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Morphometric analysis of ice-walled lake plains in Northern Illinois: Implications of lake elongation by wind-induced dual-cycle currents

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ABSTRACT

Ice-walled lake plains (IWLPs) are rounded, flat-topped mounds that formed in stagnant ice environments along the margins of the Laurentide Ice Sheet. We conducted detailed morphometric and statistical analyses of the shape, size, and orientation of more than 400 IWLPs identified from aerial photos aided with LiDAR data in DeKalb County, Illinois, USA. Lake elongation theories include extraterrestrial impact (e.g. the Carolina Bays), ice flow dynamics and crevasses, and wind induced currents that preferentially erode the shorelines perpendicular to the dominant wind direction. The results indicate that elliptical IWLPs with a perimeter greater than 3050 m have preferred orientations roughly normal to the paleo-wind direction as indicated by contemporaneous parabolic dunes located 50 km to the west. The orientations of the IWLPs with a perimeter less than 1220 m are scattered and show no apparent trend. The IWLP orientation is not related to ice flow dynamics or glacial crevasses because no statistically significant relationship exists with regard to the ice flow as proxied by the moraine direction. The orientation of large IWLPs in DeKalb County are consistent with wind-induced lake elongation observed in modern permafrost thaw lakes, suggesting that the prevailing wind also played an important role in controlling the orientation of IWLPs during the last glacial period and led to the preferred orientation we see today.

1. Introduction

Ice-walled lake plains (IWLPs) are rounded (in map view), flat-topped mounds (some with mildly depressed centers) that formed in stagnating, supraglacial environments along the margins of the Laurentide Ice Sheet during the last glaciation (Clayton and Cherry, 1967; Eyles et al., 1999; Clayton et. al. 2008; Young and Joseph, 2009). The lakes, when they were active, were surrounded by dead-ice permafrost. IWLPs formed as the bounding, dead ice melted, leaving the sediment previously at the bottom of an ice-walled lake higher than the surroundings (i.e., creating an inverse topography), often within or near hummocky terrain (Clayton et al., 2008; Fig. 1). In Illinois for example, the IWLPs are located within the same morainic system as hummocky terrain. The IWLPs vary in size (typically from 10 m to 10 km across) and relief (typically between 2 and 25 m) and occur in areas adjacent to the Great Lakes and Alberta, including the Dakotas, Minnesota, Wisconsin, and Illinois. IWLPs are most abundant atop wide recessional moraines and morainal reentrant, but also on the glacier side of the recessional moraines and near the edge of terminal moraines (Fig. 1).

Supraglacial development of the IWLPs is evidenced by the positive-relief mounds along with the rhythmically bedded lake sediment composition. In Illinois, low-relief IWLPs are composed of the following sedimentary facies, from bottom to top, including; 1) poorly sorted sand and gravel or sand, 2) rhythmically bedded silt and very-fine sand (often containing fossils of pill clams, ostracods, tundra plants, and wood fragments reworked from paleosols), 3) sand and gravel or loose, sandy diamicton, and 4) a mantle of loess (Clayton et al., 2008; Curry et al., 2011). The successions rest on diamicton which, in places, diapirically intrudes the successions (Curry and Petras, 2011) and in some extraordinary cases completely punches through the entire sedimentary section (Eyles et al., 1999; Curry, unpublished data).

In Illinois, the oldest dated IWLPs began forming on the Ransom Moraine about 22,000 cal. yr BP (calibrated years before present); the youngest IWLPs, located on the Deerfield Moraine (a Lake Border Moraine near Wadsworth, IL) began forming about 17,000 cal. yr BP, implying a period of over 5000 years to complete the IWLP formation (Fig. 2; Curry and Petras, 2011). Outside of Illinois, the youngest documented IWLPs began forming on the Algona Moraine just southwest of Minneapolis at about 14,500 cal. yr BP (Jennings et al., 2011). Younger dates are associated with IWLPs in North Dakota, but the ages are from analyses of fossils from the upper parts of the rhythmic lacustrine layers, whereas the ages from Illinois and Minnesota IWLPs are from basal stratigraphic positions, and thus provide a minimum age of

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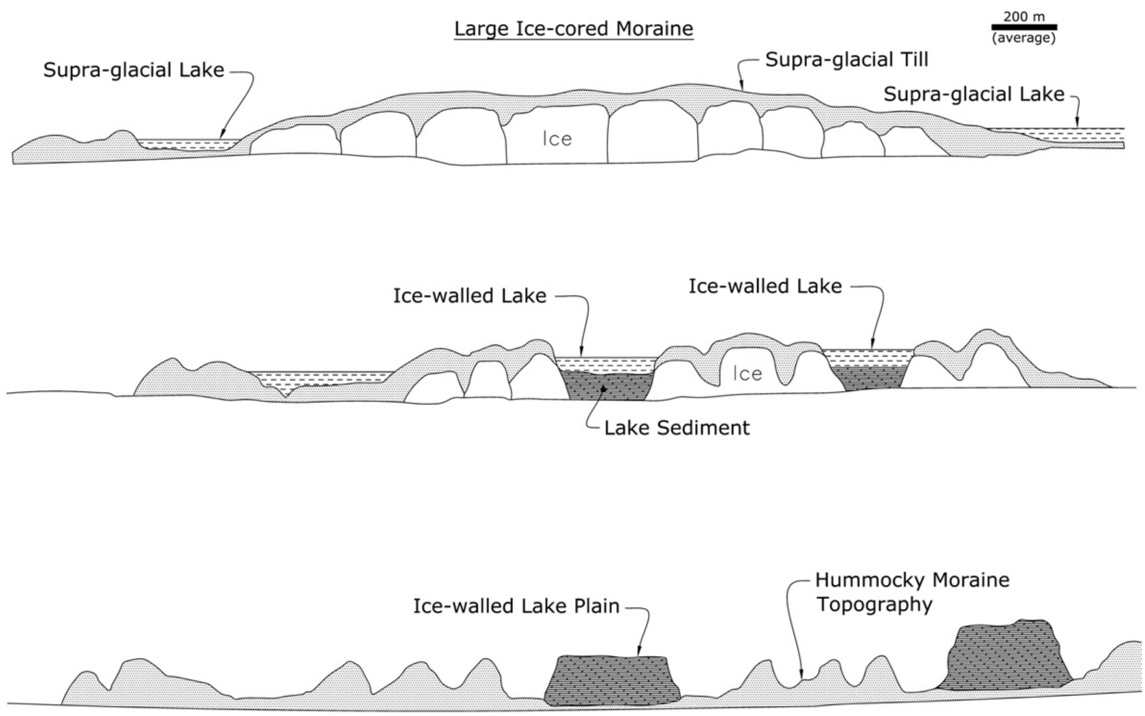

