Morphology of Drumlins: A Comparative Analysis of Selected Drumlin Fields in North America

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ABSTRACT

Pleistocene glaciers revealed numerous types of land formations in their retreat northward during climatic warming. The postglacial landscape contains various features, such as moraines, flutes, and drumlin fields. Drumlin fields in southeastern Wisconsin and west central New York are compared in terms of drumlin morphology to ascertain regional differences between drumlin fields formed by different lobes of the Wisconsinan Laurentide ice sheet. Topographic maps of the Wisconsin and New York study areas are used to measure physical characteristics of individual drumlins. Drumlins from the two glacial lobes differ significantly on the basis of length, width, and relief, but are similar in terms of nearest neighbor proximity and width/length ratios. Differences between the drumlin belts in Wisconsin and New York may result from natural variations in glacial conditions during formation, although the specific mechanisms remain elusive.

INTRODUCTION

Repeated advances and retreats of continental ice sheets characterized the late Pleistocene epoch (130,000 to 10,000 years BP.). The Pleistocene ice expansion during Wisconsin Glaciation occurred approximately 20,000 to 10,000 years BP. At about 17,000 to 18,000 years BP., the Laurentide ice sheet extended to its maximum position south of the Great Lakes, marked by a terminal moraine (Easterbrook, 1993, Benn and Evans, 1998). In the years following maximum advance, the ice sheet revealed numerous types of land formations in the retreat northward during climatic warming. The postglacial landscape of Wisconsin and New York contains various features, including the formation selected for analysis, drumlins. Drumlins in southeastern Wisconsin were formed during phases of glaciation of the Wisconsinan Laurentide ice sheet (Figure 1).

The area of interest for the study is located between the Green Lake advance and the Lake Mills advance in southeastern Wisconsin. The drumlin field that occupies west-central New York State is probably the largest drumlin field in the world, containing some 10,000 drumlins. Created by the Wisconsinan Laurentide ice sheet, the field is located within a 250 km x 60 km area between Lake Ontario and the Finger Lakes (Rice, 1977).
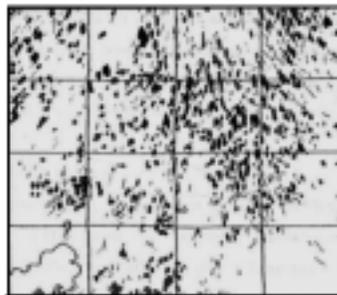

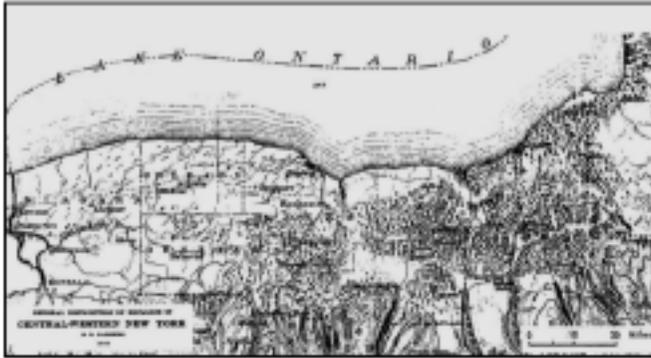**Figure 1. Drumlin Field in Southeastern, Wisconsin (Hole, 1970).**

Figure 2. Distribution of Drumlins in West Central New York (Miller, 1972).

Figure 2 depicts the general distribution of drumlins in west central New York.

Drumlins are one of the most distinctive features produced by glaciers and are arguably the most intensively studied glacial landform. This is due in part to their utility in providing evidence for describing the processes that operate beneath glaciers and ice sheets (Hambrey, 1994). Previous studies have focused on geomorphological aspects such as deriving explanations for underlying patterns of glacial features. Research on drumlins has tended to concentrate on three general areas: drumlin shape and distribution, stone orientations within drumlins, and theoretical considerations of pressure distributions within ice and till (Price, 1973).

