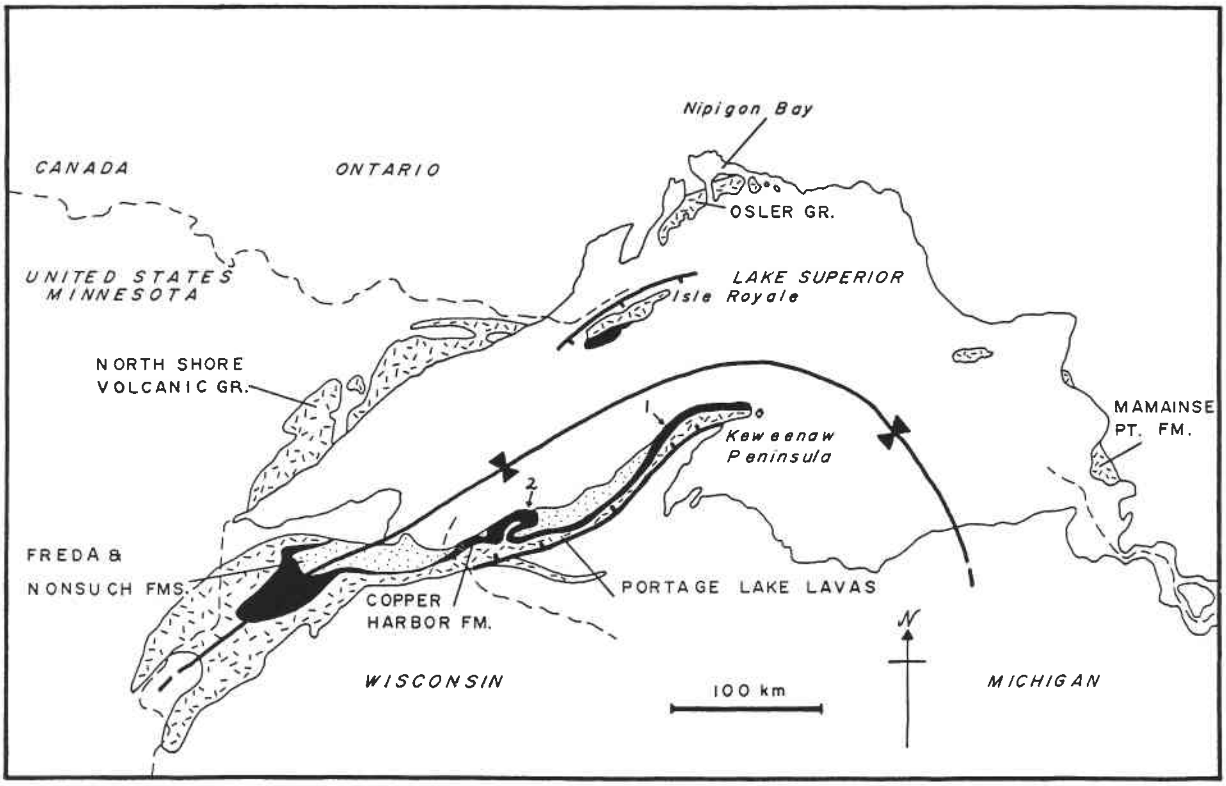

FIG. 1. Middle and upper Keweenawan geology of the Lake Superior basin. Structural features are shown as heavy lines. Ticks show the direction of dip of fault planes. The syncline between Isle Royale and the Keweenaw Peninsula is known as the Lake Superior syncline. Locations referred to in the text are numbered: 1, Five Mile Point; 2, Union Bay.

FIG. 2. Large-scale cross-stratified sandstone. The hammer is resting on a reactivation surface (laminae of the overlying set truncate against the top lamina of the underlying set).

