Assessing the style of advance and retreat of the Des Moines Lobe using LiDAR topographic data

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Geology

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Iowa State University
Ames, Iowa
2014

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ACKNOWLEDGEMENTS

I would like to thank some of the people who helped me with this research and guided me through the writing process. First, I'd like to thank my advisor, Neal Iverson, for his guidance and patience throughout the entire research process. His insight and attention to detail have helped me make this thesis something I can be proud of. Furthermore, given the additional responsibilities he took on as department chair, the amount of time he spent helping me with research and writing is astounding.

Next, I'd like to thank Lucas Zoet, Neal's post-doc, who helped me appreciate the power of computer coding. He helped me process much of my data, and without his vast knowledge of different programing platforms, this research would not have been completed.

In addition, I would also like to thank a few other people who have helped me throughout this process. I'd like to thank the second and third members of my Program of Study committee, Chris Harding and Bill Simpkins, for their time and effort in perfecting this project. I would like to thank DeAnn Frisk, the department administrative specialist, for her patience, knowledge, and support. I would also like to thank the rest of the Iowa State geology department for making my time as a graduate student successful and enjoyable.

Finally, I'd like to thank my friends and family for supporting me even when I was frustrated. Without their love and support through the entire process I would not have been able to finish this journey as a graduate student.

ABSTRACT

Successive advances of the late-Wisconsinan Des Moines Lobe to form three major end moraines in Iowa—sequentially the Bemis, Altamont, and Algona moraines—are thought to be the result of the lobe surging out of balance with a warming climate. Various styles of hummocky topography, collectively sometimes called stagnation moraine, are interpreted to be the result of widespread stagnation and down-wasting of ice following surges. Alternatively, end moraines could be recessional—a result of incremental back-wasting of the glacier margin and unrelated to surging.

To study the retreat style of the Des Moines Lobe, high resolution LiDAR data were used to re-evaluate the subtle landscape of the lobe's footprint in Iowa. Results indicate that ~90% of the lobe's area, excluding major Holocene stream drainages, consists of stagnation features. Some landforms are more prevalent than mapped previously, including eskers and features interpreted to be subdued ice-walled lake plains. Importantly, subglacially formed minor moraines (a.k.a. washboard moraines), which resulted from sediment filling of transverse crevasses, cover ~60% of the lobe's area with stagnation landforms. Also, ~25 previously unmapped end moraine ridges have been identified.

Transverse crevasse-fill ridges in the forefields of modern glaciers form due to longitudinal ice extension associated with surging and are not found in the forefields of non-surge-type glaciers, so minor moraines are good evidence of Des Moines Lobe surges. Most end moraines have minor moraine sets associated with them, consistent

with a surge-like advances, and many areas have multiple sets of minor moraines indicating a surge history more complicated than one advance for each of the three major end moraines. Therefore, asserting stagnation and down-wasting after three surge-like advances provides an incomplete characterization of the Des Moines Lobe's advance and retreat. The surge-type Bering Glacier in Alaska is a good but imperfect modern analog for the lobe.

CHAPTER 1: INTRODUCTION

A. The Des Moines Lobe

The Des Moines Lobe, the largest of the lobes along the southern margin of the Laurentide Ice Sheet (Fig. 1.1) during the last glacial maximum, advanced south into a relatively warm, boreal climate (Clark, 1994; Hooyer & Iverson, 2002; Mickelson & Colgan, 2003). At its maximum extent at approximately 13,800 ^{14}C yr BP, the lobe covered more than 100,000 km^2 in southern Minnesota and north-central Iowa and extended 600 km beyond the main body of the Laurentide Ice Sheet (Mathews, 1974; Clayton & Moran, 1982; Patterson, 1997; Hooyer & Iverson, 2002). The lobe had retreated from Iowa by 11,700 ^{14}C yr BP (Clayton & Moran, 1982).

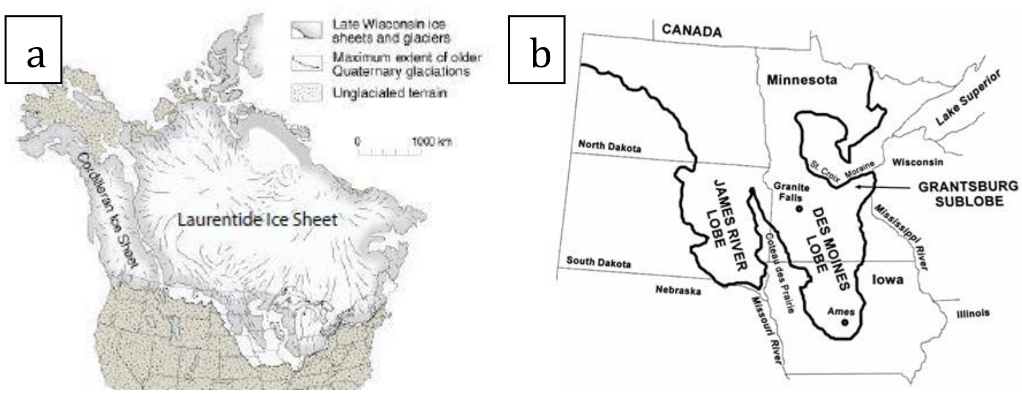

Figure 1.1: a. Maximum extents of the Laurentide Ice Sheet and Cordilleran Ice Sheets during the late Wisconsinan and during earlier Quaternary glaciations (Illinois State Geological Survey, 2008). **b.** Extent of the southern Laurentide Ice Sheet lobes in the western Midwest ~13,800 radiocarbon years ago (Hooyer & Iverson, 2002).

A detailed chronology of the Des Moines Lobe in Iowa is well established by radiocarbon dates from trees overridden by the glacier and buried in till (Kemmis et al. 1981; Clayton & Moran, 1982). The Bemis (13,800 ^{14}C yr BP), Altamont (13,500 ^{14}C yr

BP), and Algona (12,300 ^{14}C yr BP) end moraines (Fig. 1.2) mark three major advances of the lobe (Ruhe, 1969; Kemmis et al., 1981). These moraines are broad, 1-10 km wide, swaths of hummocky topography characterized by linked-depressions, kames, ice-walled lake plains, and elongate flow parallel ridges (Kemmis, 1991).

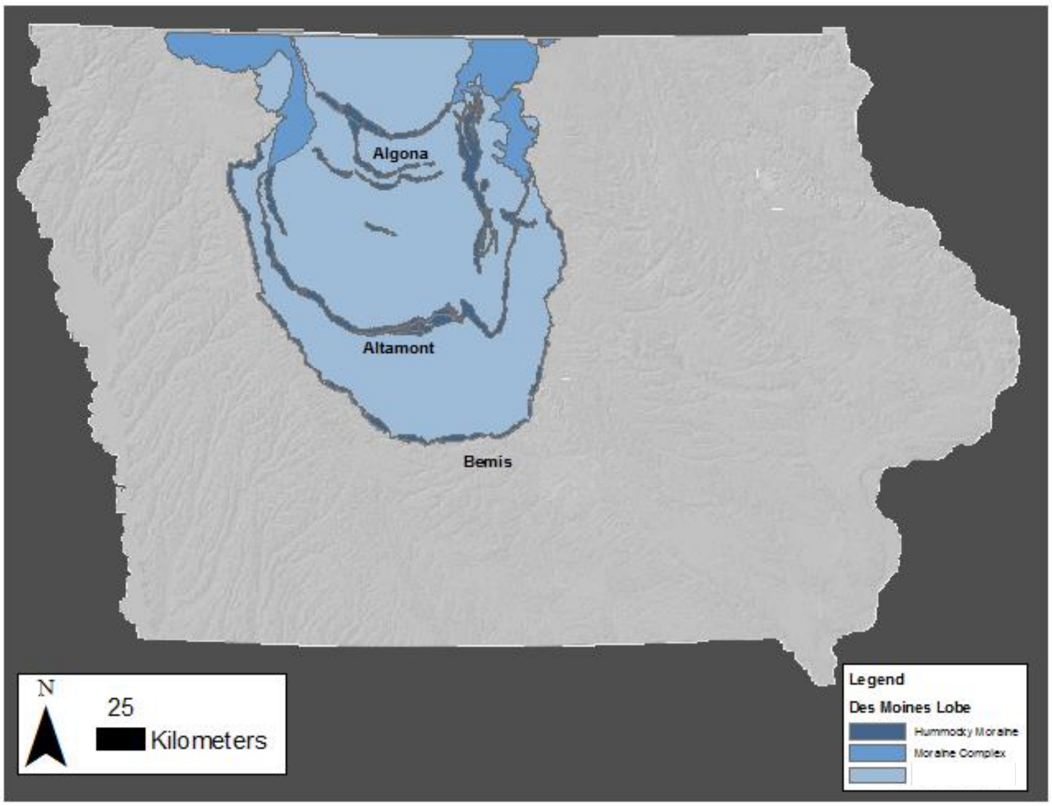

Figure 1.2: Iowa footprint of the Des Moines Lobe. The three major end moraines are the Bemis, Altamont, and Algona, delimited by areas of hummocky topography. The moraine complex includes areas where the moraines merge laterally.

Paleoglaciology

Reconstructions of the Des Moines Lobe using modern moraine elevations and minor moraines to indicate flow direction indicate the lobe's probable geometry at its maximum extent (Clark, 1992; Iverson and Hooyer, 2002). The lobe was unusually thin and gently sloping. Clark (1992) calculated its thickness to be only 300 m, 275 km up-glacier from the terminus, a factor of ~10 thinner than the margin of the Greenland Ice Sheet. Hooyer and Iverson (2002), assuming the moraines may have been ice cored at the time of deposition, determined only slightly larger thicknesses. These estimates are consistent with the earlier reconstruction of Matthews (1974), who did not use minor moraines as flow direction indicators.

Driving stresses computed from reconstructions range from 0.7 to 15 kPa (Clark, 1992; Hooyer & Iverson, 2002), about 3-70 times lower than those of a typical glacier, ~50 kPa (Cuffey & Paterson, 2010). Owing to the lack of ice bordering the lateral or terminal margins of the Des Moines Lobe and its large area relative to its thickness, unlike many modern ice streams (Alley et al., 1987) the reconstructed driving stress of the lobe should provide a good estimate of its average basal shear stress, at least in areas away from the glacier margin where slopes do not vary too much spatially. The low basal shear stress indicates that the lobe was likely not frozen to its bed, an inference consistent with the relatively warm climate inferred from fossil vegetation and insects (Schwert & Torpen, 1996; Baker, 1996; Bettis et al., 1996).

Even though the Des Moines Lobe was thin, gently sloping and had low driving stresses, it had a high ice flow velocity. Radiocarbon dates of wood found within end moraines and farther up-glacier indicate that the ice flowed rapidly to each end moraine position (Clayton et al., 1985). The time-averaged rate of margin advance of the Des Moines Lobe has been estimated to be 2 km yr^{-1}, based on radiocarbon dates along flow lines (Clayton et al., 1985). This value is much higher than the range of measured velocities for non-surge-type mountain glaciers and many ice-sheet outlet glaciers, approximately 10-200 m yr^{-1}, but is comparable to speeds of some surge-type glaciers, tidewater glaciers, and ice streams (Cuffey & Paterson, 2010).

The Des Moines Lobe moved over a fine-grained basal till. It is generally massive and relatively homogeneous, made up of ~15% clay, ~36% silt, and ~47% sand and larger particles (Kemmis et al., 1981), although it contains isolated pods and stringers of sand and gravel. The till's fine-grained texture, together with the low slope of the lobe would have, according to the leading theoretical model of subglacial water flow for soft-bedded glaciers (Clark & Walder, 1994; Walder & Fowler, 1994), resulted in channels cut into the bed surface and under high water pressure, resulting in high pore-water pressure in adjacent till. This conjecture is consistent with the sparseness of well develop eskers within the limits of the Des Moines Lobe, which require R-channels cut upward into the glacier sole (Clark & Walder, 1994). High basal pore-water pressure would have reduced the till's shear strength and could have resulted in basal till deformation that promoted unstable and rapid glacier flow (Clark, 1994). Clark (1994) found that areas of the Laurentide ice sheet that experienced unstable rapid ice-margin fluctuations (Fig. 1.3a) were underlain by fine-grained till and these regions tend to correspond to areas of sedimentary bedrock (Fig. 1.3b). He argued that till deformation occurred to depths as great as 10 m. Many have noted that high basal pore water pressure and resultant till deformation can produce subglacial topography (Alley, 1991; Clark, 1994; Eyles et al., 1999; Boone & Eyles, 2001), for example, where sediment is squeezed upward into crevasses at the bed, forming crevasse-fill ridges (e.g., Sharp, 1985a; Rea and Evans, 2011).

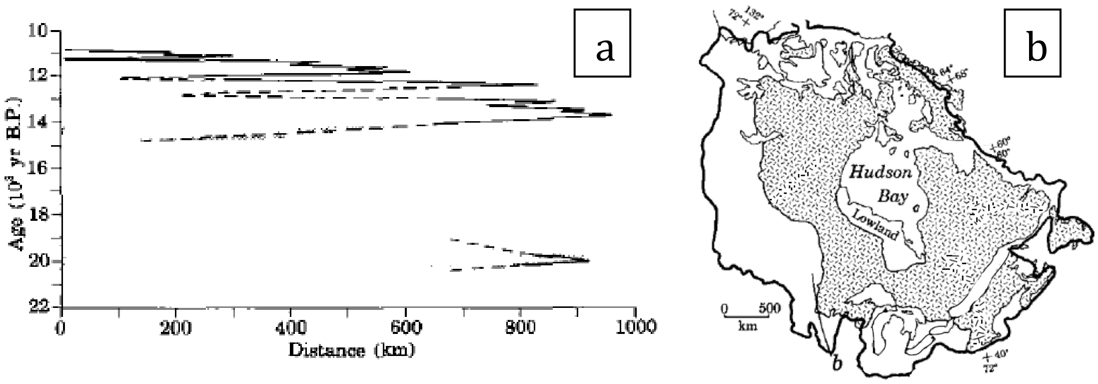

Figure 1.3: a. The time-distance plot for the Des Moines Lobe constructed using radiocarbon dates of wood entrained in the till. **b.** Generalized map with the distribution of crystalline bedrock (patterned area) and sedimentary bedrock (unpatterned area) (Clark, 1994; Clayton & Moran, 1982).