Fig. 1. IWLP formation from an ice cored moraine covered with till (top), to the formation of ice-walled lakes filled with lake sediment (middle), and IWLPs that rise above the surrounding area which are an example of inverse topography (bottom).
After Below (2006).

when the ice became stagnant. Dates obtained from artifacts at both the top and bottom of the IWLP give a range of dates for the presence of the ice, giving temporal data to glaciers in the area.

Curry et al. (2010) and Curry and Petras (2011) addressed the sediment architecture, fossil content, and age of IWLPs through soil boring analysis and classified them into three basic geometries based on their aerial shape: circular, elliptical, and complex. However, we found no literature that considered the spatial distribution and orientation of IWLPs. Cursory observation of IWLPs in the DeKalb region suggested a preferred orientation roughly normal to wind-direction as indicated by sand dunes on the Green River Lowland within Whiteside, Lee, and Rock Island counties, Illinois (Miao et al., 2010; Fig. 2). Our investigation is a morphometric exploration (shape, size, ellipticity, and orientation) of the hypothesis that prevailing wind directions account for the orientations of the long-axes of IWLPs.

The Carolina Bays are a collection of thousands of commonly oriented circular or elliptical lakes along the Atlantic seaboard of North America (Kaczorowski, 1977; Grant et al., 1998; Firestone et al., 2007; Pinter and Ishman, 2008, Firestone, 2009). One hypothesis regarding their formation is a continental-scale extraterrestrial impact event occurring over North America from which either some ejecta reached the Earth surface or a massive shockwave was sent across the continent, and created the lakes. This event is termed the Younger Dryas impact hypothesis (YDIH) because it has been attributed as the cause of the Younger Dryas cooling approximately 12,900 cal yr. BP (Firestone et al., 2007; Pinter et al., 2011). This hypothesis is highly controversial and has been the cause of much debate. Evidence in favor of the impact includes a sediment layer composed of magnetic grains and spherules, megafaunal remains, carbon remnants, increased radioactivity and several elliptical lakes throughout North America that are all approximately oriented with the Great Lakes where the proposed impact was thought to occur (Firestone, 2009). However, little evidence exists that signifies that an impact was the cause of the Carolina Bays and other oriented lakes. Very little meteoric material has been gathered from the lake rims; there is a considerable variation in the lake orientations, both locally and regionally, and the Carolina Bays did not form instantaneously, but rather over multiple periods of erosion (Pinter et al., 2011).

Other previous studies have attributed the common orientation of some modern lakes in periglacial and permafrost environments (e.g., those found in parts of Alaska and Canada) to wave action and currents created by the prevailing wind (Cooke, 1954; Livingstone, 1954; Rex, 1961; Carson and Hussey, 1962; Cote and Burn, 2002; Hinkel et al., 2005). Instead of the wave energy creating surface and rip currents which would direct energy parallel to the prevailing winds, the wave energy is split as it approaches the far shore, establishing a two-cell circulation in the lake (Fig. 3). In this scenario, maximum littoral drift is approximately 50° away from the prevailing wind direction (Rex, 1961; Cote and Burn, 2002). This mechanism preferentially erodes the shorelines perpendicular with the wind, elongating the lake in the direction normal to the prevailing wind (Fig. 3). It has been demonstrated theoretically (Livingstone, 1954), reproduced in laboratory (Kaczorowski, 1977), and supported by empirical evidence in the field in Alaska and Canada (Livingstone, 1954; Carson and Hussey, 1962). More recently, Cote and Burn (2002) measured the location and morphology of 578 lakes and basins in Canada using digital base maps. They used GIS tools to find best fit ellipses of the lakes and basins and found that their orientation was almost exactly normal to the prevailing wind direction. Hinkel et al. (2005) used image processing techniques to automatically detect 13,214 thaw lakes and 6539 drained thaw lake basin in Alaska. They concluded that the close relationship between the orientations of the thaw lakes and drained thaw lake basins may be indicative of the current and paleowind direction, respectively, although they do no attempt to interpret or derive that direction. Therefore, a part of the intent of this research is to investigate this wind driven mechanism for IWLP formation since, to the best of our knowledge, it has not been established for IWLPs formed during the last glacial period.