Sparks (1986) describes drumlins as elongated, streamlined hills of drift that resemble an upturned boat. Chorley (1984) describes the general form of drumlins to be 10-3000 m long and 5-50 m high. Flint (1971) narrows this description, stating that the ideal drumlin is 1000-2000 m long, 400-600 m wide, and 15-30 m high. However, he also notes that there is considerable variation in size and shape for most drumlins. Features that are of drumlin type but do not exhibit the ideal form have been called drumlinoid features (Sparks, 1986). Vernon (1966) noted that drumlins are concentrated in bands both parallel and perpendicular to ice flow but that drumlin spacing can be variable. Doornkamp and King (1971) remarked that where drumlin density is high, individual drumlins tend to be small. They also report that drumlin density is higher at glacial margins where the ice moves at a slower pace with less consistency.

Chorley (1959) examined the shape characteristics of drumlins. Drumlins were found to be symmetrical along the long axis, rather than elliptical. Chorley described drumlins as possessing a rounded end facing into the direction of ice flow and a tapering end facing away from the ice flow direction. Smaller drumlins are elongated to a lesser extent than larger ones, with rounded and smaller drumlins occupying regions near glacial margins. Chorley argued that drumlin elongation is related to the velocity of ice movement. Chorley also noted that the maximum width of a drumlin was located at approximately 3/10 of the distance from the leading edge of the formation. Smalley and Unwin (1968) argued that drumlin elongation increases toward the center of the field, where pressures are greatest, and drumlin concentration should increase toward the edges of the drumlin field. This relationship was consistent with the findings of Chorley (1959). Trenhaile (1975) hypothesized that drumlin fields have (1) a regular component, where drumlin shape and distribution are governed by thinning and

spreading of marginal ice and (2) a random (or irregular) component, which is related to local stress conditions within the ice as well as variations in topography, slope, depth, and lithology of the drumlin materials.

Although drumlin size, shape, and distribution have been intensively studied to provide additional understanding for the processes that operate beneath glacial ice sheets, no completely satisfactory theory has emerged to explain drumlin formation. As a result, any assessment of causal factors must be viewed with caution because of the present inadequacy of knowledge concerning processes at the base of ice sheets. The objective of this study was to examine possible causal factors of drumlin formation and their influence on drumlin parameters.

METHODS

Topographic maps were selected as the field site for the comparative study of the morphology of drumlins. Criteria for the inclusion of a particular map were: availability, location within a state, and drumlin field coverage. Limitations on the location of the quadrangle within the state were placed so that specific lobes of glacial advancement could be studied. Map selection was also based on an apparent drumlin field cover of at least fifty percent. The latter criterion maximized the random placement of study quadrats within each quadrangle.

Figure 3 (Sugden and John, 1976).

Seven study quadrats were selected from the glacial lobes in Wisconsin and New York. The quadrats were 4000m x 4000m, delineated by the UTM coordinate grid system. Quadrat size was large enough to be sensitive to variations in drumlin shape, size, and density, but small enough to encompass only the immediate area around a drumlin. The location of each quadrat was randomly chosen within the topographic map by selecting the coordinates of the northwest corner of the block (the last two digits) from a random numbers table (Ott and Longnecker, 2001). Due to discrepancies in map availability between the two states, each Wisconsin quadrangle held a single quadrat, while New York quadrangles accommodated two quadrats. Assumptions of parametric t-tests (see below) require samples to be spatially independent of one another (Ott and Longnecker, 2001). Therefore, quadrat overlap was not permitted; if an occupied combination was chosen, a new set of coordinates was generated.

One of the biggest challenges in studies of drumlin morphometry involves the identification of drumlins and elimination of topographical features not considered drumlins. Therefore, all studies of drumlins contain some degree of subjectivity (Trenhaile, 1975). In this study, drumlins were operationally defined as features containing two closed contours and having a shape similar to those depicted in Figure 3.