Hooyer and Iverson (2002) did preconsolidation testing on intact basal till samples to help confirm that high basal pore water pressure may have been responsible for the low basal shear stress of the lobe and its seemingly high velocity. The maximum past effective stress on the till determined from these tests, when considered together with the lobe's thickness determined from the geomorphic reconstruction, allowed the minimum basal pore water pressure to be determined (Hooyer &Iverson, 2002). The corresponding potentiometric surface plotted on surface profiles of the Des Moines Lobe (Fig. 1.4) indicates that pore-water pressures were sufficiently high that the lobe was nearly floating on its bed (Hooyer & Iverson, 2002). Following the model of Walder and Fowler (1994), the subglacial hydrology may well have consisted of a distributed system with channels cut into the bed supporting higher water pressures (Hooyer & Iverson, 2002). Unlike Clark (1994), relatively weak fabrics in the basal till of the lobe

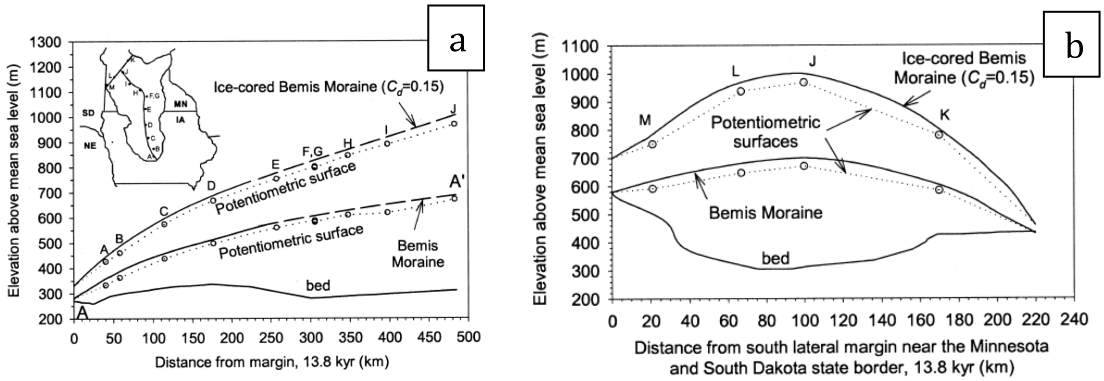

Figure 1.4: a. Longitudinal and **b.** transverse potentiometric surfaces of the Des Moines Lobe. Two ice surface profiles and two potentiometric surfaces are depicted in **a.** and **b.**; the lower of the two ice surface profiles was calculated assuming that the elevation of the Bemis moraine reflects the elevation of the ice surface at the margin. The higher ice surface profile assumes that Bemis moraine was ice cored during deposition and hence at a higher elevation than it is today. A potentiometric surface was calculated for each of these ice surfaces using both preconsolidation pressures measured from intact samples of the Des Moines Lobe basal till and ice pressures based on the reconstructed ice thickness (Hooyer & Iverson, 2002).

(the Alden member of the Dows Formation (Kemmis et al., 1981; Bettis et al., 1996)) measured by Hooyer and Iverson (2002) led them to conclude that the glacier was likely decoupled from its bed over much of its area, with clast plowing as the dominant mechanism of motion rather than pervasive and deep deformation of till (Alley, 1989; Clark, 1994; Boulton, 1996).

Models of Des Moines Lobe motion

Early workers believed that the Des Moines Lobe underwent climate driven advance and retreat in response to changes in the glacier's mass balance. End moraines and minor moraines, also known as washboard moraines (Elson, 1968; Cline, 2011) and corrugated moraines (Prest, 1968; Stewart et al., 1988), were cited as evidence (Gwynne, 1942; Gwynne, 1951; Lawrence & Elson, 1953). Gwynne (1942, 1951) and Elson

(1953) were well aware that end moraines outline positions of the ice front and formed in locations where the ice margin was temporarily stable. They considered minor moraines to also outline successive positions of the ice front but where the ice margin paused for a shorter period than at the end moraines (Gwynne, 1942; Gwynne, 1951; Lawrence & Elson, 1953). Each minor moraine was estimated to represent approximately one to two years of deposition at the ice margin (Gwynne, 1942; Gwynne, 1951; Lawrence & Elson, 1953). Gwynne (1942) calculated the retreat rate of the lobe by counting the number of minor moraines along a segment of a flow line and then calculating the rate as one to two times the number of minor moraines divided by the distance. Areas of the Des Moines Lobe that do not have minor moraines were considered to be regions where the ice margin retreated too rapidly to deposit a moraine (Gwynne, 1942; Gwynne, 1951; Lawrence & Elson, 1953).

The idea that the Des Moines Lobe advanced and retreated in response to changes in its mass balance was superseded in the 1980s by the hypothesis that the lobe advanced by surging. A surge-type glacier is characterized by periodic rapid flow events, or surges, in which ice velocity increases by a factor of 10 to 100 (Cuffey & Paterson, 2010). High ice velocity, uncompensated by an associated increase in glacier net balance, results in a reduction of ice surface slope and thickness followed by widespread reduction in flow velocity that transiently results in nearly complete ice stagnation. The Des Moines Lobe's low surface slope, thin ice, and advance rate of 2 km yr^{-1} are consistent with the characteristics of surging glaciers (Clayton et al., 1985). Subsequent surge-type advances occur only after a period of many years, commonly 10-100 years in

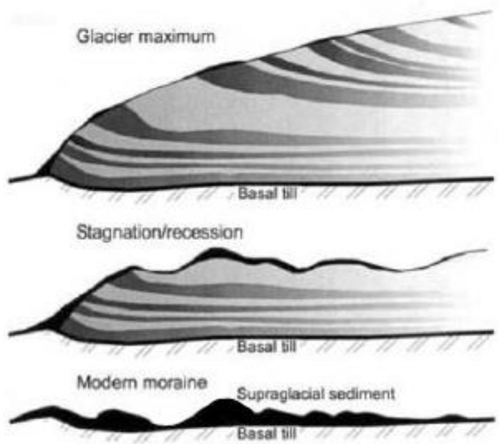

Figure 1.5: Stagnation and down wasting of the margin of a surge-type glacier, resulting in the formation of hummocky topography (Hooyer & Iverson, 2002).

valley glaciers (Cuffey & Paterson, 2010), once the glacier surface slope and thickness have recovered to threshold levels necessary for another surge (Kamb et al., 1985; Roush et al., 2003). For surge-type glacier advances, each end moraine represents the farthest down-glacier extent of a given surge front (Fig. 1.5). Landforms such as minor moraines and ice-walled lake plains are thought to develop after a surge during stagnation (Sharp, 1985a; Boone & Eyles, 2001; Clayton et al., 2008; Rea & Evans, 2011).

The Des Moines Lobe's low driving stresses, high basal pore water pressure, and gently sloping profile are also consistent with some of the characteristics of ice streams (Fig. 1.6) (Patterson, 1997; Patterson, 1998; Jennings, 2006). Ice streams are zones of rapidly moving ice, 300-15,000 m yr^{-1} (Cuffey & Paterson, 2010), flanked by slowly moving ice (Clarke, 1987; Stokes & Clark, 1999). As noted, the rapid advance the Des Moines Lobe is well established based on radiocarbon dating. There is less evidence adjacent to the lobe for the slowly moving ice which flanks an ice stream. Over the lobe's full extent in Iowa there was no ice along the lobe's lateral flanks. Farther north there may have been slower moving adjacent ice as a result of escarpments and bedrock topographic features that restricted ice flow (Patterson, 1997; Patterson, 1998; Stokes & Clark, 1999; Stokes & Clark, 2001; Jennings, 2006).

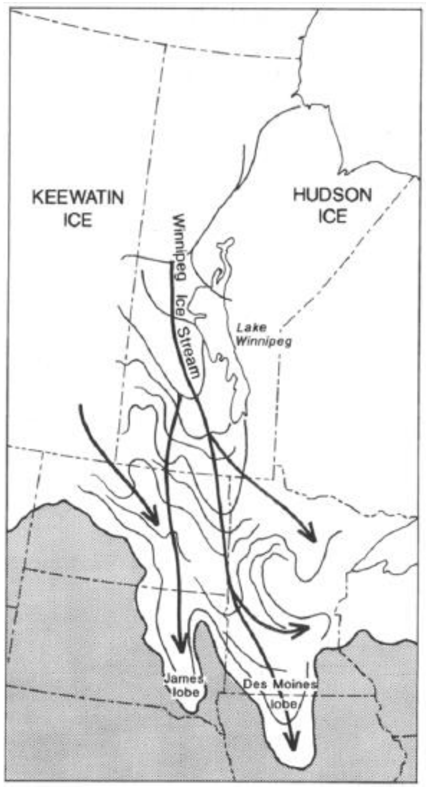

Figure 1.6: Map of the Des Moines Lobe, considered to be an ice stream by Patterson (1997).

Patterson (1997) discussed landforms of the Des Moines Lobe that may indicate it was an ice stream, but these characteristics are not unique to ice streams and more characteristic of surge-type glaciers. According to Patterson (1997) tunnel valleys at the glacier margin would have increased basal drag by evacuating large amounts of water from the bed, thereby causing stagnation. Although the evacuation of water through tunnel valleys may be associated with ice streams, this style of water evacuation has been linked more commonly to the periodic advances of modern surging glaciers (Kamb et al., 1985; Walder & Fowler, 1994; Roush et al., 2003), with high discharges occurring as the surge ends. Patterson (1997) also links transverse crevasses and the development of minor moraines to ice stream motion. Transverse crevasses develop due to longitudinal ice extension, (Sharp, 1985a) and can result in crevasse fill ridges, interpreted by many to be the origin of minor moraines (Stewart et al., 1988; Clark, 1992; Patterson, 1998; Ankerstjerne, 2010; Cline, 2011). Crevasse-fill ridges are associated most commonly with the forefields of surge-type glaciers rather than ice streams (Sharp, 1985a; Rea and Evans, 2011).

Landform identification

Landforms of the Des Moines Lobe have been studied in Iowa for more than 100 years (Chamberlin, 1883; Macbride, T.H., 1909), but the most detailed Quaternary landform map was produced by Kemmis (1991). Kemmis's map (Fig. 1.7) covers the northernmost third of the Des Moines Lobe in Iowa. Using low-resolution aerial photographs and field studies, Kemmis (1981, 1991) developed a complex landform classification scheme (Fig. 1.8) with 24 different positive-relief features, such as moraines and plains, and additional negative-relief features including abandoned channels and linked depressions (Kemmis, 1991).

His positive-relief landforms include ridges and plains. Hummocky moraine ridges are defined as having a distinct front and back slope. These moraines are 1-10 km in width and are locally interrupted by stream valleys or abandoned channels (Kemmis, 1991; Bettis et al., 1996). Plains are broad extensive areas of moderate to low relief and have various surface patterns (Bettis et al., 1996); they are the most diverse and extensive landform identified. Transverse lineated low relief features or minor moraines are one such surface pattern. A second surface pattern was identified based on rounded circular features (Kemmis, 1991; Bettis et al., 1996), possible ice-walled lake plains (Fig. 1.9), which form when a glacial lake develops within the ice and subsequent melting leaves a topographically inverted, circular, flat-topped plain (Clayton et al., 2008).