Evidence exists to suggest that during the end of the Quaternary period, sand dunes were mobilized across the northern Midwest states and their formation was influenced by the prevailing winds of the period (Arbogast and Packman, 2004; Rawling III et al., 2008). Miao

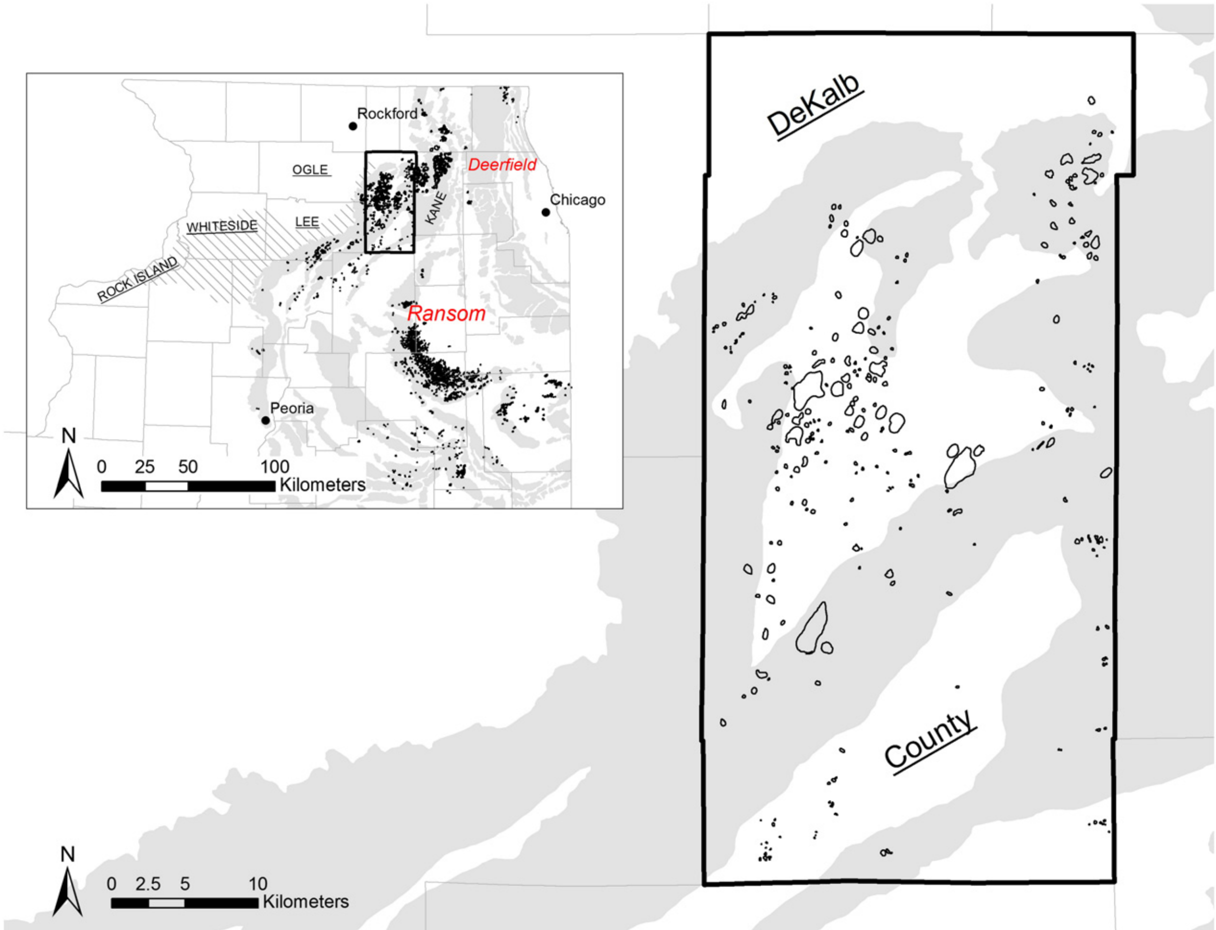

Fig. 2. IWLP location (black outlines) in DeKalb County along with the surrounding moraines (gray). The study area is shown in the inset along with additional IWLPs located throughout Northern Illinois. The location of the Green River Lowlands is given as the hatched area in the inset. Selected moraine names are given as the italicized text in the inset map.

et al. (2010) have recently studied, amongst other factors, the age and orientation of the dunes in the Green River Lowland in northwestern Illinois (Fig. 2). They found an average lineal orientation of N65°W, indicating a northwest to southeast wind, and an approximate age of 17,500 $\pm$ 570 yr BP. The west-northwesterly dune orientation represents the dominant paleo-wind direction at that time (Anderson and Miao, 2011). In addition, the Illinois type paha (i.e., elongated ridges composed of till and capped with loess) located in Whiteside and Rock Island counties (Flemal et al., 1972) have the same orientation and formed during the same time period (Rodbell et al. 1997), verifying the dominant paleo-wind direction. Furthermore, the wind direction and timing are also consistent with the findings of Muhs and Bettis (2000) where loess geochemical and particle-size data were utilized to infer a northwesterly wind during the LGM (last glacial maximum).

The purpose of this study is to address the two research questions: (1) is there a common preferred orientation of the IWLPs in Northern Illinois and, (2) if there is a common orientation, what are the causational mechanisms? The first question is addressed by investigating the morphological properties (ellipticity and size) of a selected field of IWLPs. The second question is addressed by comparing the orientations of IWLPs with structures of glacial origin and process such as moraine orientation, likely crevasse patterns, and extraterrestrial impact, as well as prevailing wind direction. Answers to these questions will bring further understanding to the origin of the IWLPs and the environment in which they were formed. The hypotheses considered, a summary of them, and how this study is related, is presented in Table 1.