Following quadrat delineation, each drumlin within a quadrat was traced onto tracing paper and assigned a number for data recording. A minimum of twenty-five percent of the drumlin had to be contained within the quadrat for it to be counted. Percent drumlin cover

was estimated by dividing the area of the drumlin portion contained within the quadrat by the total area of the drumlin. Multiplying the length by the width approximated the area.

Measurements taken from the topographic maps included: length of the longest axis (length), length of the shorter axis (width), contour relief (height), distance to the nearest neighbor, and density. Measurements for long and short axis lengths were based from the midpoint of the highest contour line. Relief was obtained by subtracting the highest and completely enclosed contour from the lowest contour and adding one half of the contour interval. Distance to the nearest neighbor was measured from the midpoint of the highest contour line of the selected drumlin to the midpoint of the highest contour line of the nearest drumlin. Density was determined by counting the number of drumlins located within the quadrat. Length and distance measurements were obtained from the maps in millimeters and contour relief was observed in feet. All measurements were converted to meters via topographic map scales for ground data calculations. Drumlin characteristics were checked for accuracy against topographic maps by ground truthing for the Wisconsin study sites. The drumlin depicted in Figure 4 is characteristic of drumlins in the Wisconsin study area.

Figure 4. Photograph from the top of drumlin looking toward the up-glacier end.

Drumlins that overlapped drumlins selected for measurement were individually accounted for if the overlapping drumlin contained at least two closed contour lines within it. If an overlapping drumlin had only one closed contour, it was considered an extension of the selected drumlin for measurement. By making this determination, overlapping drumlins that would otherwise not have been accounted for were included in statistical evaluations of the landscape, primarily impacting longest axis length, density, and width/length ratio data.

Means, variances, and standard deviations for length, width, height, nearest neighbor, and density ground measurement data were calculated following the methods outlined in Ott and Longnecker (2001). Mean data calculations were derived by obtaining totals for length, width, height, and nearest neighbor measurements for drumlins in each quadrat and dividing by the number of drumlins located within the quadrat. The formula used for variance calculation was $s^2 = (\sum x\text{-}x')/(n\text{-}1)$ where x is the value for data of a particular drumlin, x' is the mean value of the drumlin data in each quadrat, and n is the total number of drumlins held within each quadrat. Standard deviations were obtained by taking the square root of the variance.

F.H. Muller (1963) suggested a classification of streamline topographic features based on length to width ratios. However, width to length ratios were considered preferable for this study because the values can only range between 0 and 1. Values closest to zero are most elongate; values closest to one have a more rounded shape. Table 1 displays a morphometric classification of glacial streamline features, as interpreted by E.H. Muller (1974) from the work of F.H. Muller (1963). Histograms were created for comparisons of length, width, relief, and nearest neighbor distributions among

Table 1. Classification of Glacial Streamline Features
(F.H. Muller, 1963, E.H. Muller, 1974).

Width/Length Ratio	Morphometric Classification
0.4 – 1.0	broad ovoid
0.3 – 0.4	ovoid
0.2 – 0.3	long ovoid
0.12 – 0.2	ridge
0.0 – 0.12	fluting

all drumlins in Wisconsin and New York. Histograms provide a visual representation of similarity between drumlins in the two glacial lobes. Independent samples t-tests for equality of means were used to test for significant differences in parameters between the two glacial lobes. A confidence interval of 90% was constructed around point estimates of parameters under consideration. This somewhat liberal confidence level was selected to accommodate inaccuracies in the topographic maps. Significance was tested at the alpha = 0.10 probability of type I error. If p (the variable of significance) was less than alpha, the relationship was deemed significant. If p was greater than alpha, the relationship was not found to be significant and data was deemed similar for both regions. In addition, if the 90% confidence interval contained the value zero, a less significant relationship between the two glacial lobes was observed. Data used in statistical t-tests and confidence intervals were based on measurement averages of all drumlins in each quadrat. Statistical analysis was conducted with SPSS software, version 10.1.