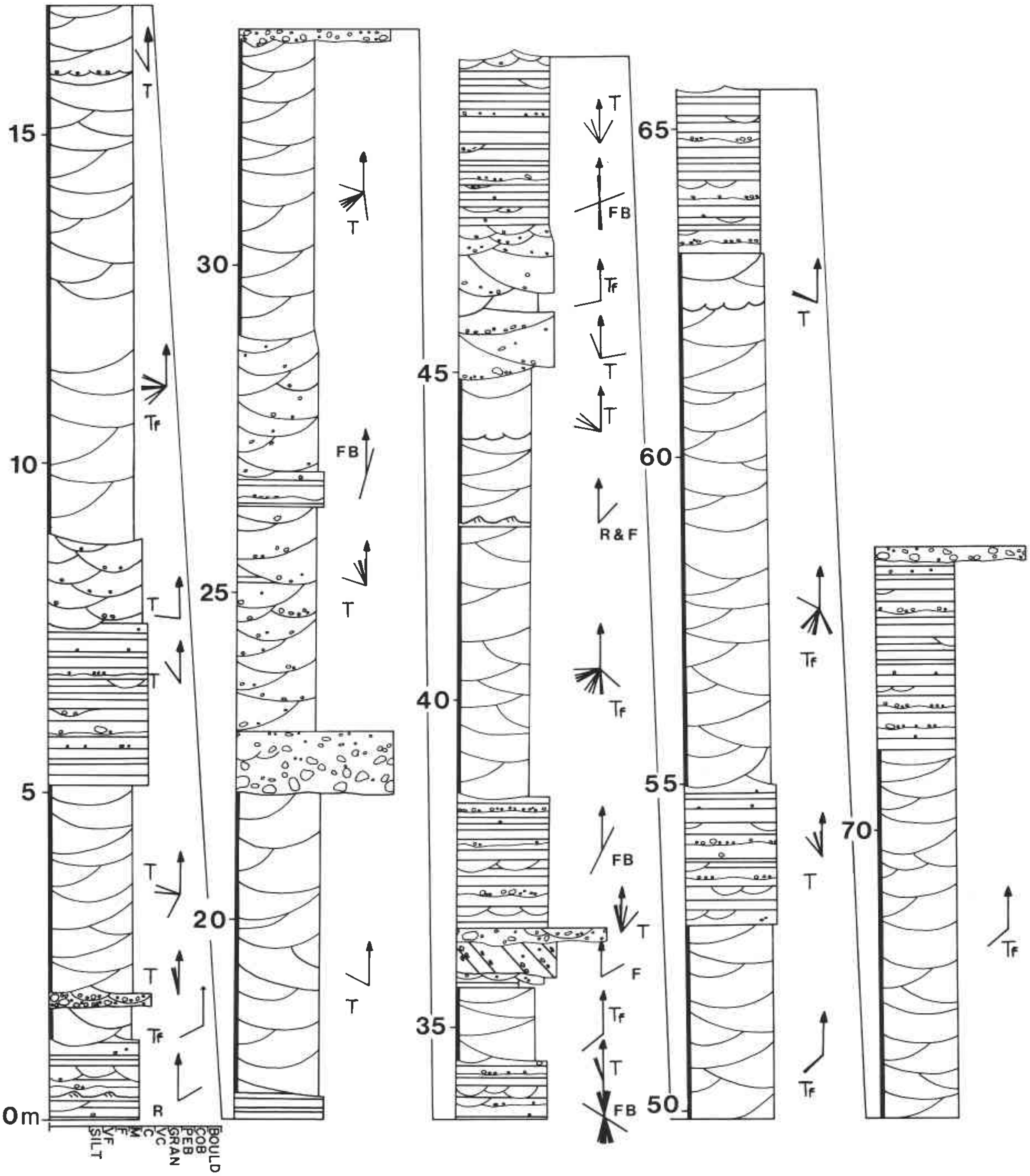

FIG. 3. Stratigraphic section in the Copper Harbor Formation at Five Mile Point, Upper Michigan (stratigraphically below the lava flow at this location). Palaeocurrent measurements at various levels are represented as lines radiating from the base of a north arrow. Each line represents a single measurement: T, trough axis measurement; T_f, measurement perpendicular to the trace of an approximately straight foreset on a bedding plane, measured in the direction of foreset dip; R, measurement perpendicular to crests of current ripples preserved on a bedding plane; R & F, rib and furrow measurement; F, dip direction of planar foresets; FB (double-ended lines), upper flow regime flat-bed current lineation directions. Units interpreted as aeolian are identified by a bar on the left side of the stratigraphic column.