2. Study area, data, and methodology

2.1. Landform delineation and ellipse derivation

We focused our study area on DeKalb County, Illinois (Fig. 2) where we have access to high resolution aerial photos and Light Detection and Ranging (LiDAR) data, acquired by the county government in 2009. These high resolution data allow for a very good spatial resolution (~1.5 m) and increased three dimension capabilities, which are instrumental for the delineation of IWLPs, as they are often subtle and hard to identify from traditional topographic maps. The LiDAR point clouds were processed to build a gridded digital elevation model (DEM), which can then be used to derive several views of the terrain, including a shaded relief map and a slope view. With these different views and aerial photo imported into ArcGIS as layers that can be turned on and off, we visually identified and digitally mapped IWLPs as closed features with positive relief, flat tops (some with slightly depressed centers) and light toned rims and darker interiors, along with an abrupt change in slope (Curry et al., 2010). Fig. 4 shows a few examples of digitized IWLPs along with the aerial photo.

The best fit ellipse for each IWLP was derived using the Zonal Geometry tool in ArcGIS, which also calculates the major and minor axis lengths and the major axis orientation, along with other information, and stores them in a linked GIS database table. The orientation of each IWLP is represented by the major axis orientation of the best fit ellipse and ranges from 0 to 180°, which is measured counterclockwise from due east. To be consistent with common usage, we converted all of the IWLP orientations to bearings. For example, a major axis with an

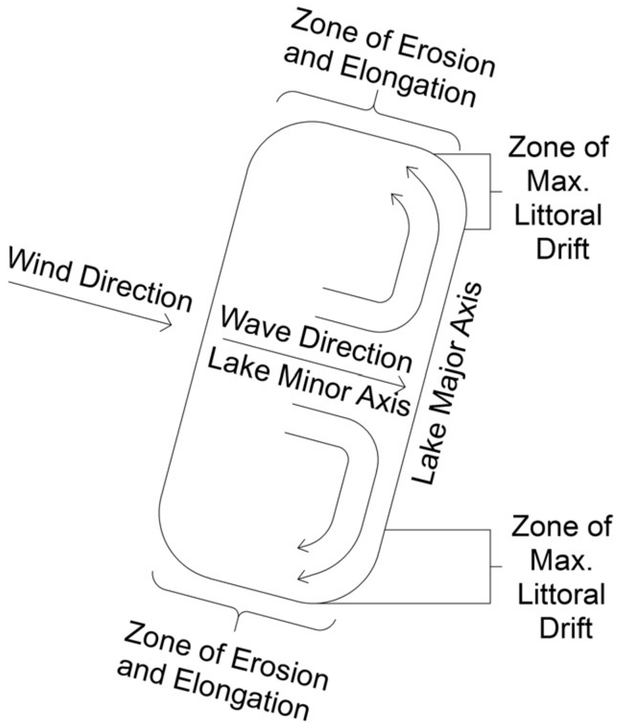

Fig. 3. Diagram illustrating the wind induced elongation theory for periglacial lakes, after Carter (1987) and Cote and Burn (2002).

orientation of 35° would have a bearing of N55°E, and an orientation of 130° would represent a bearing of N40°W. Although the bearings used give a direction, our intent in using them is only to follow similar angular notation from previous authors (e.g. Flemal et al., 1972; Miao et al., 2010) and not to imply single directionality of the landforms or wind. In this study, our focus is to investigate the mechanisms that may have caused that preferred orientation of the IWLPs; the bearing notation is only used as a mean to identify the orientation and should generally not be viewed as a direction in a vector sense.

2.2. Statistical analysis

The metric we used to analyze orientation of angular data is the Ajne–Stephens Test (Stephens, 1969). It is based on a statistic presented by Ajne (1968) which tests for the uniformity of circular distribution (i.e., what is the maximum number of points that can be encompassed in a chosen semi-circle) and is useful in determining whether a preferred orientation exists in angular data. It works by evaluating the distances between the data on a unit circumference (circumference = 1) as opposed to the distribution on a unit circle (radius = 1) such that the former simplifies the equation. The Ajne–Stephens Statistics is calculated as follows:

$$A_n = 1/2 - n/4 + (2/n)\sum_{j=2}^{n}\sum_{i=1}^{j-1}\left|1/2 + x_j - x_i\right| \tag{1}$$

where A_n is the Ajne–Stephens Test statistic, n is the number of observations, and x_i is the azimuthal angle of the i-th observation divided by 360°. We selected this metric because it makes no assumption about the distribution of the data. Where the calculated A_n is greater than the critical value, strong clustering of the data is suggested. The null hypothesis of this test is that the IWLPs do not exhibit a preferred orientation and are randomly distributed in their orientation. The alternative hypothesis is that the IWLPs do have a preferred orientation.

Linear regression is also utilized to compare the morphometric variables and orientation attributes. With multiple linear regression specifically, several explanatory parameters are compared to one response variable so that a common intercept is calculated, but the "slope" of the trend line is given as the sum of the corresponding coefficients for each variable. This type of analysis shows how much each independent variable ($x_1, x_2, \ldots, x_n$) contributes to the dependent variable (y) when they are assumed to work together and is given by the equation

$$y = C + ax_1 + bx_2 + \ldots + cx_n. \tag{2}$$

where C is an intercept and $a, b\ldots$ are coefficients.

The results of the regression analysis are then interpreted to verify whether the assumption holds for each of the parameters. Linear

Table 1
Dominant hypotheses of lake elongation.