RESULTS

There were no significant differences in length measurements between the two glacial lobes (Table 2, p = 0.307, df = 12). However, a comparison of frequency histograms (Figure 5) between the two study sites yields a different result, possibly because of its basis on a different measure of central tendency. Histograms display modal frequency of occurrence rather than means.

Figure 5. Drumlin Length Comparison.
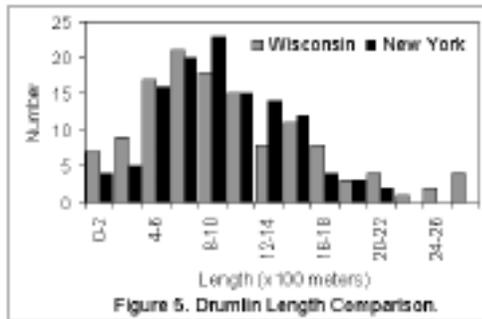
The Wisconsin histogram is skewed right, with a modal interval of 600-800 m. The New York histogram appears more normally distributed and the mode for the data occurs in the length interval 800-1000 m. Wisconsin drumlins have a tendency for greater variability in length than the New York drumlins. This may account for the result of no significant difference in the two-sample t-test. Drumlins occurring in the greatest frequency interval for the Wisconsin length distribution tend to be shorter than the length of drumlins occurring in the greatest frequency interval in the New York distribution. The results from the frequency data correlates to Mills' unpublished results that drumlins in southeast Wisconsin are generally shorter when compared to drumlins in other areas of the United States (Whittecar and Mickelson, 1979).

Statistical analysis of measurements for short axis length indicated a significant difference in width between drumlins in Wisconsin and New York (Table 2, p = 0.056, df = 12). The confidence interval was positive and its range did not include zero, indicating that Wisconsin drumlins had a greater short axis length.

Table 2. T-test and Confidence Interval Statistics for Wisconsin and New York Drumlin Morphometry.

| | | 90% Confidence Interval | | |
Measurement	**p Value**	**Lower**	**Upper**	**Significance Test**
Length	0.307	-88.650	353.450	not significant
Width	0.056	7.170	83.715	significant
Relief	0.002	-9.908	-4.400	significant
Neighbor	0.683	-164.643	102.026	not significant
Density	0.847	-2.776	6.204	not significant
Width/length	0.861	-0.005	0.00834	not significant

The frequency histograms for drumlin width correlate with these statistical results (Figure 6). While the mode intervals for the two glacial lobes were similar, the distribution pattern for width distribution were different. The Wisconsin histogram was skewed right, with a gradual decrease in frequency as short axis length increased. The New York distribution was also skewed right, but exhibited a rapid decrease in frequency as width increased. Stated differently, the majority of Wisconsin drumlins tended to have greater variation in width over a large number of intervals, while the majority of New York drumlins fell into two intervals. In general, drumlins in southeastern Wisconsin were found to be wider than drumlins in west central New York.

Figure 6. Drumlin Width Comparison.

Differences in relief measurements were found to be highly significant (Table 2, p = 0.002, df = 6.999). The 90% confidence interval was negative, indicating that drumlins in New York contained significantly more relief. The frequency histograms for Wisconsin and New York reiterate the differences between the two glacial lobes and indicate that New York drumlins tend to contain more relief (Figure 7). However, these findings may be a result of inaccuracies in data collection; the topographic maps contained differing contour intervals (Muller, 1974).