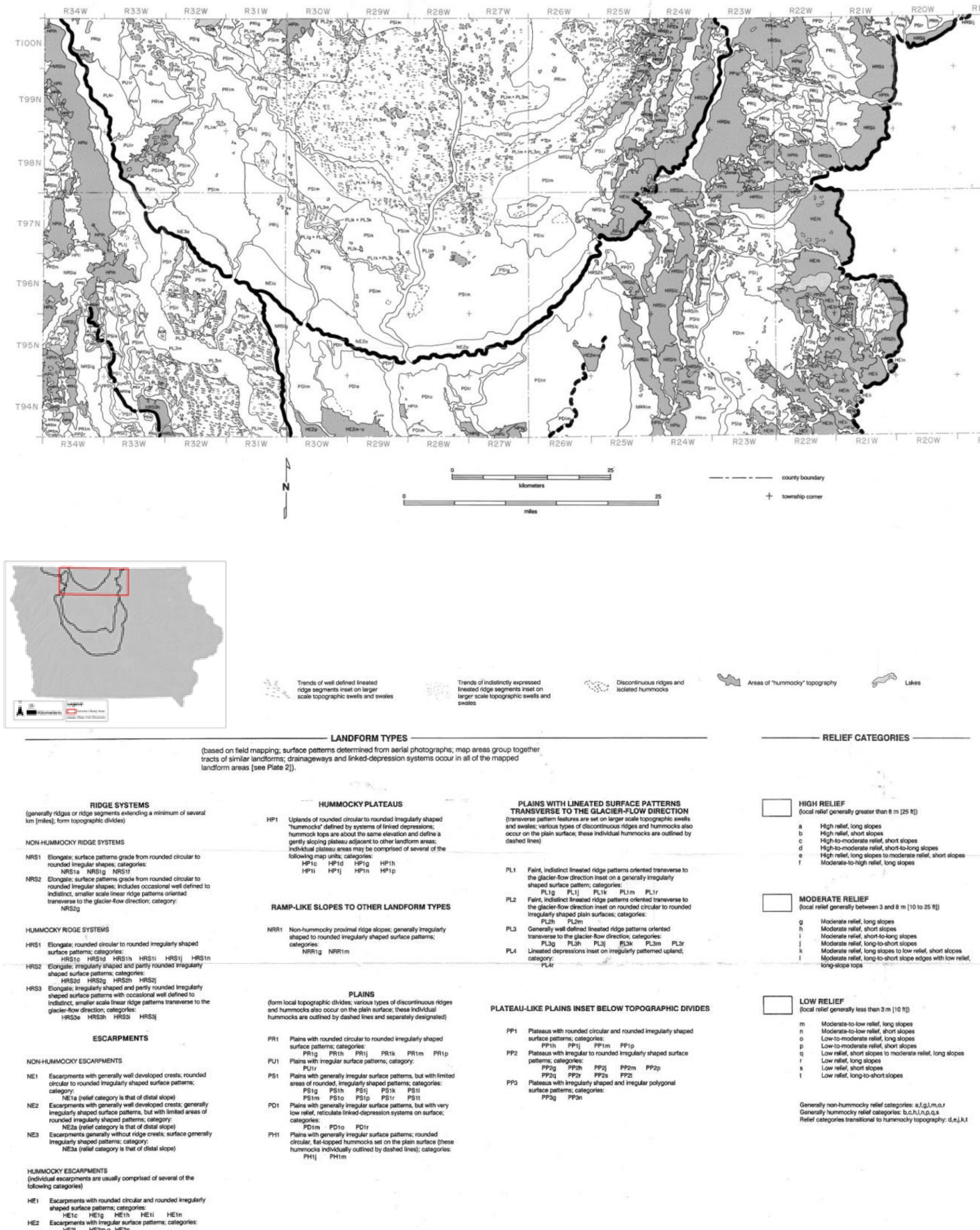

Figure 1.7: Quaternary landform map of the northern third of the Des Moines Lobe in Iowa (from Kemmis 1991).

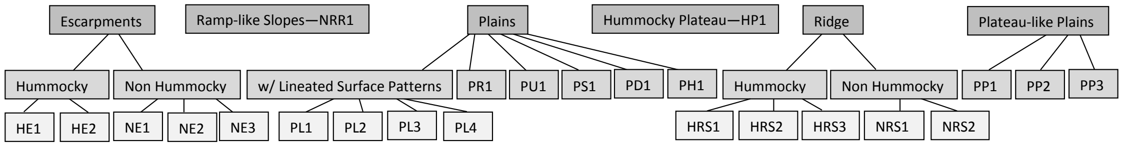

Figure 1.8: Landform classification scheme of Kemmis (1993). See legend of Figure 1.7 for descriptions of landform types (e.g. PL3).

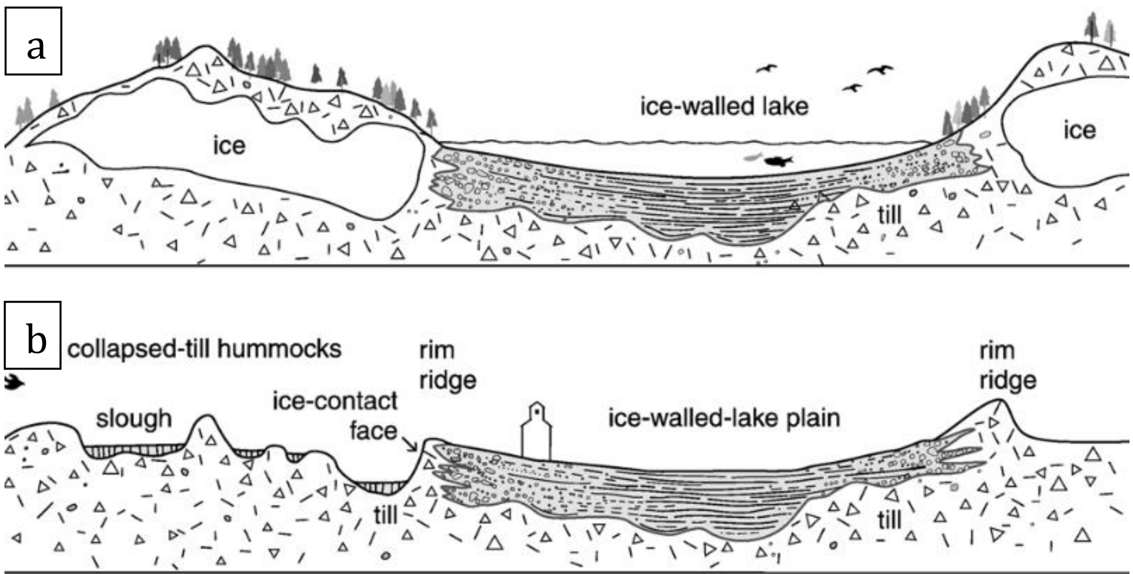

Figure 1.9: Ice-walled lake plain formation **a.** prior to ice fully melting and **b.** following ice melting (Clayton et. al, 2008).

Negative-relief landforms are abandoned channels and linked depressions (Bettis et al., 1996). Abandoned channels are former tunnel valleys (fig. 10) or more minor drainages and are frequently connected to or are part of a linked depression system (Kemmis, 1991; Bettis et al., 1996). Linked depression systems are valleys and depressions that connect to form drainage networks, often found super-imposed on positive-relief landforms (Kemmis 1991). They tend not to have smoothly graded channel bottoms, are branching rather than linear, and typically connect to modern drainages (Kemmis, 1991; Bettis et al., 1996).

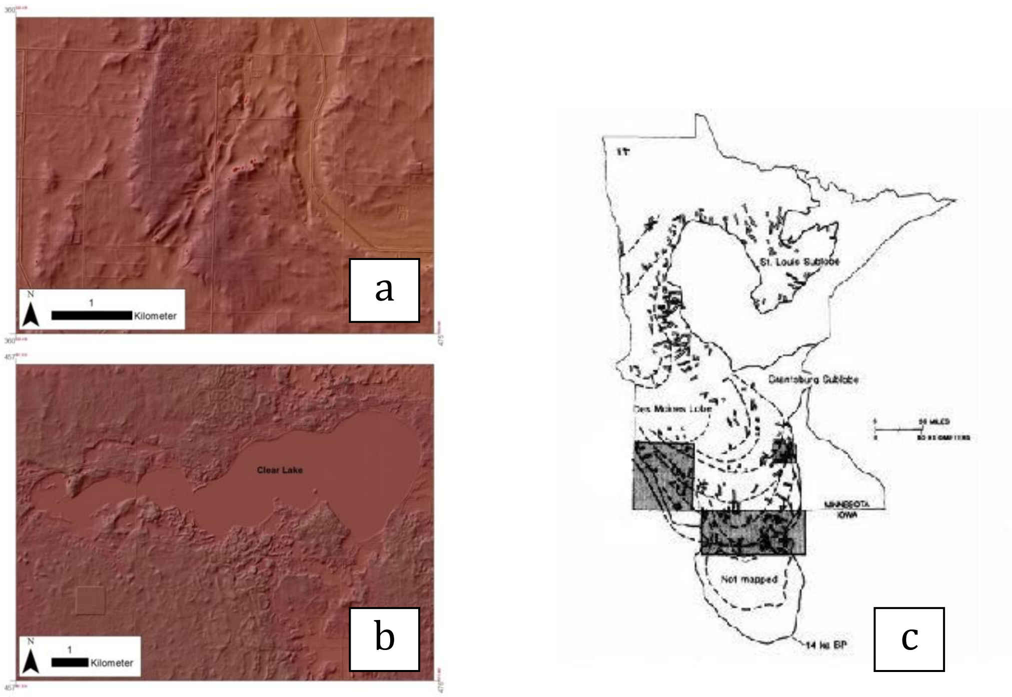

Figure 1.10: a. Tunnel valley south of Mallard. **b.** Clear Lake, Iowa, inferred to occupy a tunnel valley. **c.** Map of Des Moines Lobe extent of tunnel valleys (Patterson, 1997). Note that no tunnel valleys have been previously mapped south of the Kemmis map area.

Although Kemmis (1991) developed a very detailed map and classification scheme, his work is insufficient to describe the lobe in Iowa. He mapped only the northern third of the lobe in Iowa (Fig. 1.7), and when the map was completed, high resolution 1 m DEMs were not yet available. Due to the subtle relief over the footprint of the lobe, high resolution imagery can illuminate previously overlooked landforms. Additionally, Kemmis' classification scheme (Fig. 1.8) is very complex, including 24 landforms, nine of which are different types of plains. The distinction between the nine types of plain identified by Kemmis is not clear; some definitions overlap others (Fig. 1.7). In order to gain a better understanding of the lobe in Iowa, landforms over the entire footprint of the lobe in Iowa need to be examined with the newly available 1 m DEMs and the Kemmis classification scheme re-evaluated.

Additional landforms have also been examined separate from Kemmis' (1991) work such as doubly blown-out doughnuts and eskers. Although doubly blown-out doughnuts have not previously been mapped in Iowa, they have been identified in the glaciated landscape of North Dakota as part of the Northern James River and Des Moines Lobes (Fig. 1. 1). Doughnuts, before being truncated by erosion (blown-out), tend to be circular ridges a few hundred feet across and a few tens of feet high (Clayton & Freers, 1967). These features form in three stages (Fig. 1.11). First, sediment fills a depression in stagnant ice. Second, the surrounding ice melts, leaving an ice cored hill, and third,

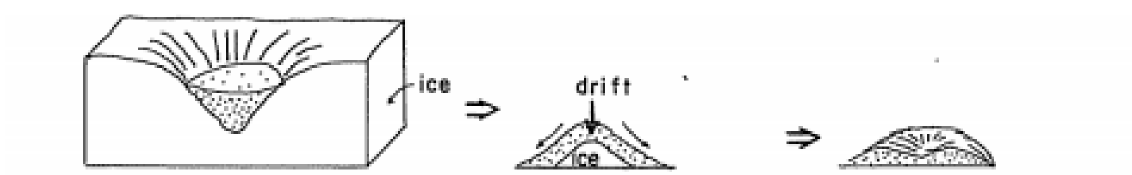

Figure 1.11: Three stages of doughnut formation (Clayton, 1967).

the ice core melts and a depression forms at the center, leaving a circular ridge (Clayton & Freers, 1967). Doughnuts are commonly breached on opposite sides of the ridge ring, possibly resulting from the collapse of a buried ice-cored crevasse fill (Clayton & Freers, 1967), and identified as doubly blown-out doughnuts. Eskers have also been identified in the footprint of the lobe. Traditionally, very few eskers have been identified in Iowa, and are located near the Iowa-Minnesota border (Quade & Seigley, 2006). Additional sinuous ridges, that are similar to the morphology of an esker, have been noted but not previously identified as eskers. One such sinuous ridge is located ~ 3 km north of Lake Mills, Iowa, (Fig. 1.12) identified by Leverett in 1932 as a moraine ridge.

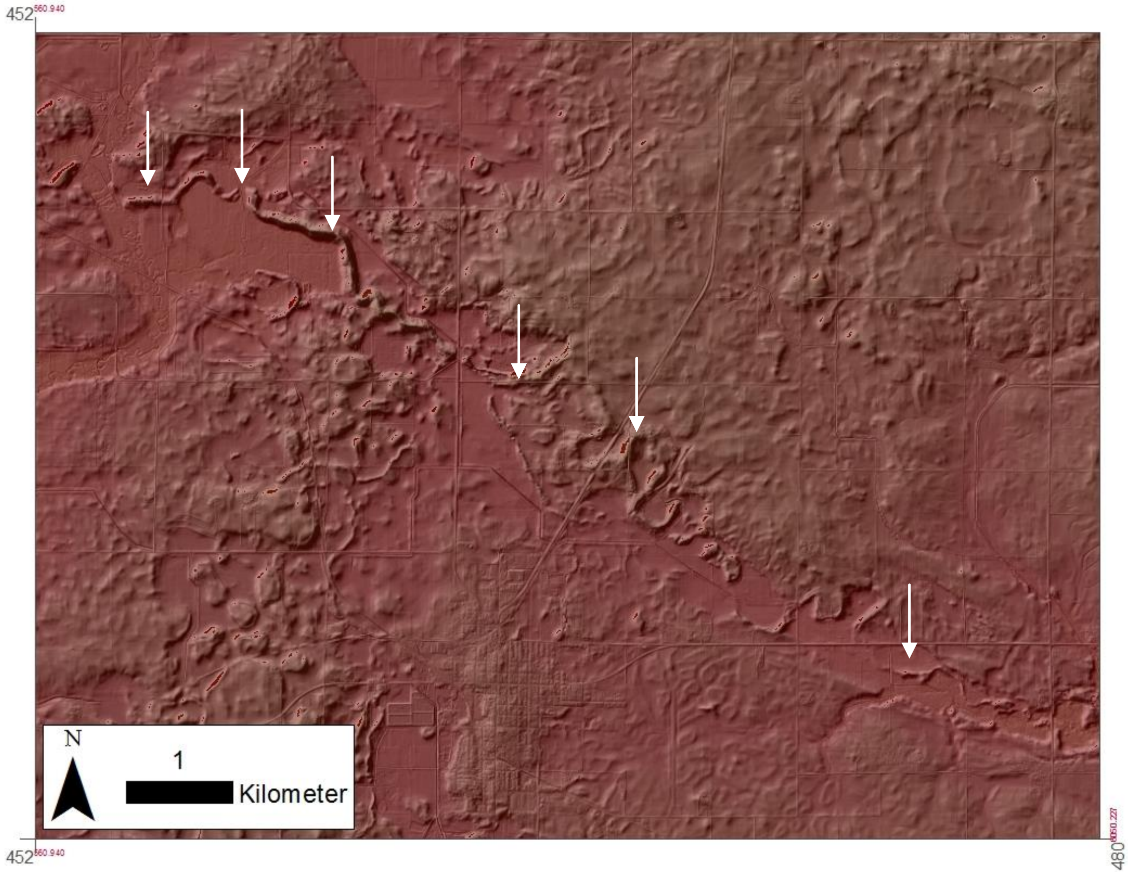

Figure 1.12: Esker north of Lake Mills, Iowa, near the Minnesota border. The esker is approximately 5 m high at its crest and extends to eastern margin of the lobe.