Hypothesis	Summary	Supporting evidence for this research
Dual-cycle lake erosion powered by wind	Wind-induced currents preferentially erode lake shores in a direction perpendicular to the dominant wind direction	The orientation of the landforms is approximately normal to parabolic dunes found in the region that formed concurrently.
Ice-flow directionality or ice crevasses	Supra-glacial lakes are influenced by and the result of the ice flow direction or crevasses that occur at the margins of the glacier	The landforms are grouped adjacent to the moraines in Northern Illinois.
Extra-terrestrial impact	An extra-terrestrial impact occurred over North America either sending ejecta to the Earth's surface or a massive shockwave was created that formed elliptical lakes with a common orientation	• The Carolina Bays formation hypothesis is debated but possibly applicable to all oriented lakes in North America. • The landforms are somewhat oriented towards the Great Lakes, similar to other oriented lakes explained by this phenomenon.

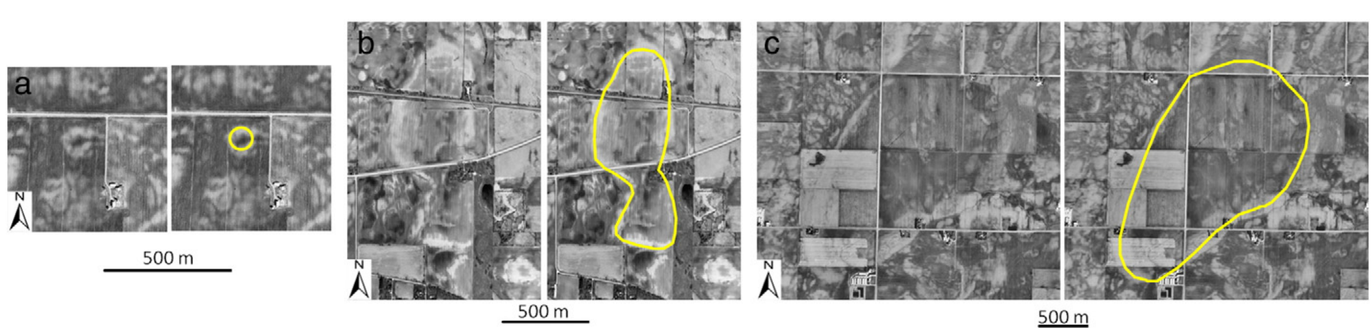

Fig. 4. Identification of a) a small symmetrical IWLP, b) a multi-lobate IWLP, and c) a large elliptical IWLP. Images are centered at a) 41.876°N, 88.567°W, b) 42.049°N, 88.567°W, and c) 41.885°N, 88.729°W.

regression is a common analysis technique to find the effect of one variable on another. For example, Arp et al. (2011) used a linear regression to show the effects of shoreline erosion and lake temperature on the thermokarst lake depth. They used multiple linear regression to show the collective effect of precipitation and evapotranspiration on the lake area and specific conductance as a proxy for water quality. Similar to Arp et al. (2011), linear regression is an applicable technique in this study because it shows the relationship between the orientation and two other lake and environmental characteristics being the size and ellipticity.

3. Results

In total, 443 landforms were classified as IWLPs in DeKalb County (Fig. 2). For this study, we mapped as many IWLPs as possible, and counted those that had a length to width (L/W) ratio (the ratio of major-to-minor axis lengths of the fitted ellipse) greater than 1.15 as elliptical. In addition to excluding the non-elliptical forms based on the L/W ratio, the IWLPs that had an extremely irregular shape, based on the ratio of the IWLP perimeter and the corresponding best fit ellipse, were also not counted; the cutoff value was 0.935. These ratio values were empirically established by analyzing histograms of the IWLP data; there are 306 elliptical IWLPs that fit our criteria.

The calculated A_n for the 306 IWLPs in DeKalb County included in our analysis is 229.52. The critical value is 0.656 at 5% significance level or 1.3 for 0.1% significance level; they are obtained from Stephens (1969) and are based on the distribution of A_n for varying x_i dispersions. The calculated values are much greater than the critical value so we reject the null hypothesis and accept the alternative hypothesis that the landforms share a preferred orientation.

The calculated mean orientation of the 306 IWLPs is N3°W, with a standard deviation of 43.41°. Although the Ajnes–Stephens test above shows that the orientation is unlikely to be random, the calculated standard deviation indicates some variability in the data. To explore this and to help identify factors which might be controlling the IWLP orientation, we ran regression statistics on the orientation of IWLPs against their shape as measured by the length to width ratio (i.e., ellipticity) of the best fit ellipses, their size as measured by perimeter of the IWLPs, and the adjacent moraine orientation as a proxy for the ice flow direction. To test the orientation of the IWLP versus the ice/moraine direction, DeKalb County was divided into 18 equal gridded zones and the IWLPs in each zone were compared to the likely ice-flow direction associated with the moraine in that zone. Hence, the orientation of the elongated IWLPs should change in harmony with ice-flow direction if their development was influenced by the structural elements of the glacier. The moraine orientation was determined by manually measuring the average orientation of each moraine through every gridded zone.

The results of the regression are shown in Table 2. With this multiple linear regression, the perimeter, length-to-width and moraine orientation are considered the independent variables (x) which are interactive but separate variables. Based on the t-statistic of the regression shown in Table 2 ($R^2 = 0.02$), the perimeter or size was found to be statistically significant at a 95% confidence level and the length to width ratio was not. In other words, the IWLP orientations are significantly influenced by their size as measured by perimeter.

Table 2
Linear regression results for IWLP orientation as a function of size (perimeter), ellipticity (L/W), and moraine orientation.