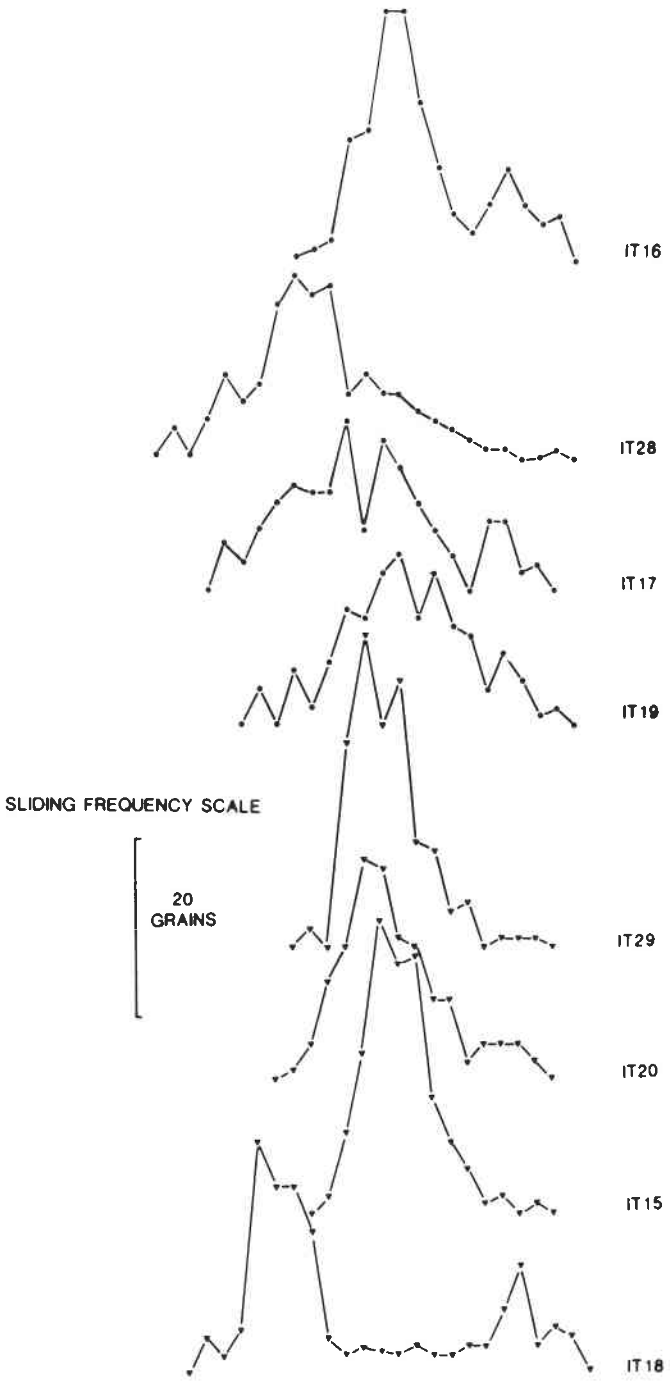

FIG. 4. Grain size vs. frequency curves for eight Five Mile Point sandstones. IT16, 28, 17, and 19 are specimens from small-scale cross-stratified (fluvial) sandstones. IT29, 20, 15, and 18 are from large-scale cross-stratified (aeolian) sandstones. Data points represent the number of grains in each 1/4 ϕ size interval. Data points for fluvial sandstones are shown as closed circles; data points for aeolian sandstones are shown as closed triangles. For each curve, the lowest data points shown correspond to a frequency of zero. See text for discussion.

using an eyepiece graticule, and geometrical means were calculated from these to produce measurements weighted by the volume of the grains, as in sieve analysis (method of Middleton 1962; no correction was made for the effect of thin sectioning on the measured sizes).

Frequency curves resulting from the point counts are presented in Fig. 4 . Photomicrographs of two of the sandstones are shown in Fig. 5. The aeolian sandstones are, in general, better sorted than the fluvial sandstones. IT18 (Fig. 6) is unique in that it consists of two populations, one with a mode in the coarse sand fraction, the other with a mode at the boundary of very fine sand and silt. Each population is relatively well sorted (the dominant population is as well sorted as the other aeolian sandstones).

Interpretation

The relatively good sorting of the large-scale cross-stratified sandstones supports the aeolian interpretation for these sandstones.

Bimodal sandstones very similar to IT18 have been described by Folk (1968), who noted that such sandstones occur in deserts as interdune deposits. Folk (1968) considered that such sandstones result from aeolian winnowing of a poorly sorted population, whereby the easily moved sand sizes are removed, leaving behind coarse and very fine sand grains, which are resistant to wind erosion. It is relevant that the unimodal Five Mile Point sandstones consist predominantly of the grain sizes missing from the bimodal population of IT18. Thus, it would be possible to produce all the observed grain-size distributions of the aeolian sandstones by winnowing one of the poorly sorted fluvial sandstones (e.g., IT28, IT19, or IT17).

IT16 is better sorted than the other fluvial sandstones, and it may be that both fluvial and aeolian processes transported this sand prior to final aeolian deposition.

Other microscopic evidence for aeolian activity

Specimens IT29, IT20, IT15, IT16, and IT28 contain rotted oncoliths (Fig. 7) that appear very similar to oncoliths in sandstones associated with stromatolite beds elsewhere in the Copper Harbor Formation (Fig. 8).

Interpretation

The stromatolite–oncolite beds in the Copper Harbor Formation formed at the margins of lakes created by flooding of parts of the Keweenawan alluvial fans (Elmore 1981; Taylor 1987). The Five Mile Point section does not contain any lacustrine sediments, so any lakes present at this time must have been more distal. The occurrence of such oncoliths at Five Mile Point would therefore appear to indicate upslope transport, presumably by wind.

Palaeocurrent data

Palaeocurrent measurements for the Five Mile Point outcrop are shown in Fig. 9. Palaeocurrents for sets of large-scale cross-stratified sandstone were taken perpendicular to foreset traces on bedding planes, measured in the direction of foreset dip, unless large trough forms were evident, in which case the trough axis direction was measured. Bidirectional palaeocurrents from the intercalated sandstones are from measurements of parting lineation; unidirectional palaeocurrents are from trough axes, current crescents, rib and furrow, and ripple casts. Figure