Statistical analysis on nearest neighbor measurements indicated no significant difference between glacial

Figure 7. Drumlin Relief Comparison.
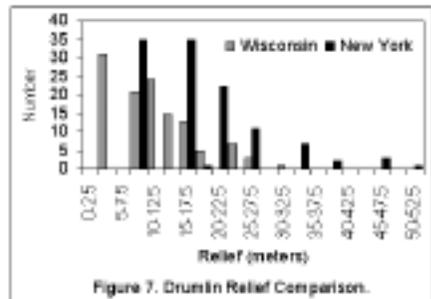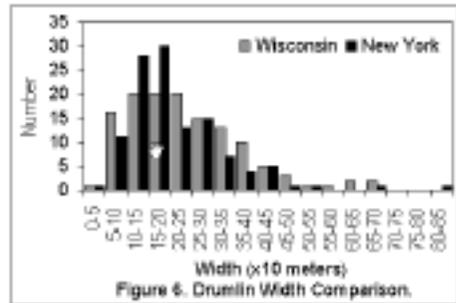
lobes (Table 2, p = 0.683, df = 12). The
frequency histograms for Wisconsin and
New York exhibit only slightly different
distributions for nearest neighbor meas-
urements (Figure 8). Both histograms
indicate the majority of drumlins are
located between 260 and 650 m apart
from one another at the midpoint of the
highest contour interval on the drumlin. A
related statistical analysis of drumlin den-
sity also revealed no significant difference
between glacial lobes (Table 2, p = 0.847,
df = 12).

Figure 8. Nearest Neighbor (x10 meters)
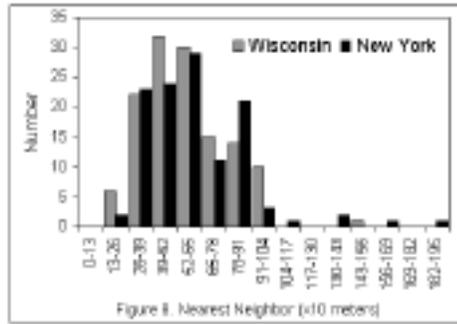
An analysis of the width to length ratios for Wisconsin and New York drumlins yielded
mixed results. The classification name of the drumlins in each quadrangle varied slightly
within the states. However, the mean data exhibited no significant difference between the two
glacial lobes (Table 2, p = 0.861, df = 12). Drumlins in both Wisconsin and New York can be
classified as possessing a long ovoid shape. The mean values for width to length ratios indi-
cate that drumlins for the Wisconsin and New York study areas are more elongate than round,
holding values of 0.239 and 0.222, respectively.

DISCUSSION

General trends in drumlin size and distribution for Wisconsin and New York emerge from
the statistical results. Wisconsin drumlins exhibit roughly the same length and nearest neigh-
bor measurements as New York drumlins. However, drumlins in Wisconsin tend to be wider
and have less relief than drumlins in New York. These trends may support differences in for-
mation conditions between the two lobes.

The results of the analysis on drumlin characteristics in two separate lobes of a glacier
may indicate differences between the two lobes in terms of conditions underlying formation.
Variations in drumlin parameters may provide useful information on ice sheet characteristics.
However, any assessment of causal factors of drumlin characteristics must be viewed with
caution because of inadequacies in our understanding of processes involved at the base of ice
sheets.

The study of the influence of drumlin parameters on possible causal factors of drumlin
formation is important in glacial geomorphology. Trenhaile (1975) noted that actual fields
diverge from theoretical models because of random or local variation of glacial stress, and
also variations in the topography, depth, lithology, and origin of the drumlin materials. When
this concept is applied to studies of two separate drumlin fields, one would expect to observe
differences in drumlin characteristics between the fields as a result of these variations in for-
mation conditions. However, the factors determining drumlin shape and size are not well
understood and definitive conclusions on methods of formation cannot yet be made. Further
work is necessary to establish the manner in which the factors determining drumlin shape
and size are correlated to changes in formation conditions within a drumlin field.