	Coefficients	Standard error	t statistics	p value
Intercept	105.7	9.3	11.4	4.2E−25
Perimeter *	0.00	0.00	−1.99	0.05
Length/width	2.86	4.06	0.71	0.48
Moraine orientation	−0.26	0.14	−1.91	0.06

* Statistically significant at 95% confidence level.

To expand on how the size of the IWLP compares with the orientation, we grouped the IWLPs by their perimeters and the results are given in Table 3. The table is organized such that each row (except the first) includes the data from the rows above it so that the count is cumulative. The breaks in the perimeters of Table 3 are based on 1000 or 2000 US-foot intervals of perimeter length. Also, it should be noted that most of the orientations listed in Table 3 are east of north, which is initially contradictory to the overall average orientation of N03°W. However, the overall average includes all 306 of the IWLPs from the study, while the largest grouping in the table only has a count of 166. By including the 140 smaller IWLPs in the average, the common orientation is pushed further west, indicating that the smaller IWLPs have an inconsistent orientation. Table 3 also shows a trend of the orientation moving further east as the IWLP size increases. Therefore, we find that the larger the IWLP perimeter, the smaller the standard deviation, or a smaller range of values, which may lead to a more common orientation. The decreased standard deviation indicates that the larger lakes are possibly more susceptible to the process that causes the orientation. It is consistent with Carson and Hussey (1962) who note that only the largest of the lakes considered by Rex (1961) are influenced by currents at the ends of the lakes. Our standard deviation at the lowest IWLP size grouping is also consistent with Hinkel et al. (2005) who included all sizes of both thaw lakes and drained thaw lake basins in their study, and found a standard deviation of 38.7° and 48.6°, respectively. However, these results are very different from those of Cote and Burn (2002), where the standard error of the 578 lakes was only 1.6°. The difference may be because the latter study only includes lakes larger than 20 ha whereas the minimum considered by Hinkel et al. (2005) was 1.1 ha. The Ajne–Stephens Statistics for each group is given in Table 3. They show the same results for the entire data, in that the null hypothesis can be rejected for each perimeter group at 95% confidence level and it is unlikely that the orientation is by chance.

To verify that the decreased standard deviation was not simply an effect of the decreasing sample size, a bootstrap analysis was applied to each of the groups outlined in Table 1. Bootstrapping is a common statistical technique to test how well a sample represents a population. It works by randomly resampling the data points with replacement to create a "mega" dataset, then resamples it many times to create subsets drawn from the "mega" dataset. For example, for n data points, one point is randomly selected, recorded into a larger dataset, and then put back, permitting the selection of one data point several times. The larger dataset is then resampled to create the subsets. The mean and standard deviation of each resampled set can be calculated. When a large number (i.e., hundreds or thousands) of resampled datasets are utilized, the mean of means and of standard deviations can be derived (Diaconis and Efron, 1983; Thompson, 1995). The standard deviation results of the bootstrapping with 1000 repetitions are comparable or better than the values calculated from the sample data (Table 1). Although bootstrapping may not be applicable to extremely small datasets, the orientations of the three IWLPs greater than 3050 m (N20.2°E, N18.3°E, and N47.9°E) show a trend that is reflected by the average.

Furthermore, the rose diagrams of the IWLP orientations in Fig. 5 also show that there is a considerable amount of clustering of orientations near the expected mean of the largest IWLPs. Therefore, while the standard deviation for the whole group is relatively large, the orientations of the landforms with large sizes are grouped closer together than smaller ones.

4. Discussion

To address the question of what influenced the common IWLP orientation, we first postulate that they are related to the glacial structure such as flow direction or crevasses that occur supraglacially. Crevasses

Table 3
IWLP orientations, the Ajne–Stephens Statistics, and the critical Ajne–Stephens Statistics at 5% significance level by perimeter group. All groups are statistically significant since the calculated A_n is larger than the critical A_n.

Perimeter (m) greater than	Count	Average orientation	Std. dev.	Bootstrap std. dev	A_n	Critical A_n (5%)
3050	3	N29°E	16.4°	11.3°	1.90	0.475
2750	6	N16.5°E	24.7°	21.7°	4.16	0.630
2135	21	N17.1°E	29.1°	27.9°	15.57	0.648
1830	26	N16.8°E	27.7°	26.8°	19.33	0.650
1220	58	N6.8°E	38.4°	37.9°	43.39	0.653
610	166	N1.2°W	44.1°	43.8°	123.73	0.654

form where extensional strain rates exceed some critical value, creating the deep cracks that are parallel to each other (Vornberher and Whillians, 1986). The crevasses have been shown to form perpendicular to the glacier margin and can extend from the base of the ice to the surface (Evans and Rea, 1999; Johnson et al., 2010). The hypothesis of IWLP orientation being associated with ice flow direction (not necessarily active ice flow) and crevasses is supported by Hambrey et al. (2008) who studied multiple glaciers, many with stagnant tongues. They conclude that the glaciers are present, leading to a range of environmental conditions, and that a complex suite of landforms is associated, including supraglacial lakes. Therefore, we investigate if IWLPs can be included in the complex. However, as shown above, the preferred orientations of elongated IWLPs are not consistently related to likely structural elements within the moraine (Fig. 2). Furthermore, the *t*-statistic and *p*-values from linear regression shown in Table 2 indicate that the association between inferred ice-flow direction and moraine orientation is not statistically significant (at 95% confidence level). Thus it is unlikely that the IWLP orientation is related to the glacial structure such as flow direction or crevasses.