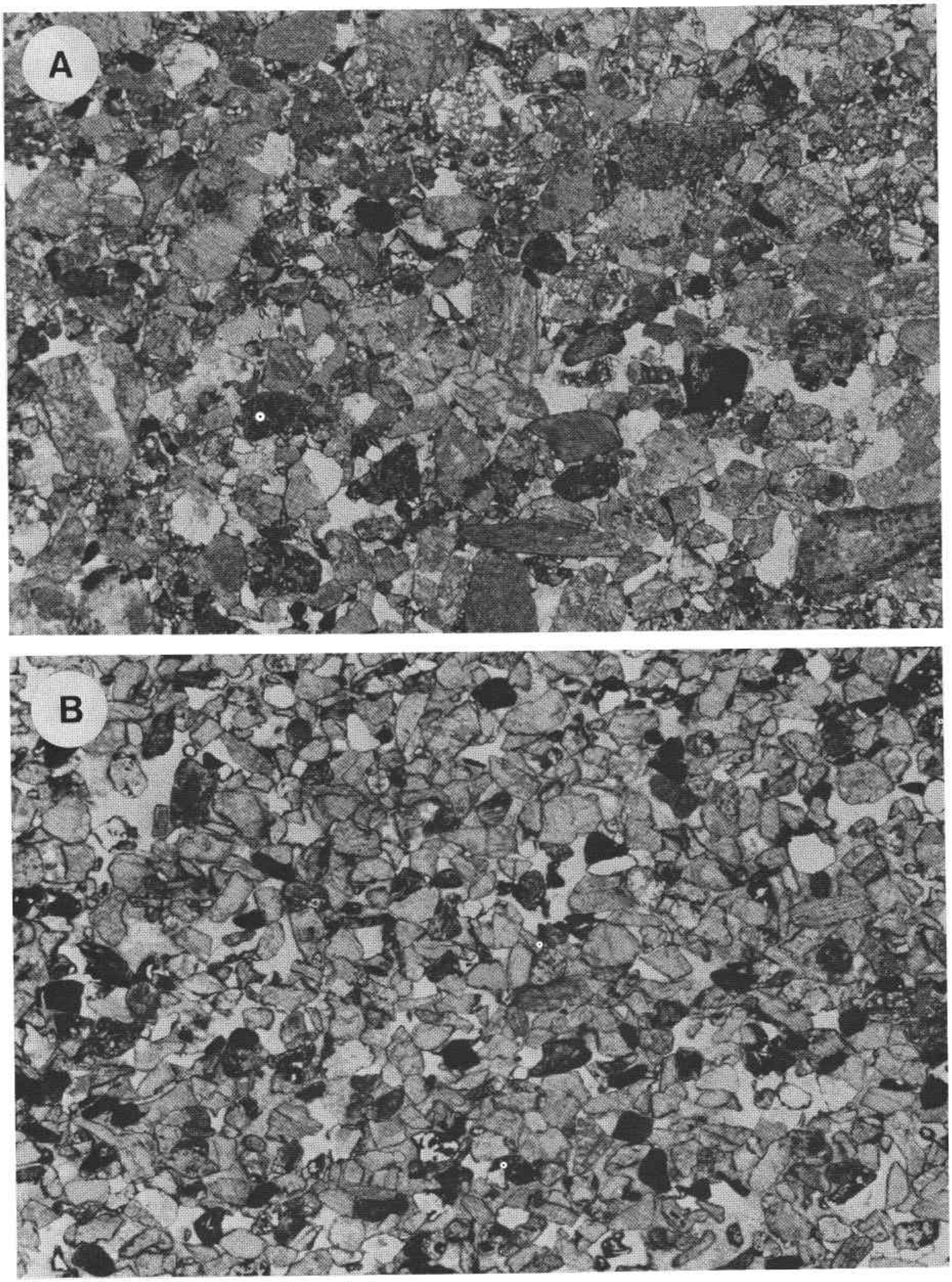

FIG. 5. Photomicrographs of (A) specimen IT28, a fluvial sandstone from Five Mile Point (the width of the field of view is approximately 6.5 mm), and (B) specimen IT15, an aeolian sandstone from Five Mile Point (the width of the field of view is approximately 4 mm). Note that the sorting of IT15 is better than that of IT28.