B. Motivation and hypotheses

Identification and interpretation of glacial landforms can improve reconstructions of ancient ice masses. Landforms provide information about glacier morphology and dynamics. In previous reconstructions of the Des Moines Lobe, the assumption is made that landforms such as minor moraines all formed simultaneously when the glacier was at its maximum extent (Clark, 1992; Hooyer & Iverson, 2002). The veracity of these reconstructions can be evaluated by developing more complete, high resolution maps of the lobe's end and minor moraines.

Landforms of the lobe also provide information about its style of advance and retreat. As noted, Gwynne (1942) proposed that the Des Moines Lobe underwent advance and retreat due to mass balance changes, which would indicate that radiocarbon dating of moraines would provide information about past climate change. In contrast, others have subsequently suggested (Clark, 1994; Clayton et al., 1985; Patterson, 1997) that the Des Moines Lobe advanced out of balance with the climate. Of these hypotheses, the most popular is that the lobe underwent surge-type advances followed by stagnation. If surges were the dominant style of advance, it is important to understand how many advances there were. Traditionally, the Des Moines Lobe is thought to have undergone three surge-like advances, each building one of the three major end moraines (Fig. 1.2). A more detailed analysis of Des Moines Lobe landforms may support this hypothesis, reveal that the that the surge history of the lobe is more complex than previously thought, or provide evidence for some moraines forming during active recession of the lobe, rather than by surging and down-wasting.

C. Objectives

The goal of this project was to use high-resolution LiDAR-derived elevation data to map the Des Moines Lobe footprint in Iowa and thereby better assess the advance and retreat style of the lobe using landform attributes. Landforms over the 30,000 km^2 footprint of the lobe in Iowa were identified, including minor moraines (Stewart et al., 1988), end moraines (Kemmis, 1991; Benn, 1992), ice-walled lake plains (Clayton et al., 2008), doubly blown-out doughnuts (Clayton & Freers, 1967), eskers (Shreve, 1985), and tunnel valleys (Kemmis, 1991; Patterson, 1997). New maps were used to identify the total area that is characterized by landforms that developed as a result of stagnation (Sharp, 1985a; Benn, 1992; Clayton et al., 2008) and to determine the relationship between orientations of end moraines and minor moraines—a key relationship for assessing the extent to which surge-like advances and stagnation dominated the advance and retreat behavior of the lobe.

CHAPTER 2: METHODS

A. Introduction

Previous work on the landscape of the Des Moines Lobe, completed by Kemmis in 1991, used aerial photography, field observations, and laboratory work to map the northern third of the Des Moines Lobe's footprint in Iowa (Fig. 2.1). Kemmis developed

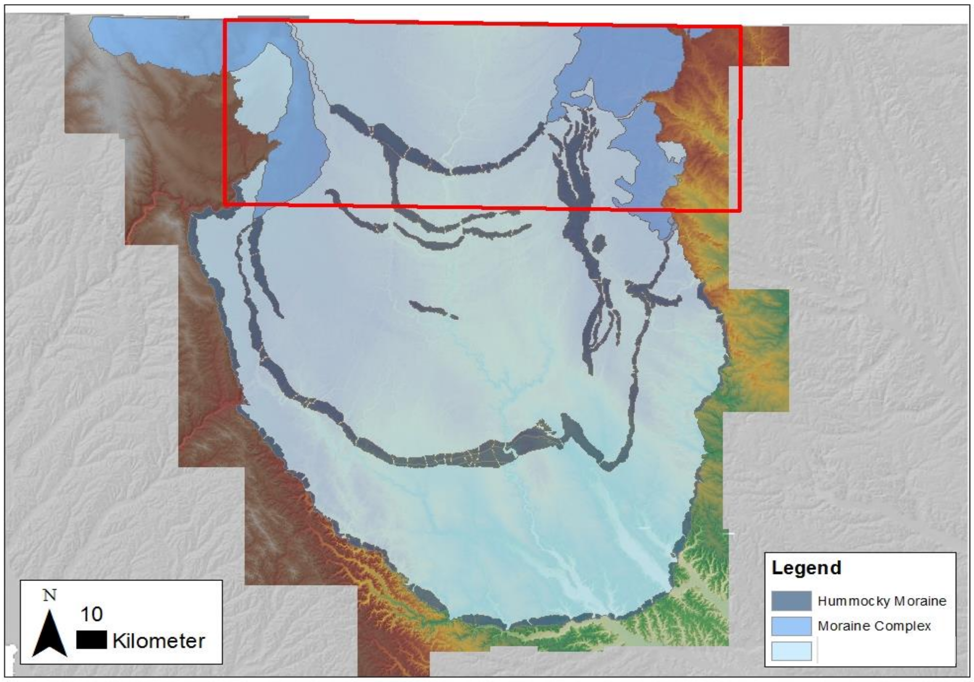

Figure 2.1: Kemmis (1991) study area, outlined in red, overlaying 1 m DEMs derived from LiDAR data and a hill-shaded relief map.

a new landform classification scheme (Fig. 1.8), and although his map is detailed, most of the Des Moines Lobe's footprint in Iowa is not included. Moreover, he was not able to observe the extent of many of the landforms and overlooked smaller, more subtle features. The limitations of this previous work and the availability of new high resolution imaging over the entire state of Iowa motivated this project. Initial observations of LiDAR derived DEMs highlighted a number of areas of interest that appeared to differ from or expand upon Kemmis's results. New maps covering the full extent of the lobe in Iowa allowed advance and retreat hypotheses for the lobe, studied by Kemmis (1991), to be reexamined.

This project used LiDAR (Light Detection and Ranging) data to produce a one-meter digital elevation model (DEM) highlighting landforms. The landforms identified include end moraines, minor moraines, ice-walled lake plains, doubly breached doughnuts, eskers, and tunnel valleys. Once they were identified and mapped, the landforms were grouped into a simplified landform regions map.

B. LiDAR

LiDAR-derived elevation data are accurate to the sub-meter scale and are particularly useful for the low-relief landscape of the Des Moines Lobe. The DNR's Iowa LiDAR Mapping Project (Iowa Department of Natural Resources) used LiDAR elevation data, collected from 2006 through 2009, to generate high-resolution one meter DEMs for the state of Iowa (Cline, 2011). With this technique, elevation is detected using light pulses; millions of pulses per second are emitted and reflected back to a single aircraft (Measures, 1984; Elachi & van Zyl, 2006). The pulse lag time and GPS position of the aircraft is used to calculate absolute elevations. Each pulse is emitted with a wavelength of 1064 nm, a much shorter wavelength than the radio waves used by radar (approximately 0.01 – 1 m wavelength) (Measures, 1984; Cracknell & Hayes, 1991; Elachi & van Zyl, 2006). As a result, LiDAR data are much higher resolution.

LiDAR data reveal details not visible on aerial photographs or 10 m DEMs (Fig. 2.2). Figure 2.2 depicts an area between Ames and Nevada, Iowa where minor moraines are prevalent. The 10 m DEM (Fig. 2.2a) has visible minor moraines over only approximately 2 km^2 of the map area, whereas in the 1 m LiDAR based DEM (Fig. 2.2b) most of the approximately 16 km^2 depicted is covered by well-resolved minor moraines. This study is the first to use LiDAR elevation data to examine the Des Moines Lobe landscape of Iowa and expands upon Cline's (2011) work on the washboard moraines of Story County.

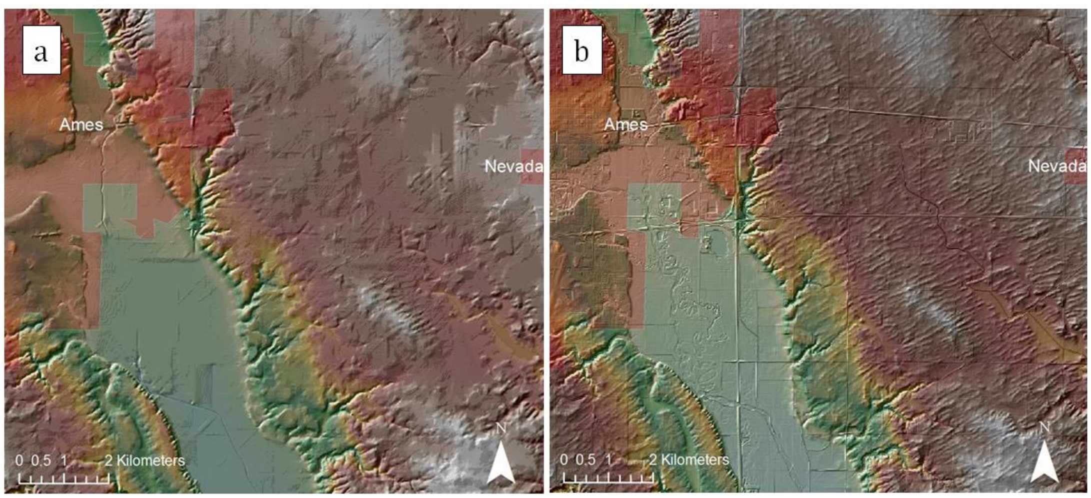

Figure 2.2: a. Map showing a 10 m DEM of the area between Ames and Nevada, Iowa, as was available prior to the LiDAR survey (Cline, 2011). **b.** LiDAR-derived DEM (1 m horizontal resolution with vertical accuracy within 18.5 cm) of the same area (Cline 2011). Both parts **a** and **b** are overlain with a hill-shaded relief map to highlight topography.

C. Mapping methodology

A landform map was generated by categorizing topographic variability over the footprint of the Des Moines Lobe. Initial landform mapping was completed by identifying individual landforms based on their size and shape using the one-meter DEMs developed from the LiDAR elevation data. Some of the landform classifications were optimized through field checking of a few areas of interest, as well as by using previous field work (Kemmis, 1991; Ankerstjerne, 2010; Cline, 2011). A landform classification scheme was developed to reflect a simplified version of Kemmis's (1991) scheme of 24 landform groups and improved through use of modern definitions and understanding of glacial landforms (Fig. 2.3, Table 2.1).

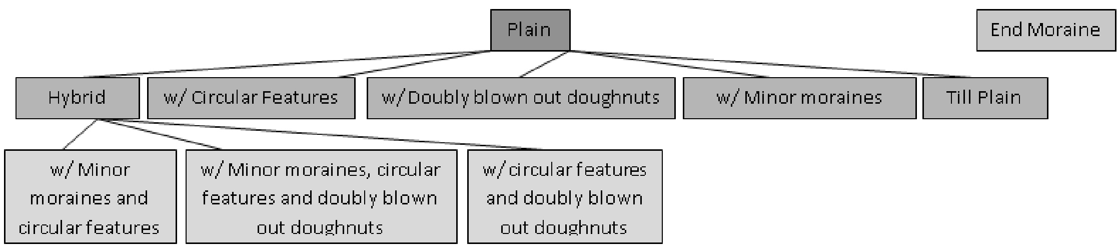

Figure 2.3: Classification scheme for the landform regions map.

End moraines are defined as either broad hummocky moraines or moraine ridges. Broad hummocky end moraines, such as the Altamont moraine (Fig. 2.4a), have approximate heights of 5 to 15 m, are 1 to 10 km wide, and are characterized by hummocky topography that may contain multiple ridges (Kemmis, 1991). In contrast, end moraine ridges have one distinct ridge form with a foreslope and a backslope and are generally 5-10 m high, with a width of ~1 km. (Fig. 2.4b, c).

Additional landforms identified, including minor moraines, ice-walled lake plains, and doubly blown-out doughnuts, occur in groups across broad plains. Minor moraines (Fig 2.4d, e), are composed of subglacial till with minor sand and gravel. Each moraine has a distinct ridge form with amplitude of 1-5 m and wavelength of ~100 m (Cline,

Table 2.1: Descriptions of the landform regions.