Other than the direction of the ice flow or crevasses, we also postulate that the common orientation of the IWLP is related to prevailing winds during the time of the IWLP formation. We investigated whether their orientations may become more consistent with the expected orientation based on wind induced elongation theory as IWLP size increases. The orientation of the dominant paleo-wind direction in the study area can be derived from local sand dunes and was found to be blowing from northwest to southeast (Arbogast and Packman, 2004). More specifically, the dunes identified by Miao et al. (2010) have an average orientation of S65°E with a standard deviation of 11°, implying a dominant wind direction during the time period. If the wind induced lake elongation mechanism (Fig. 3) was operative when the lakes were active, the IWLPs would be expected to orient 90° from the prevailing paleo-wind direction, which would be N25°E.

Although the overall mean orientation of all elliptical IWLPs is N3°W, 28° off from the orientation expected based on the wind induced lake elongation theory, the mean orientation of larger IWLPs becomes closer to the expected direction, if the size of the IWLPs are considered along with decreasing standard deviation as the IWLP size increases (Table 3 and Fig. 5). Therefore, the largest IWLPs are indeed oriented in a direction roughly perpendicular to the prevailing paleo-wind, consistent with the wind induced lake elongation theory, whereas the orientations of smaller IWLPs are more variable (Figs. 5 and 6). The frequency distribution of the perimeter (not shown) reveals that there are many smaller IWLPs, which may contribute more to the mean orientation. This may indicate that smaller lakes are at an earlier stage of the development and have not developed into an orientation fully perpendicular to the prevailing wind direction.

The result mentioned above suggests that the preferred orientation of lakes takes time to form and a critical size of lake is necessary before the convection cells become powerful enough to circulate water and melt the ends in an elliptical fashion. As the wind blew across the ice-walled lake, the wave action eroded the shore (i.e., melting the ice) at the ends perpendicular to the wind direction, elongating the lake over time. This also refutes the extraterrestrial impact theory since the lake elongation is a time consuming process. Moreover, bedrock topography and the dynamic horizontal and vertical velocities of a glacier (Hooke, 2005) contributed to the formation of supra-glacial lakes (Selmes et al., 2013). As those that were able to persist were elongated, they also grew to cover more area. The orientations of the smaller IWLPs deviate more from the expected direction simply because they have not had enough time to elongate in any preferred direction. Along those lines, we propose one scenario where several small IWLs are formed,

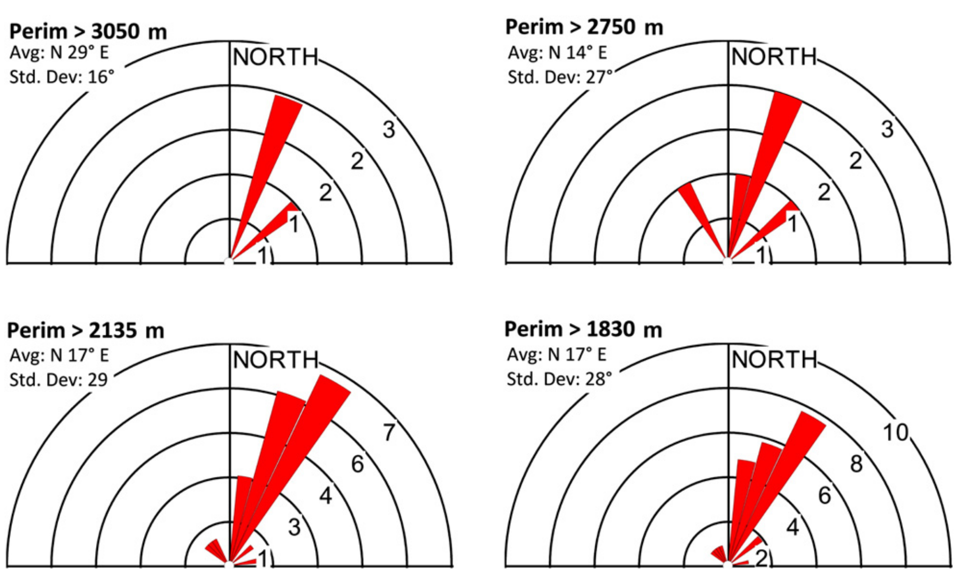

Fig. 5. Orientation distribution of the elliptical IWLPs larger than various perimeter lengths.

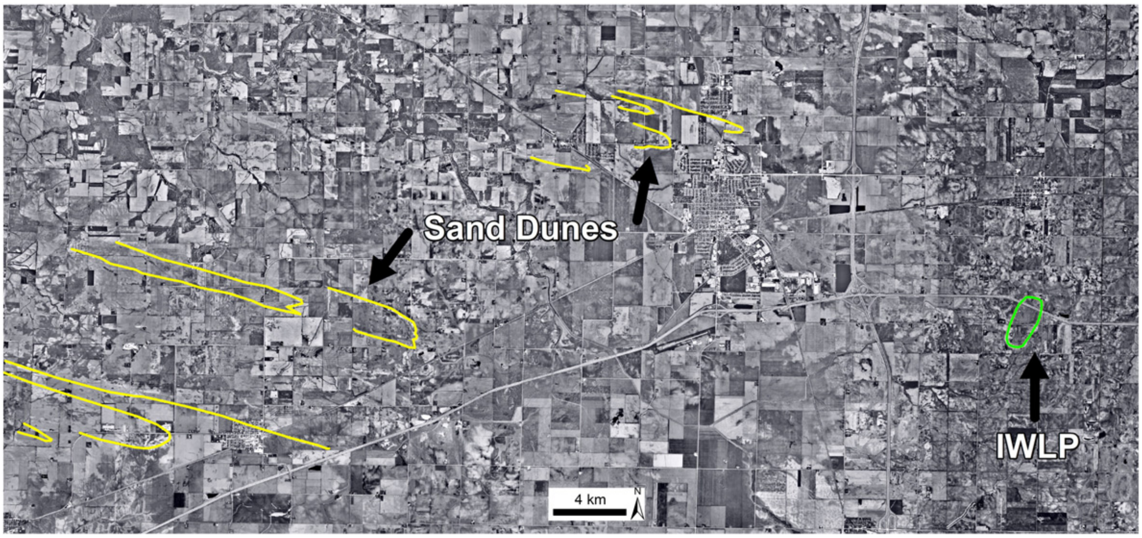

Fig. 6. Orientation comparison of the IWLP and sand dunes from Miao et al. (2010). Image is centered at 41.899°N, 88.966°W.