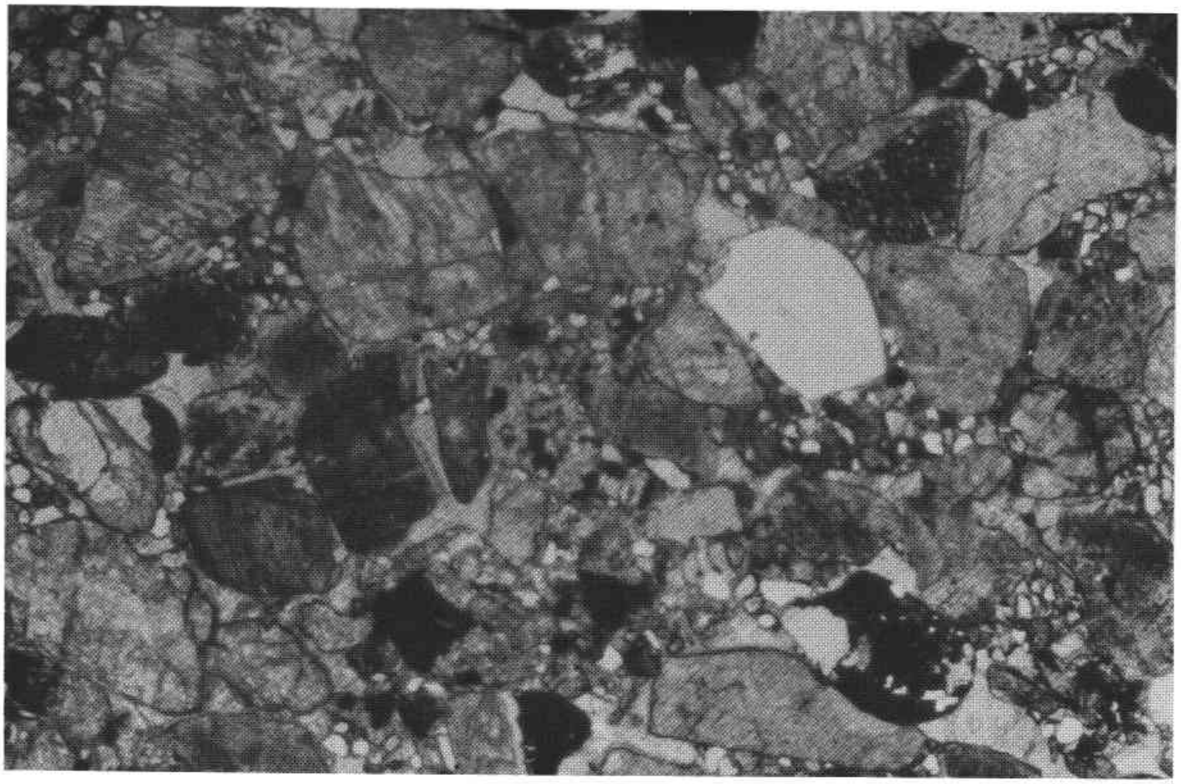

FIG. 6. Photomicrograph of specimen IT18, showing the marked bimodality of this sandstone. The width of the field of view is approximately 4 mm.

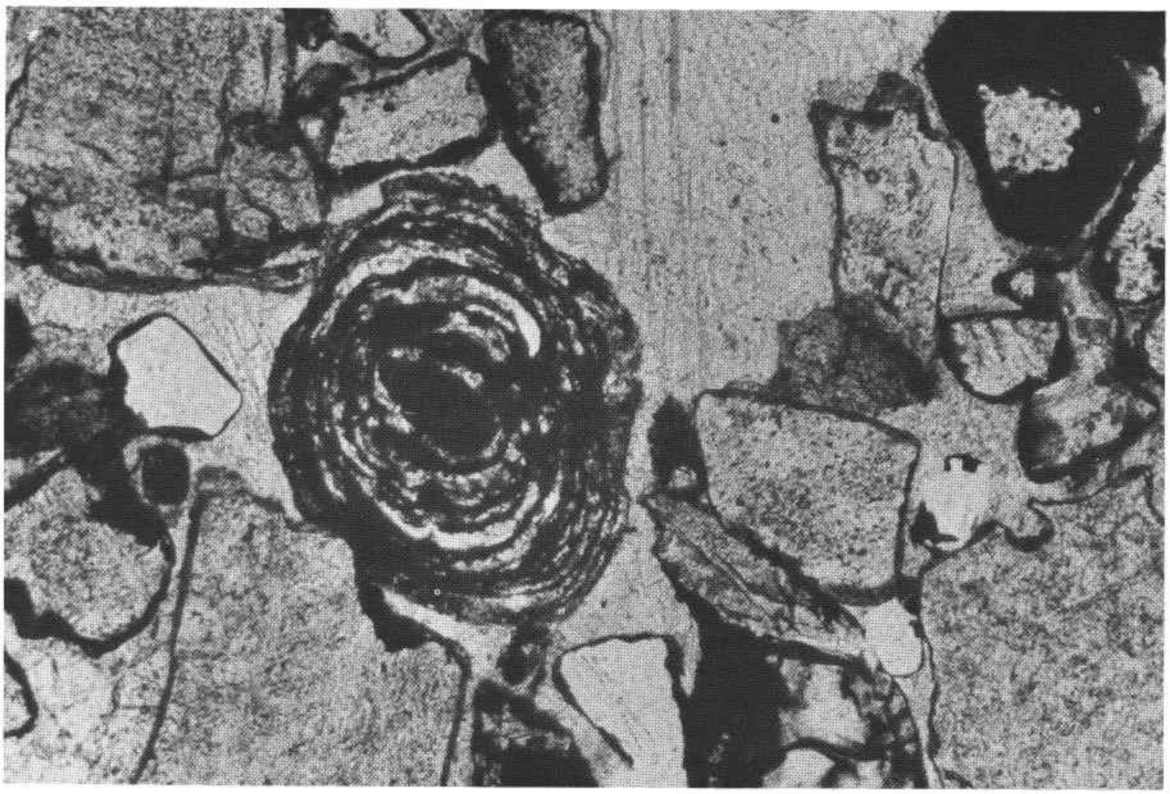

FIG. 7. Photomicrograph of an oncolith within specimen IT16 from Five Mile Point (the width of the field of view is 0.63 mm).