Landform Region	Description
End moraine	Distinct ridge form or topographically high broad swath of hummocky topography that may contain distinct ridges.
Plain with circular features	Broad area of low relief containing depressions and hills that are quasi-circular in map view. Some of the hill features are characterized by relatively flat surfaces indicative of ice-walled lake plains.
Plain with doubly blown out doughnuts	Broad area of low relief with pairs of short parallel ridges, approximately 100 m long, one to two meters high, and 30-50 m apart.
Plain with minor moraines	Broad area of low relief with minor moraine ridges. There may be more than one set of minor moraines with varying trends.
Hybrid Plain with minor moraines and circular features	Broad area of low relief with a combination of minor moraines and quasi-circular features.
Hybrid Plain with minor moraines, circular features and doubly blown out doughnuts	Broad area of low relief with a combination of minor moraines, circular features, and doubly blown-out doughnuts.
Hybrid Plain with circular features and doubly blown out doughnuts	Broad area of low relief with a combination of circular features and doubly blown out doughnuts.
Till Plain	Broad area of low relief with no distinct landforms.

2011). Ice-walled lake plains (Fig. 2.4f) are characterized by a quasi-circular, flat-topped hill composed of sorted sand. Doubly blown-out doughnuts are breached (commonly on opposite sides) circular ridges (Clayton & Freers, 1967), resulting in short (100 m or less), paired, parallel ridges with heights of 1-2 m and spacings between ridges of 20-50 m (Fig. 2.4g).

Channelized subglacial drainage of water resulted in two other less prevalent landforms: eskers and tunnel valleys. Eskers are sinuous ridges perpendicular to the ice margin composed of sorted sand and gravel (Fig 1.12). They likely represent locations where a subglacial tunnel carried water toward the margin and the tunnel filled with sediment. Alternatively, eskers could reflect supraglacial channels that contained sediment that was let down on the landscape during stagnation (Benn and Evans, 2010). Tunnel valleys (Fig. 1.10), also typically perpendicular to the margin, are valleys where water flowed at the glacier bed near the margin. Water likely did not fill the valley but occupied a smaller channel that migrated back and forth across the bed to form the valley (Cofaigh, 1996; Clayton et. al, 1999).

Eight landform regions are divided into two major types: moraines and plains. End moraines, as noted, are characterized either by broad belts of hummocky topography, such as the Altamont Moraine (Fig. 2.4a) (Kemmis, 1991), or by one distinct ridge form with a fore-slope and a back-slope (Fig. 2.4b, c). The plain regions are subdivided based on whether minor moraines, circular features such as ice-walled lake plains and kames, doubly

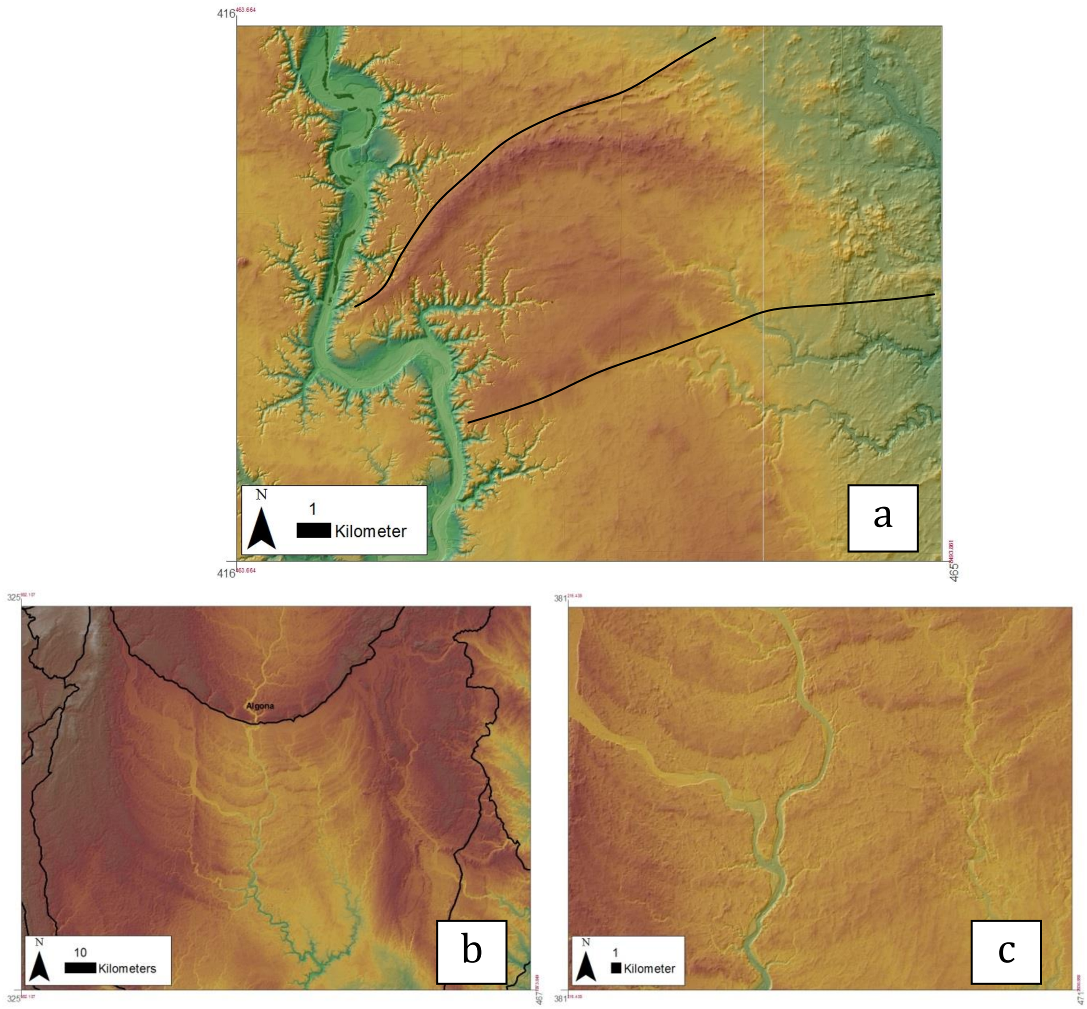

Figure 2.4: Examples of each of the eight landform regions. The Altamont moraine **a.**, a broad hummocky end moraine, delimited by black lines. The area shown is just north of Boone, Iowa, and east of Fraser, Iowa. Note the multiple ridges and undulating topography within the area of the broad ridge. **b.** End-moraine ridges south of the Algona moraine. **c.** A closer view of the same end moraines south of the Algona moraine and east of Humboldt, Iowa. Plains with minor moraines, **d.** trending north-east between Ames, Iowa and Nevada, Iowa, and **e.** with multiple sets southeast of Gilmore City, Iowa. **f.** Plain with circular features, ice walled lake plains, west of Dolliver, Iowa. **g.** Plain with doubly blown-out doughnuts east of Forest City, Iowa. Note the short ridge pairs in the central portion of the map. **h.** Plain with circular features and minor moraines east of Dolliver, Iowa. **i.** Plain with circular features, minor moraines, and doubly blown-out doughnuts south of Clear Lake, Iowa. **j.** Plain with circular features and doubly blown-out doughnuts west of Joice, Iowa. **k.** Till plain south of the Algona moraine near Algona, Iowa.

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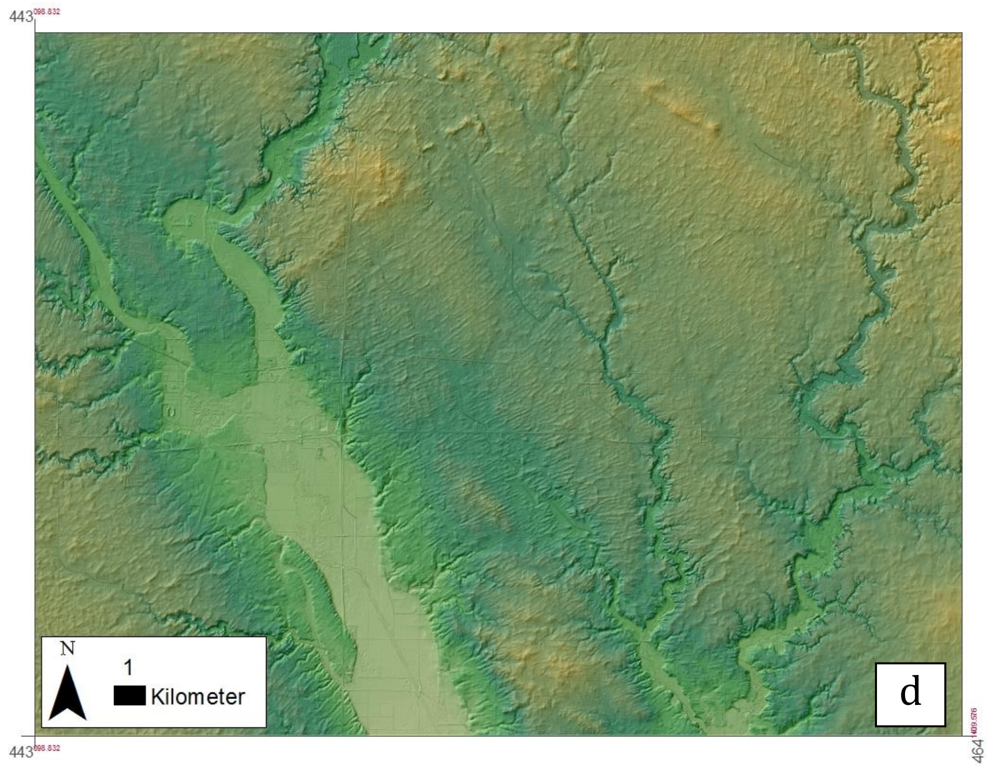

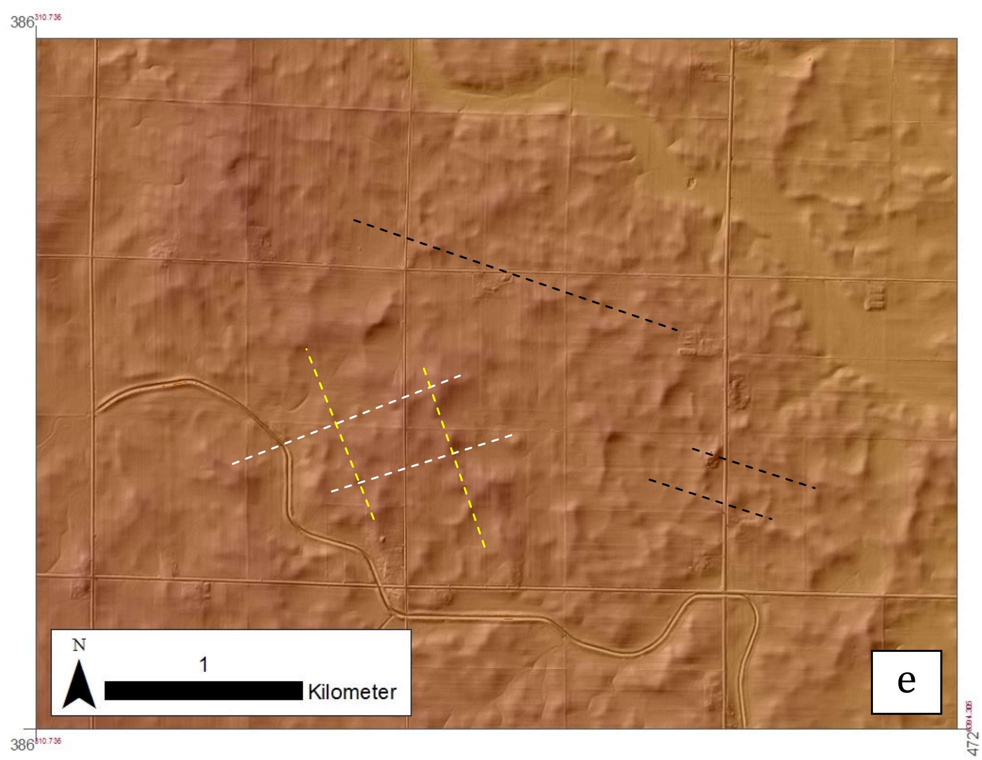

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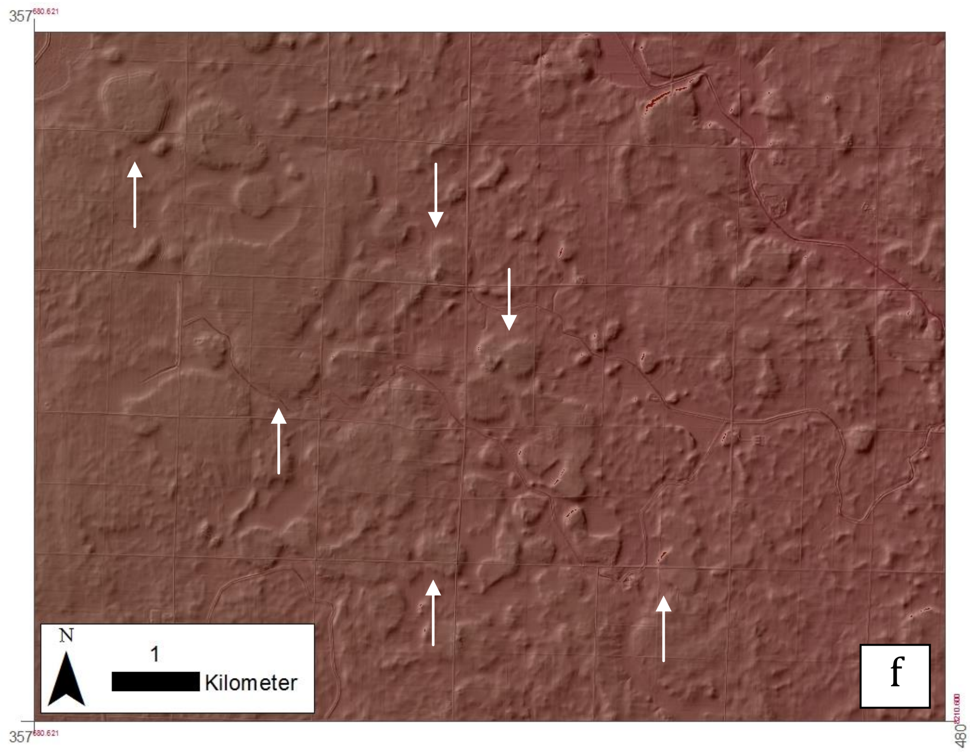