The variation in drumlin parameters, such as size and shape, are partly modified by local
variations in the conditions of the ice and variations in the land underneath the ice. Variations
in glacial till availability and stress conditions under the ice are arguably the most important

variables for drumlin formation, assuming that stress conditions fall within a certain critical range. However, lithology may also play an important role.

Smalley and Unwin (1968) noted a nonrandom pattern of drumlin distribution in relation to stress conditions, and predicted that the frequency of drumlins should decrease in the parts of the field that were further under the ice. They argue that the center of a drumlin field contains drumlins that are more elongated and less concentrated than drumlins at the edge of the field. Based on the observations by Smalley and Unwin, drumlins in both the Wisconsin and New York study areas tend to be located closer to the edges of the drumlin field.

Muller (1963) suggested that as a glacier's basal load decreases, the sole of the glacier became less resistant to flow and moves faster, producing more elongate drumlins. Therefore, slower ice flow and lower ice pressure produce rounder drumlins (Hill, 1973). Miller (1972) suggested that the lengthening of streamlined features where the velocity of ice flow was probably fastest has been noted for the Green Bay Lobe in southeastern Wisconsin. However, drumlins in Wisconsin were found to have no significant difference in length when compared to the drumlins in New York. In addition, there were no significant differences found for width/length ratios for drumlins in Wisconsin and New York. As a result, it may be possible that glacial ice flow velocity and basal load were similar for both study areas.

The variation in drumlin parameters, such as size and shape, are partly modified by local variations in the lithology of the land underneath the ice. However, the effect of lithology on drumlin formation plays a lesser role in this study than other causal factors. Lithology's lesser role as a causal factor results because Wisconsin's ice flow paralleled the rock outcrops instead of crossing them, as in upstate New York (Miller, 1972). This difference in the direction of ice flow creates difficulty in comparing the significance of changes in the topography across variations in lithology. Therefore, further work is necessary in determining the relative importance of lithology in the formation of differently sized and shaped drumlins. The possible similarities in ice sheet characteristics and differing bedrock orientation for the study areas is problematic for the determination of causal factors of differences in drumlin parameters. As a result, no definitive method of drumlin formation could be determined.

An explanation for the absence of drumlins within the fields as a condition of formation may be a result of drumlin removal via ice erosion or melt water erosion, or that drumlins were never formed in the undrumlinized areas, either because of uneven deposition of drift or uneven streamlining tendencies within the glacier. Variations in the deposition of materials may also explain the prevalence of multiple or compound drumlins formed within the drumlin groups where deposition was abundant (Miller, 1972). Melt water erosion as an explanation for the absence of drumlins may not be relevant to this study, as major glacial drainage pathways did not appear to flow through the study areas (Figure 0b).

Drumlins are thought to form when stress conditions within the ice are in a critical range with pressures significant to mold and streamline till, and depend on the availability and depth of drift, topography, lithology, and origin of drumlin materials. However, previous knowledge concerning the processes involved at the base of ice sheets has been inadequate. Current studies of active glaciers using seismic profiles are attempting to characterize and provide information about subglacial conditions. By utilizing seismic data contemporary researchers have been able to describe some of the causal factors of glacial landscape formation during the process, rather than making assumptions many years after glacial retreat (Anderson, et al., 2001). Studies such as these offer a promising future for studies in drumlin morphology.

SUMMARY

Two belts of drumlins, one in southeastern Wisconsin and the other in west central New York, were used to compare the morphology of drumlins in differing lobes of the Wisconsinan Laurentide ice sheet of the Pleistocene ice epoch. Drumlins in the two glacial lobes differ significantly on the basis of length, width, and relief, but are similar for nearest neighbor proximity, density and width/length ratios. The differences between the drumlin belts in Wisconsin and New York may result from natural variations in glacial conditions during formation. Variations in the causal factors may help to explain the differences in drumlin parameters between the two belts, but any assessment of causal factors must be extremely tentative because of the inadequacy of knowledge concerning processes operating at the base of ice sheets.

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