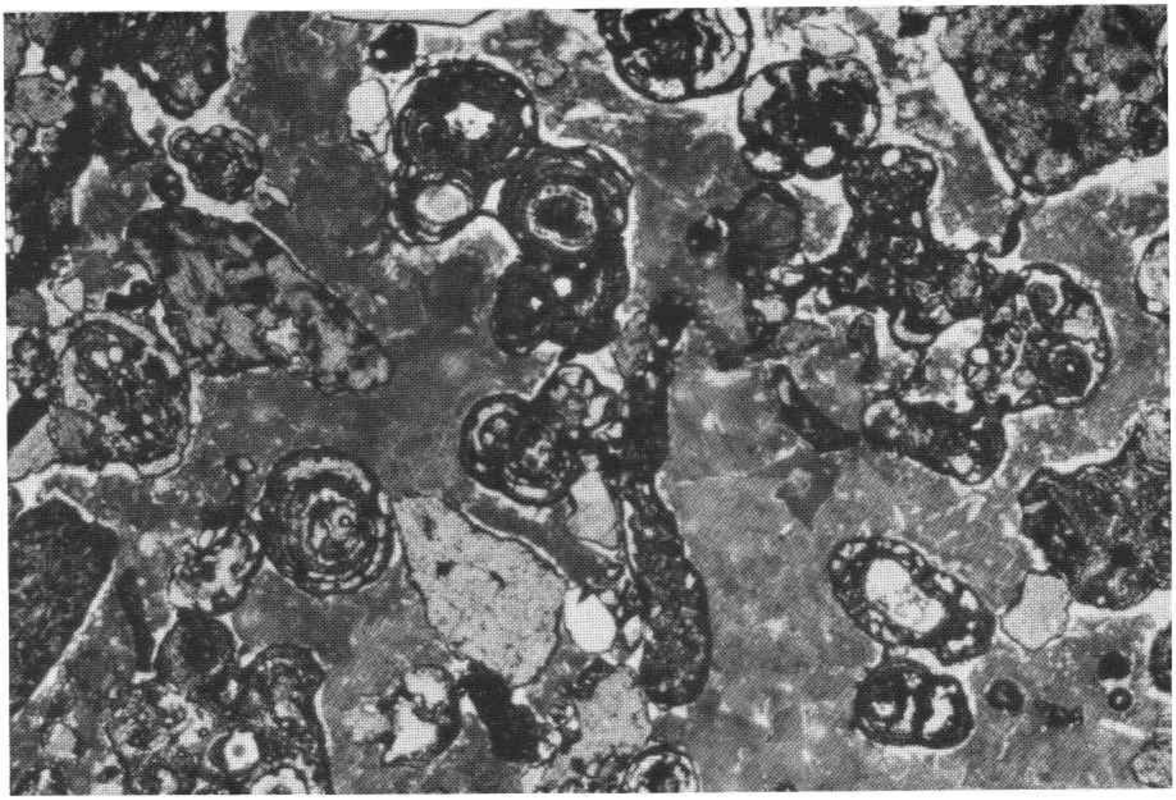

FIG. 8. Photomicrograph of oncoliths and grapestones in a specimen from close to a stromatolite horizon in the Copper Harbor Formation (the width of the field of view is 4 mm).

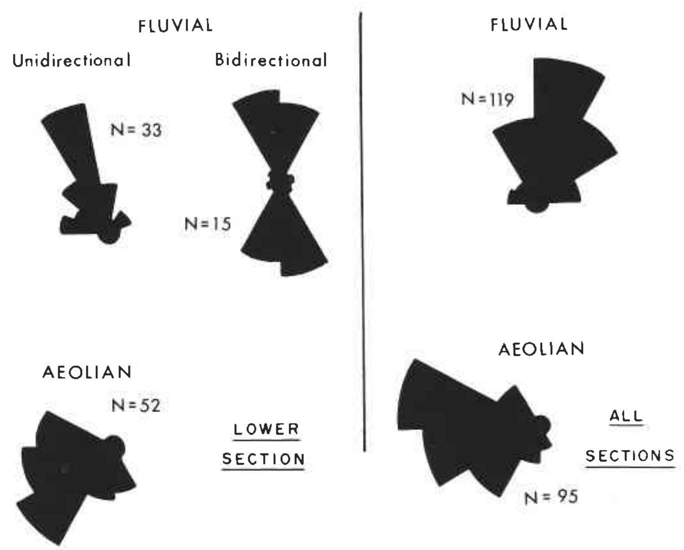

FIG. 9. Palaeocurrent roses for aeolian and fluvial sandstones at Five Mile Point. Because of the shape of the coastline there is exposure of several sections at Five Mile Point, with some repetition. The "lower section" is the section shown in Fig. 3 (stratigraphically below the lava flow that outcrops at Five Mile Point). The number of measurements (N) is indicated for each of the roses. For the lower section, unidirectional fluvial palaeocurrents had a mean azimuth of 342° and a vector consistency (L) of 79; aeolian palaeocurrents (large troughs) had a mean azimuth of 234° and a vector consistency of 80. For all sections, fluvial palaeocurrents had a mean azimuth of 15° and a vector consistency of 76; aeolian palaeocurrents had a mean azimuth of 259° and a vector consistency of 77. All means were statistically significant at the 0.01 level.