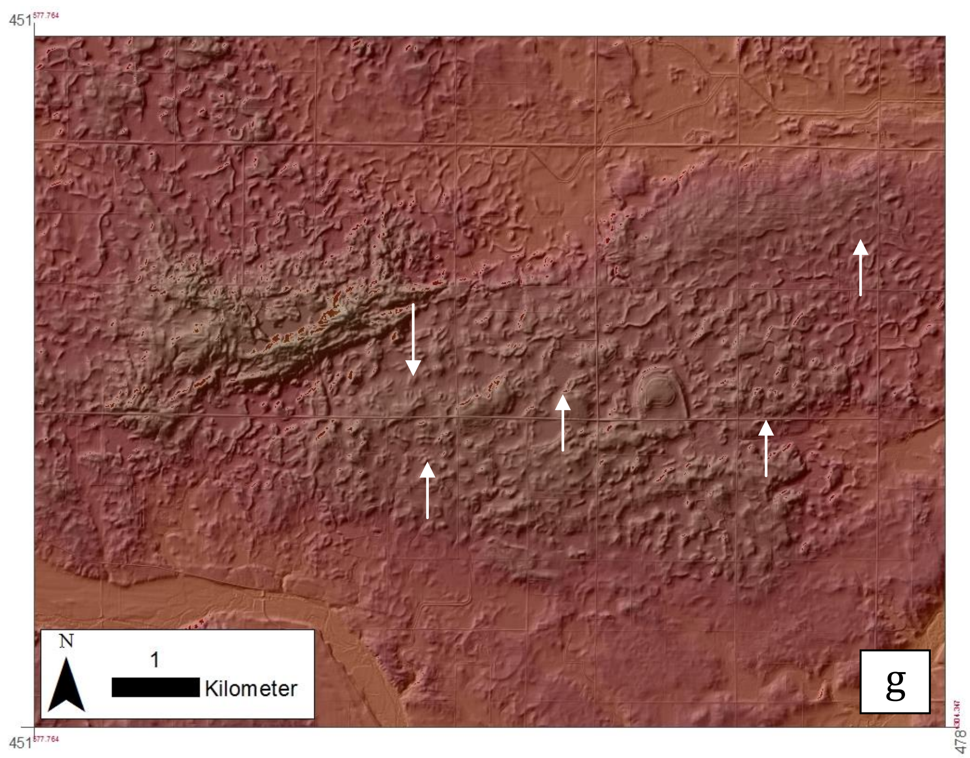

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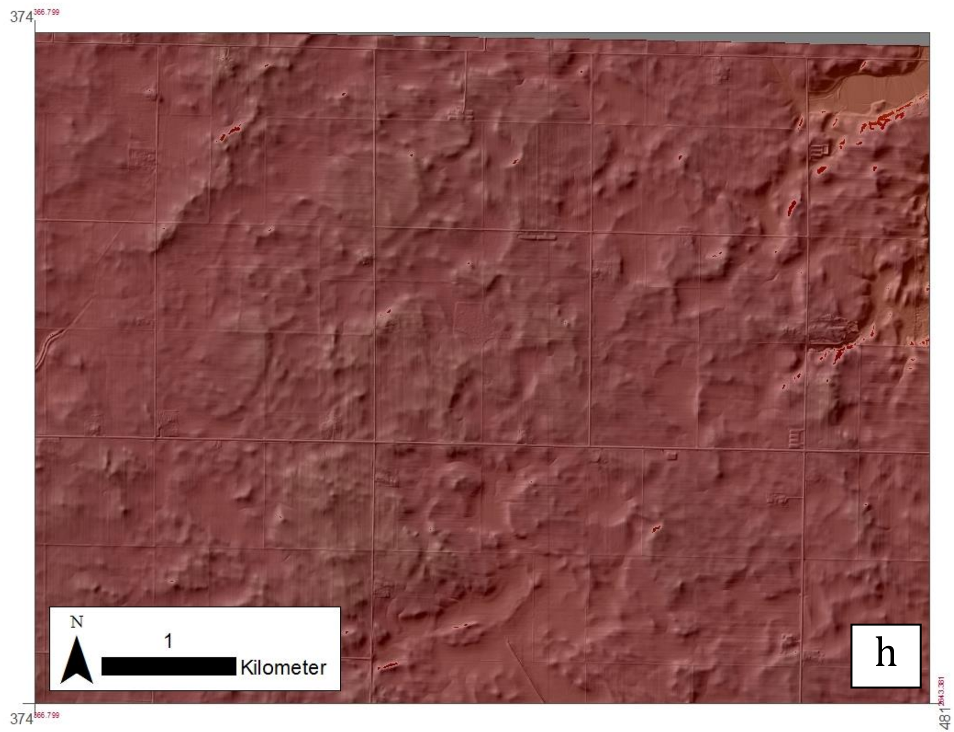

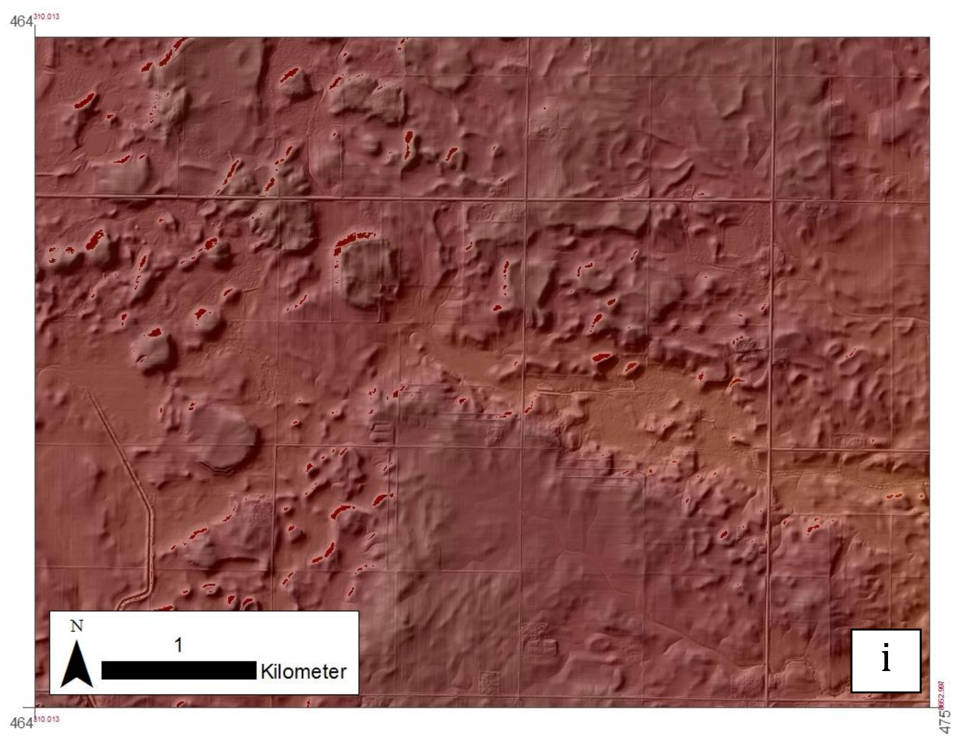

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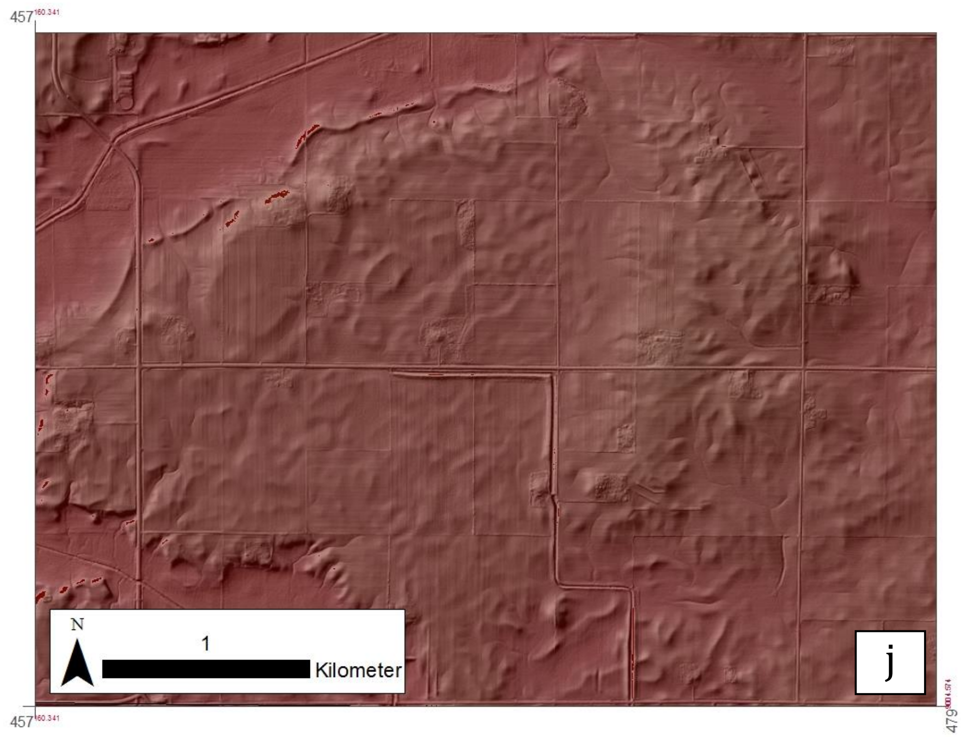
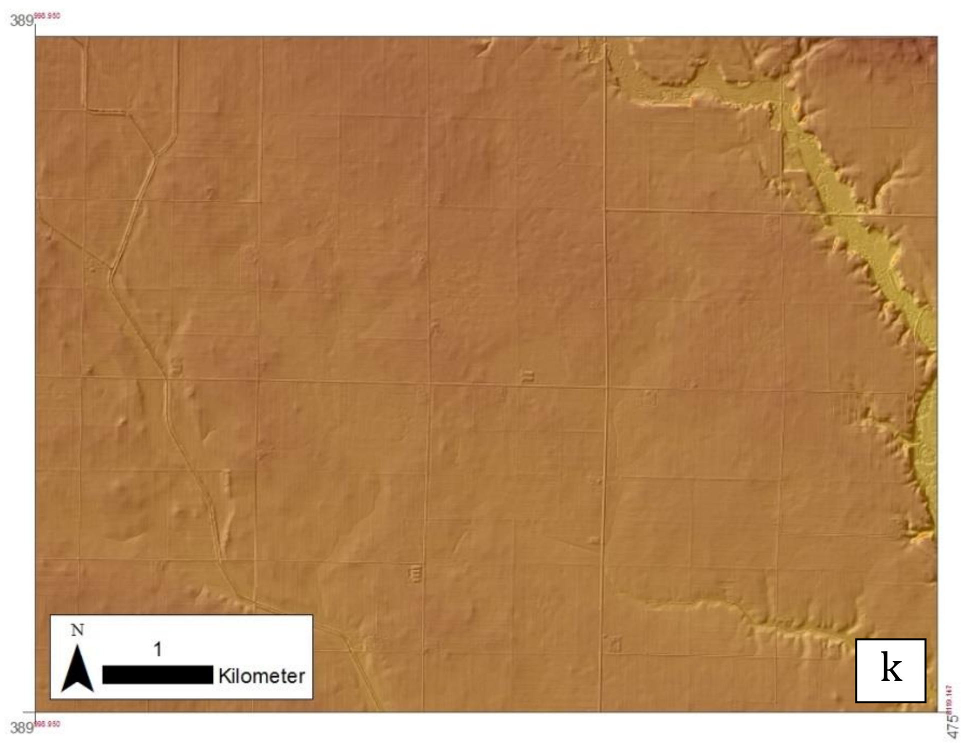




blown-out doughnuts, or a combination of these are present. Hybrid plains are defined as a plain with a combination of landforms. There are three sub-categories of hybrid plains: those with circular features and minor moraines, with circular features and doubly blown out doughnuts, and one with all three landform types. Additionally, there are small plains where there is no evidence of any specific landforms; inferring they consist of basal till, they are called till plains, (Fig. 2.3, Table 2.1). Examples of each of the eight landform regions are shown in Fig. 2.4 a-k.

D. Testing retreat hypothesis

One purpose of the maps was to examine the relationship between minor moraines and end moraines to try to test different retreat hypotheses for the Des Moines Lobe. As noted in Chapter 1, the leading hypothesis is that the lobe surged three times out of balance with a warming climate, then stagnated and down-wasted to form the three major end moraines. Alternatively, the lobe could have receded as a result of incremental back-wasting of the margin, unrelated to surging, leaving recessional end moraines. Diverse evidence indicates that minor moraines form as subglacial crevasse fills (Stewart et al., 1988; Ankerstjerne, 2010; Cline, 2011). During a surge the glacier undergoes longitudinal extension, resulting in the development of rather uniformly spaced transverse basal crevasses. Subglacial till then deforms into basal crevasses during stagnation leaving minor moraines (Stewart et al., 1988; Ankerstjerne, 2010; Cline, 2011) with amplitudes that degrade with subsequent hill-slope processes (Burras & Scholtes, 1987). Over much of the lobe's area there are locations where there are two or more orientations of minor moraines. If the leading hypothesis is true, such that end moraines formed by surging, then minor moraine orientations up-glacier from each end moraine should parallel the down-glacier end moraine. In contrast, if an end moraine has no parallel minor moraine orientations, it could reflect active glacier recession.