which grow to coalesce, and are affected by the prevailing wind so that they elongate in a direction perpendicular to it, which is analogous to the process involving modern thaw lakes in permafrost (Fig. 7).

One limitation of this research is that we relied on our ability to visually identify the IWLPs from aerial photos and LiDAR data, and then we manually digitized (traced) the edge of the IWLPs. Both practices can introduce uncertainty. Future work may include an automated approach to delineate and extract the boundaries of the IWLPs more objectively. In addition, it will also be interesting to examine other areas with IWLPs to see if our findings will hold and to determine the critical lake size above which the wind induced elongation will occur. Alternatively, in regions where elliptical lakes are grouped, their orientation may help to determine the paleo-wind direction, assisting in climate model studies and similar research.

5. Conclusion

We have conducted a detailed morphometric analysis of over 400 IWLPs in DeKalb after manually digitizing them based on aerial photos and LiDAR data. Statistical tests show that there is a preferred common orientation of the largest IWLPs. Regression analysis indicates that it is unlikely that the IWLP orientation is related to the glacial structure such as flow direction or crevasses. The wind induced lake elongation theory derived from modern thaw lakes in periglacial environment states that the lakes in such environment elongate in a direction orthogonal from the prevailing wind. However, to the best of our knowledge, this mechanism for oriented lakes has not been tested in IWLPs, which were formed during the last glacial period. Our morphometric and statistical analyses show that although the mean orientation of IWLPs is somewhat off from the expected direction based on the wind induced lake elongation theory, the orientations are found to be related to their size. The larger the IWLPs, the closer their mean orientation to the expected value, suggesting that it took time for the wind induced elongation process to work and a critical size of lake is needed before the convection cells become powerful enough to circulate water and melt the ends, forming the elliptical shaped lakes with preferred orientation. Thus, in our study area the paleo-environment and associated wind conditions played a significant role in elongating the ice-walled lakes during the last glacial period, similar to the contemporary thaw lakes studied in permafrost in the Arctic.

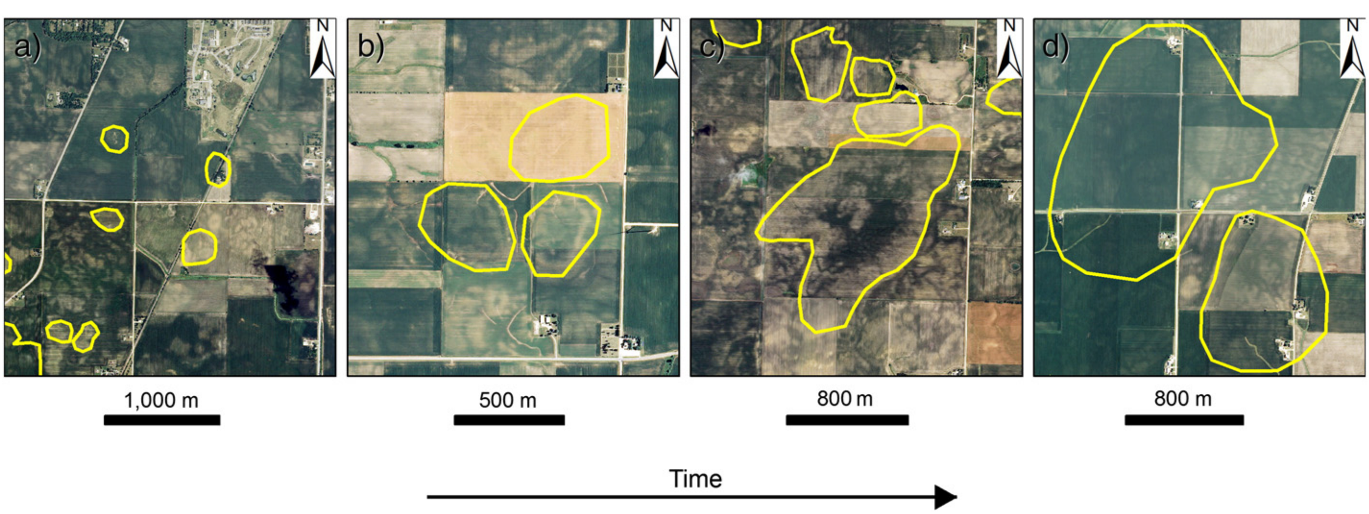

Fig. 7. Proposed evolution of IWLPs in the study area. a) Ice-walled lakes originated as melt pits in stagnant glacial ice (image center: 41.878°N, 88.769°W). b) Lakes grown in size (41.855°N, 88.947°W). c) Some lakes that grow large enough to coalesce with neighboring lakes (41.862°N, 88.718°W). d) Lakes that have reached a critical size where winds elongate them perpendicular to prevailing wind direction (41.900°N, 88.965°W).

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2014.05.022.

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