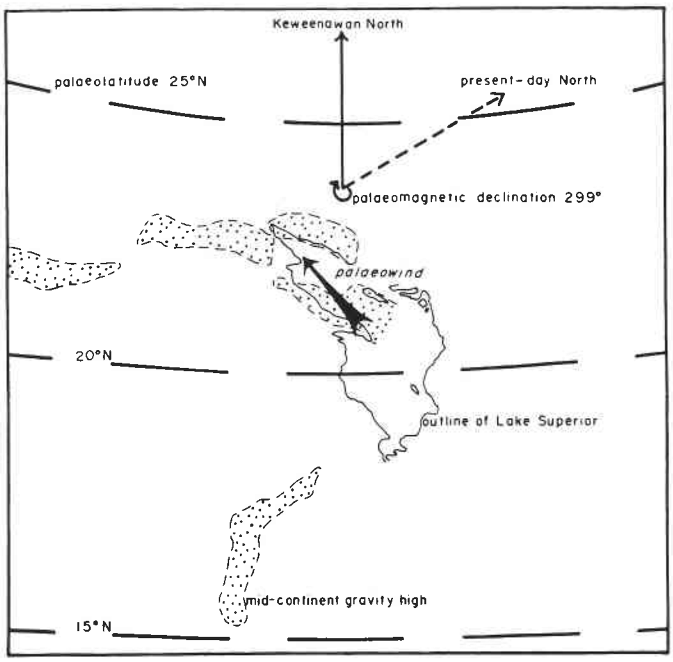

FIG. 10. Map showing the palaeowind direction as inferred from the aeolian cross-strata at Five Mile Point, drawn so that the orientations and palaeolatitudes are those of the Lake Superior region in late Keweenawan time (constructed using the palaeomagnetic data of Halls and Palmer 1981). The stippled pattern indicates the position of the mid-continent gravity high, marking the line of the Keweenawan rift. Gravitational anomalies are weakly defined in the eastern Lake Superior region.

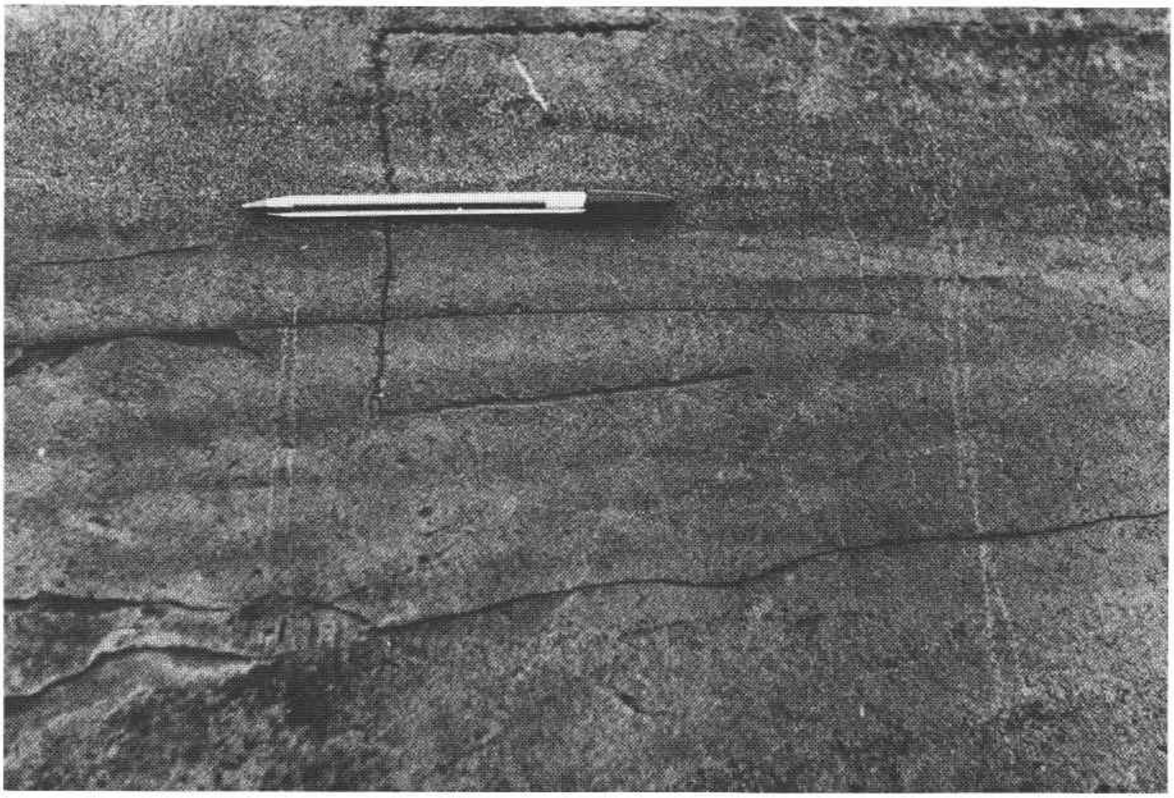

FIG. 11. Possible ripple translatent strata of aeolian origin. Pen for scale.

FIG. 12. Bedding surface covered with knobbly structures. Notebook is 20 cm long.

9 shows a 90° divergence between palaeocurrents for sandstones of the large-scale cross-stratified facies and palaeocurrents for the intercalated sandstones.

Interpretation

The marked divergence of palaeocurrents for the large-scale cross-stratified sandstones from palaeocurrents for the intercalated sandstones (which agree with palaeocurrents at other outcrops of the Copper Harbor Formation in this region) supports an aeolian origin for these sandstones.