In order to study minor moraine orientations, flow paths were defined based on the reconstruction of the lobe at its maximum extent by Hooyer and Iverson (2002). Using MATLAB scripts to automate the process, positions were picked every 5 km along 19 flow paths north from the Bemis moraine margin to the Minnesota border. A box, 5 km^2, was drawn around each position, and the orientation for every minor moraine within the sample area was measured. The orientation of each measured moraine was then calculated and sorted into five degree bins for a rose diagram. Of the 19 flow paths used, 573 rose diagrams were produced. These diagrams were then used to illustrate the orientations of the minor moraines at each position.

One to three dominant minor moraine orientations at each location were compared with the orientations of the nearest down glacier end moraine. Angular differences between minor moraines that are most parallel and least parallel to the orientations of the nearest down-glacier end moraine were measured. Averages and standard deviations of these angular differences were calculated by considering only the sampled area immediately up-glacier from the moraine along multiple flow paths and by also considering all sampled areas between the end moraine immediately down-glacier and the next end moraine up-glacier. This process helped illuminate whether end moraines had associated (parallel or sub-parallel) minor moraine sets—the criterion used in this thesis for a surge-type end moraine.

CHAPTER 3: RESULTS

A. Mapping

Quaternary landform mapping of the Des Moines Lobe footprint in Iowa resulted in a map of major landforms (Fig. 3.1a) and second map of landform groups (Fig. 3.1b), each covering approximately 30,000 square kilometers. Previous Quaternary maps of the area included broad areas of hummocky topography, also known as stagnation moraine (Hallberg et al., 1991), including the three major end moraines of the lobe: the Bemis, Altamont, and Algona (Fig. 1.2). These maps also include moraine complexes where these moraines merge, intervening areas of low-relief "ground moraine," and three small end moraines (the Clare, Renwick, and West Bend). The new maps of this thesis provide a more detailed picture of the Des Moines landscape.

The new Quaternary landform map (Fig. 3.1a) expands upon Kemmis' work (1991) on the northernmost third of the lobe's extent in Iowa (Fig. 1.8), with a greater diversity of landforms identified in intra-moraine areas previously identified as stagnation or ground moraine (Hallberg et al., 1991). Landforms that are more prevalent than previously mapped include minor moraines (Stewart et al., 1988), ice-walled lake plains (Clayton et al., 2008), and eskers (Shreve, 1985). Doubly blown-out doughnuts (Clayton & Freers, 1967), previously unmapped for the Des Moines Lobe, were identified. In addition to stagnation landforms, approximately 25 previously unmapped end moraines were mapped.

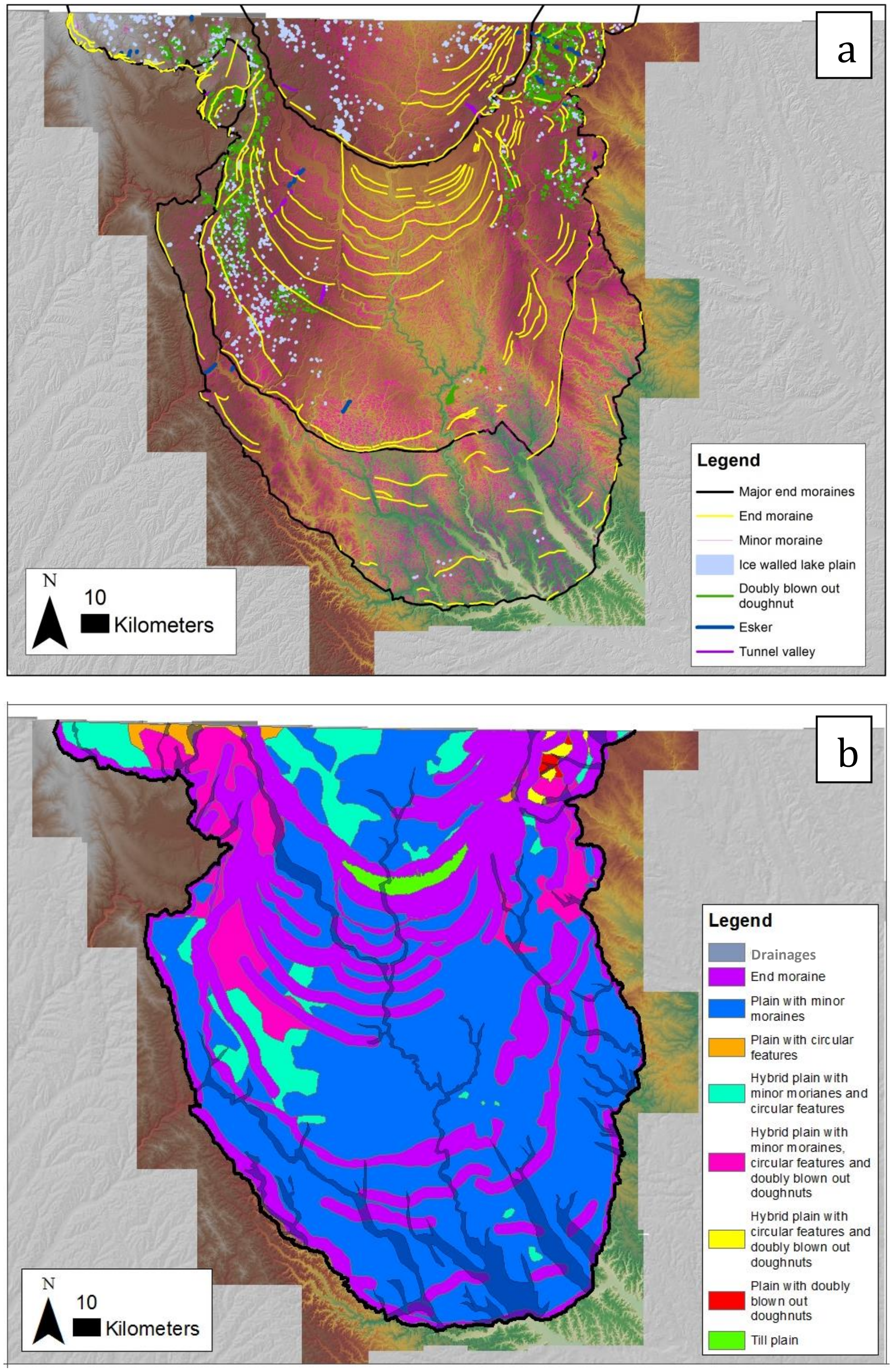


Figure 3.1: a. Quaternary landform map of the Des Moines Lobe landscape in Iowa with individual landforms overlaying 1 m resolution DEMs derived from LiDAR data and with a hill-shaded relief map. **b.** Landform regions map, with stream drainages superimposed on landform regions. Full size copies of these maps are located in the supplementary information.

The new landform regions map (Fig. 3.1b) indicates that 90% of the lobe's Iowa extent, without considering modern drainage systems, is characterized by stagnation landforms. The most important of these landforms are minor moraines, found across plains of minor moraines and hybrid plains, which comprise 60% of the area covered by stagnation features. The rest of the area covered by stagnation features includes hummocky topography (31%) common in the three major end moraine areas, ice-walled lake plains (6%), and doubly blown-out doughnuts (3%).

Minor moraines

One-meter LiDAR-based DEMs allowed both well-developed (Fig. 3.2a) and more subtle (Fig. 3.2b, c) minor moraines to be identified across the lobe (Fig. 3.2). Although

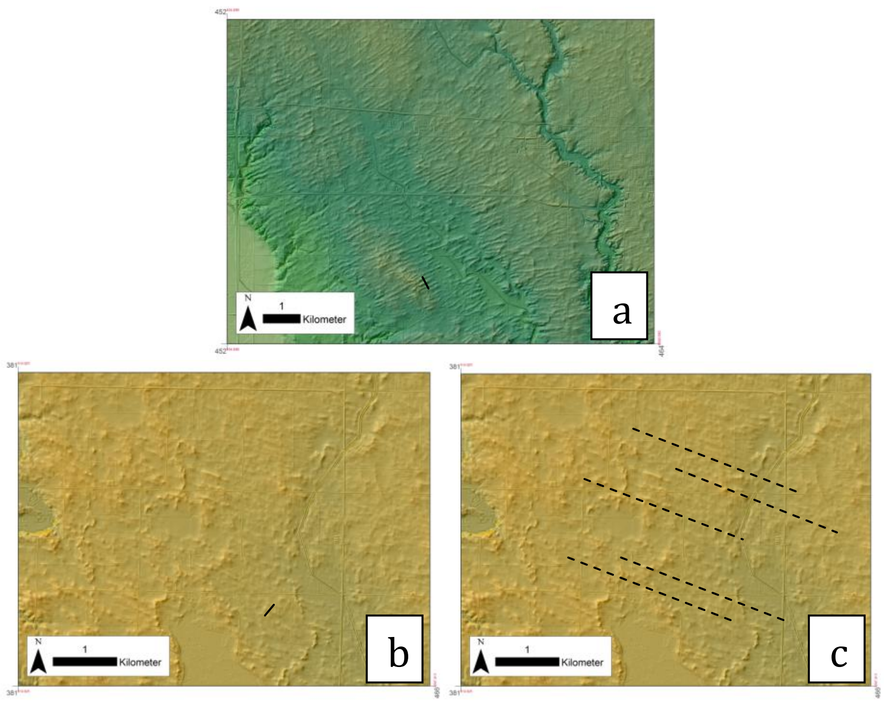


Figure 3.2: 1 m DEMs of **a.** Well-developed minor moraines, trending southwest, immediately east of Ames, Iowa. **b.** More subtle minor moraines, with less lateral continuity east of Churdan, Iowa. **c.** The minor moraines of b. with their trends outlined.

some minor moraines were difficult to identify due to limited continuity of their crests, any ridge set that could be traced as parallel or sub-parallel discontinuous lineaments were mapped as minor moraines. Minor moraines are generally 1-5 m in amplitude with a wavelength of approximately 100 m (Fig. 3.3). For the well-defined minor moraines of

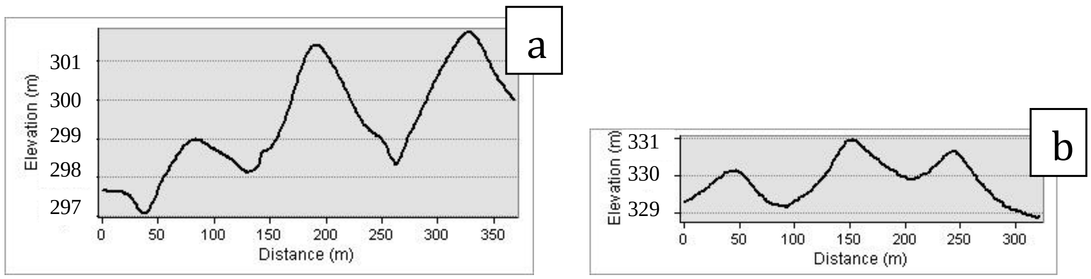


Figure 3.3: Topographic profile from **a.** Fig 3.2a and **b.** Fig. 3.2b marked by solid black line.

Story County, Iowa—the focus of Cline's (2011) study of minor moraine spatial attributes—Fourier analysis yielded a dominant ridge crest spacing of 110 m, with a lard deviation of 45.4 m. Well-defined minor moraines tend to be focused near the three major end moraines and tend to become more subtle and discontinuous farther from them. Also, away from the three major end moraines, minor moraines occasionally are well-developed, like those between the Renwick and West Bend moraines (Fig. 3.2a). Minor moraines are absent between the Algona and West Bend end moraines, as well in parts of the Bemis-Altamont moraine complex (Ruhe, 1952; Quade et al., 2005; Cline, 2011).

Across much of the lobe, minor moraines occur in two to three different sets, each with a distinct orientation (Fig. 3.4). The number of minor moraine sets varies throughout the lobe. Near the Bemis moraine there is generally only one set of minor moraines. Farther up-glacier there tends to be two to three sets. Not uncommonly, the number of minor moraine sets is different immediately up-glacier or down-glacier from an end moraine.