The probable regional palaeowinds can be estimated independently from palaeomagnetic studies of the Copper Harbor Formation. Halls and Palmer (1981) and Dubois (1962) (the two studies cited as most reliable in the review of Halls and Pesonen 1982) indicate that the Lake Superior region was about 20° north of the equator during Copper Harbor times, in the northeasterly tradewinds belt. Halls and Palmer (1981) were in fact studying the Lake Shore Traps, which pass between the Five Mile Point sedimentary sections, and so provide palaeomagnetic data for the exact time of deposition of these sediments. These authors' palaeomagnetic means are as follows: declination, 299°; inclination, 37.9°, corresponding to a palaeolatitude of 21° N. If these data are used to rotate the North American continent to its Keweenawan orientation, then the result is as shown in Fig. 10. The vector mean of all the Five Mile Point measurements of aeolian cross-strata (258°) is at 319° to Keweenawan north. This indicates a palaeowind blowing to the northwest rather than to the southwest, as would be expected for palaeo-tradewinds. However, palaeowinds may have blown in this direction (along the rift valley) as a result of topographic constraint, so the cross-bedding data are not necessarily in conflict with palaeo-tradewinds inferred from palaeomagnetic data.

Evidence for aeolian activity elsewhere in the Copper Harbor Formation

Large-scale cross-stratified sandstones, similar to those at Five Mile Point, also occur at Union Bay (for location see Fig. 1) but are not sufficiently abundant or clearly exposed to be conclusively identified as aeolian by the methods used at Five Mile Point. However, a surface at a low angle to bedding, close to the large-scale cross-strata, shows structures that may be examples of critically climbing ripple translatent strata (terminology of Hunter 1977), perhaps resulting from migration of aeolian ripples (Fig. 11). Though the example shown is not convincing, no better example was observed. Also at Union Bay, and elsewhere in the Copper Harbor Formation, are peculiar "knobbly surfaces" not previously described (Fig. 12). These might be either dewatering structures akin to sand volcanoes, or aeolian adhesion structures. Sections through the structures, examined in the field, revealed no internal structures. G. Kocurek and R. E. Hunter (personal communications, 1985 and 1986) examined photographs but were not able to resolve this ambiguity. However, it may be noted that knobbly surfaces occur in parts of the section dominated by upper flow regime flat bed and ripples, not where trough cross-strata are abundant, and are invariably associated with desiccated mud-draped surfaces and sometimes with wrinkle marks or bubble sandstones (see Reineck and Singh 1980, pp. 65–67). These features all testify to bar-top rather than in-channel sedimentation in situations where water was shallow and often absent. This association therefore favours an adhesion-structure origin for the knobbly surfaces.

Conclusions

Large-scale cross-stratified sandstones in the Copper Harbor Formation at Five Mile Point are identified as the product of aeolian sedimentation, on the basis of sedimentary structures, sorting, and palaeocurrents. The style of cross-stratification and consistency of palaeocurrents indicate that deposition was probably from small, slightly sinuous, transverse dunes that formed from time to time on dry parts of the Keweenawan alluvial fans. Palaeocurrents at Five Mile Point indicate that winds blew along the rift valley towards the northwest (as inferred from palaeomagnetic studies), possibly as the result of topographic constraint.

Daniels, P. A., Jr. 1982. Upper Precambrian sedimentary rocks: Oronto Group, Michigan–Wisconsin. *In* Geology and tectonics of the Lake Superior Basin. *Edited by* R.J. Wold and W.J. Hinze, Geological Society of America, Memoir 156, pp. 107–133.

Dubois, P. M. 1962. Palaeomagnetism and correlation of Keweenawan rocks. Geological Survey of Canada, Bulletin 71.

Elmore, R. D. 1981. The Copper Harbor Conglomerate and Nonesuch Shale, sedimentation in a Precambrian intracontinental rift, Upper Michigan. Ph.D. thesis, University of Michigan, Ann Arbor, MI.

——— 1984. The Copper Harbor Conglomerate: a late Precambrian fining-upward alluvial fan sequence in northern Michigan. Geological Society of America Bulletin, **95**: 610–617.

Folk, R. L. 1968. Bimodal supermature sandstones: product of the desert floor. In Genesis and classification of sedimentary rocks. Proceedings, 23rd International Geological Congress, Section 8, pp. 9-32.

Halls, H. C., and Palmer, H. C. 1981. Remagnetization in Keweenawan rocks. Part II: lava flows within the Copper Harbor Conglomerate, Michigan. Canadian Journal of Earth Sciences, **18**: 1395-1408.

Halls, H.C., and Pesonen, L. J. 1982. Palaeomagnetism of Keweenawan rocks. *In* Geology and tectonics of the Lake Superior basin. *Edited by* R.J. Wold and W.J. Hinze. Geological Society of America, Memoir 156, pp. 173–203.

Hine, A. C., and Botthroyd, J. C. 1978. Morphology, processes, and recent sedimentary history of a glacial-outwash plain shoreline, southern Iceland. Journal of Sedimentary Petrology, **48**: 901–920.

Hunter, R. E. 1977. Basic types of stratification in small eolian dunes. Sedimentology, **24**: 361–387.

Middleton, G. V. 1962. Size and sphericity of quartz grains in two turbidite formations. Journal of Sedimentary Petrology, **32**: 725–742.

Reineck, H. E., and Singh, I. B. 1980. Depositional sedimentary environments, with reference to terrigenous clastics. 2nd ed. Springer-Verlag, New York.

Taylor, I. E. 1987. Middle and upper Keweenawan siliciclastics of the Lake Superior basin. Ph.D. thesis, McMaster University, Hamilton, Ont.