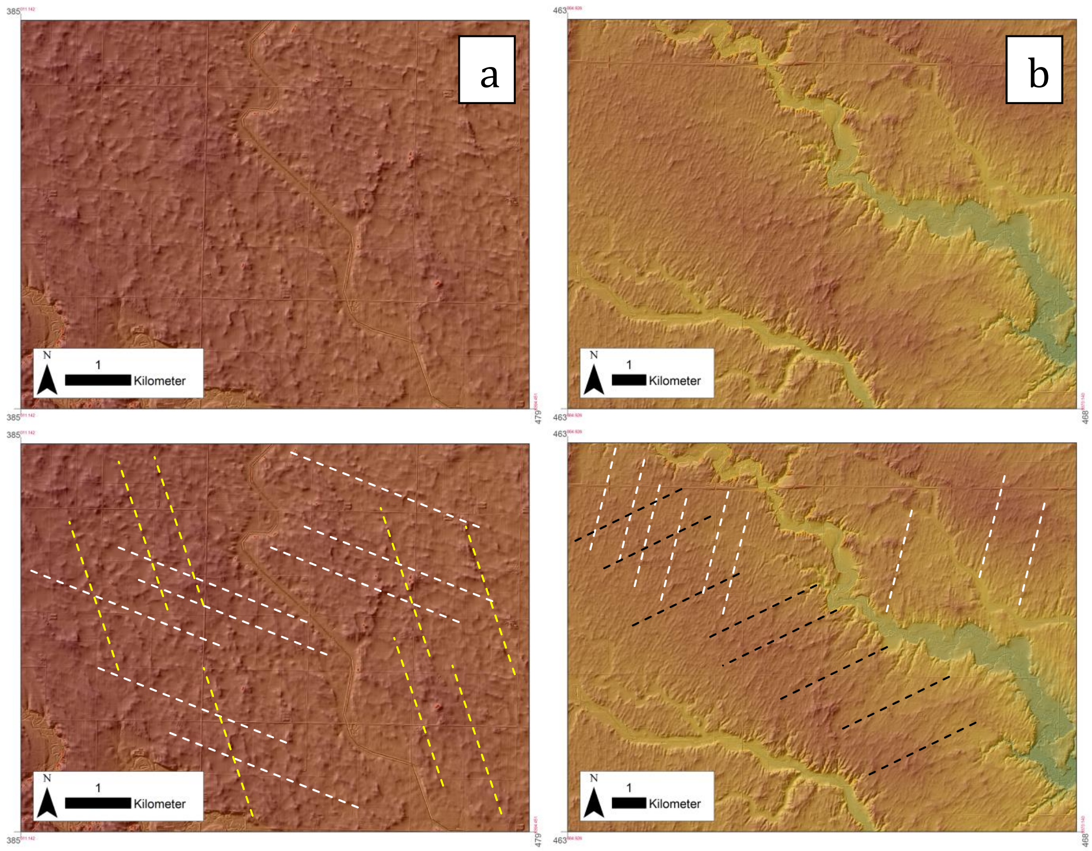


Figure 3.4: Area containing two minor sets. **a.** Map of area southwest of Swea City, Iowa, and north of the Algona moraine, with moraine trends outlined in the lower image, and **b.** of the area surrounding Buckeye, Iowa, southeast of the Altamont moraine.

In some areas of the lobe, minor moraines are associated with other stagnation features such as ice-walled lake plains and doubly blown-out doughnuts. Minor moraines occur together with these landforms most commonly near the three major end moraines. Minor moraines can be superimposed on ice-walled lake plains (Fig. 3.5). In

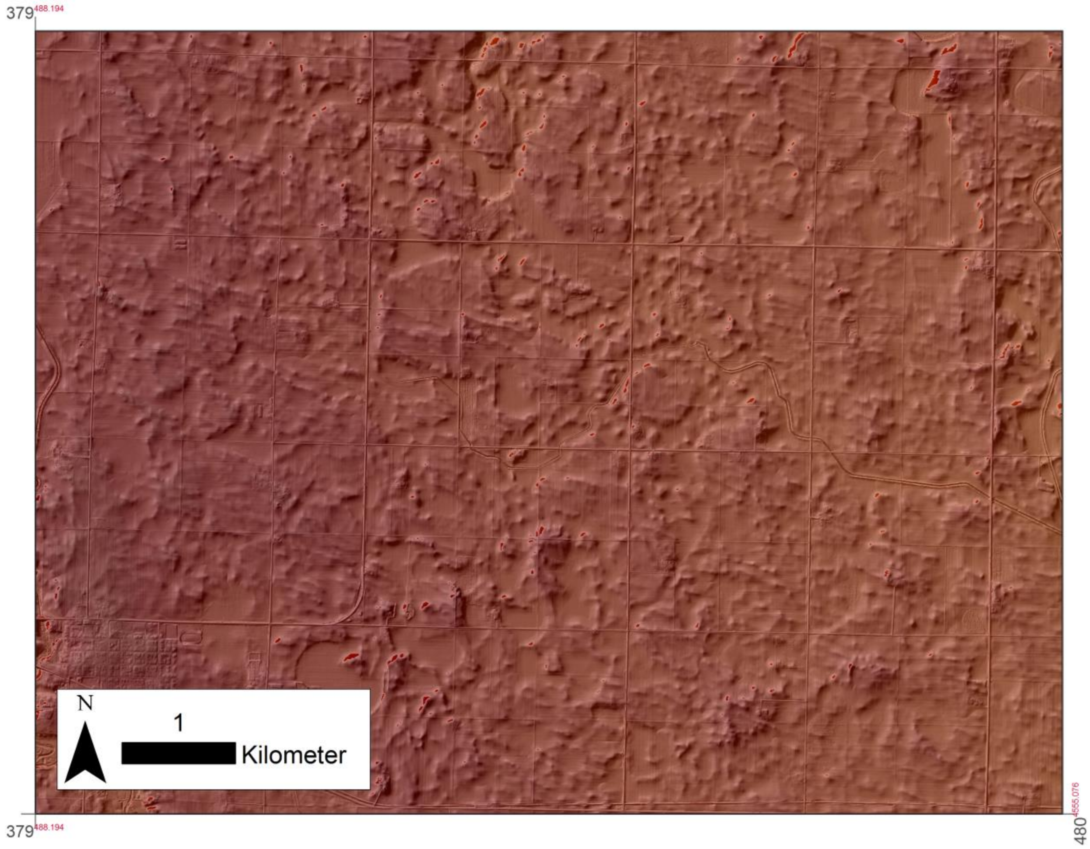
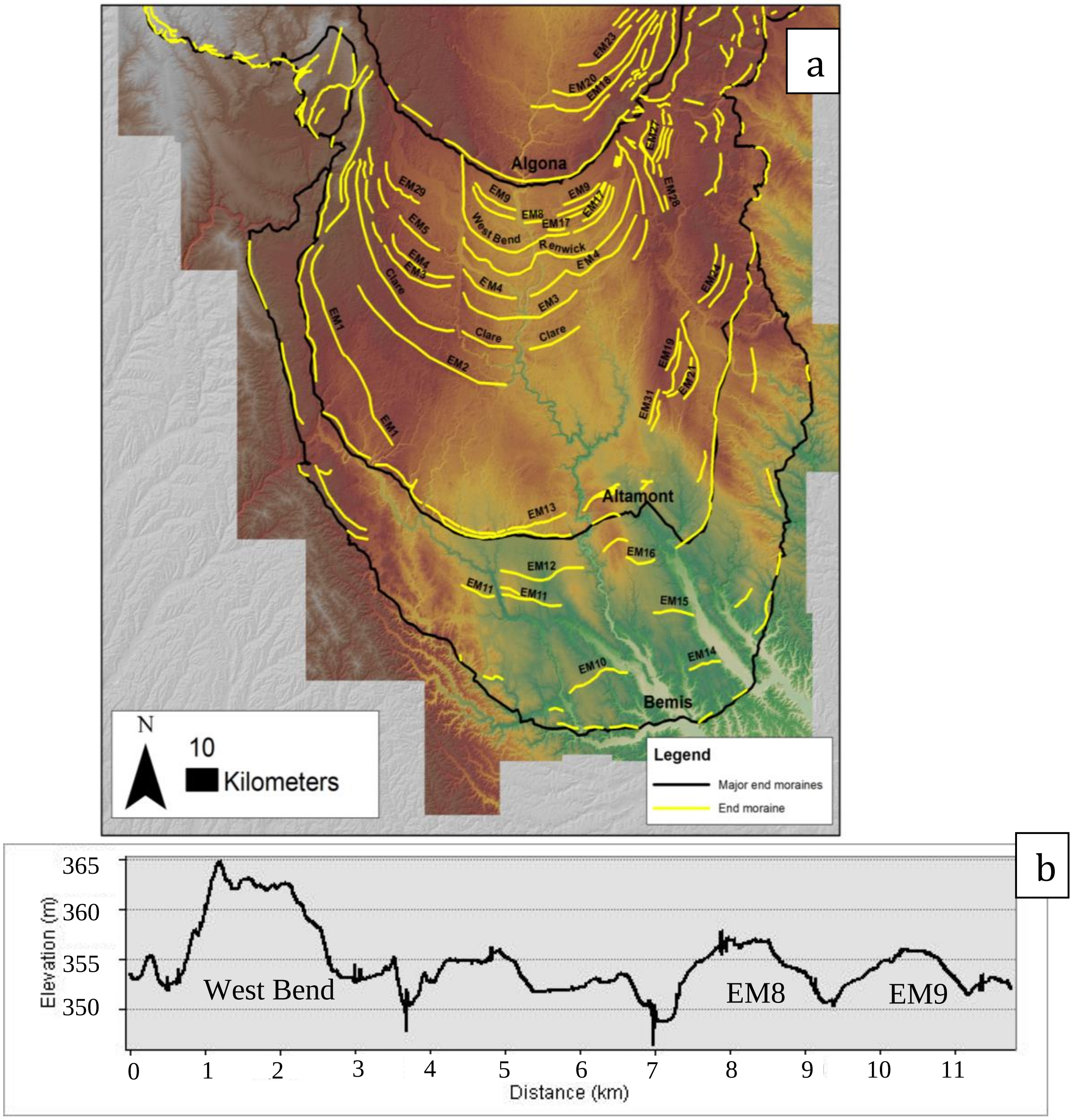


Figure 3.5: Minor moraines superimposed on ice-walled lake plains north of Ringsted, Iowa.

this case, the moraines are discontinuous in the areas between the ice-walled lake plains but can be traced across their flat interior surfaces. On these surfaces, minor moraines tend to have one dominant orientation, but in other regions of the lobe, as noted, multiple sets of minor moraines with different orientations are commonly present.

End moraines

Approximately 25 previously unmapped end moraine ridges were identified that are not apparent in lower resolution imagery, in addition to the broad belts of hummocky



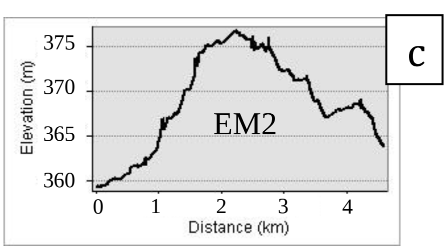


Figure 3.6: a. Map of the end moraines identified within the Des Moines Lobe. **b.** Topographic profile of West Bend moraine and of newly mapped end moraines EM8 and EM9. **c.** Topographic profile of EM2.

topography that constitute the Bemis, Altamont, Algona, and West Bend moraines and the narrow ridges with more distinct crests that constitute the Renwick and Clare moraines. The newly mapped ridges are lobate, with wavelengths of approximately 1-3 km and amplitudes of approximately 5-10 m (Fig 2.4 & Fig. 3.6).

Additional stagnation features

Doubly blown-out doughnuts (Clayton & Freers, 1967) are a landform that has not been identified in previous mapping efforts in Iowa (Fig. 3.7). These landforms are typically expressed as pairs of short parallel ridges that occur in groups with multiple orientations (Fig. 3.7a), unsystematically related to the glacier flow direction. Most ridges are 100 m or less in length, with heights of 1-2 m. The ridges of a given pair are spaced 20-50 m apart. These features are most common in the Bemis-Altamont moraine complex in the northern half of the map area (Fig. 3.7b).

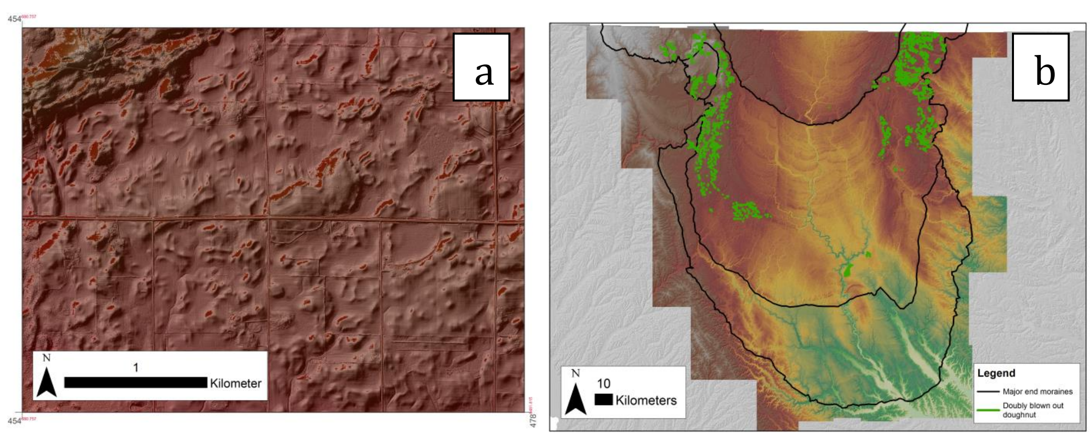


Figure 3.7: a. Doubly-breached doughnuts near Pilot Knob State Park east of Forest City, Iowa. **b.** Areal extent of doubly-breached doughnuts (green). Black lines show the distal extent of the three major end moraines.

Similar to minor moraines and end-moraine ridges, the extent and number of ice-walled lake plains are greater than previously mapped. They are more subtle than those described for more northerly lobes of the Laurentide ice sheet (Clayton et al., 2008), with heights of approximately 1-5 m and irregularly shaped areas of approximately 750 m^2 to 2.5 km^2. They occur most commonly in clusters in the northern portion of the map area and near the three major end moraines (Fig. 3.8). In addition to commonly being associated with minor moraines, ice-walled lake plains can be spatially associated with doubly blown-out doughnuts.

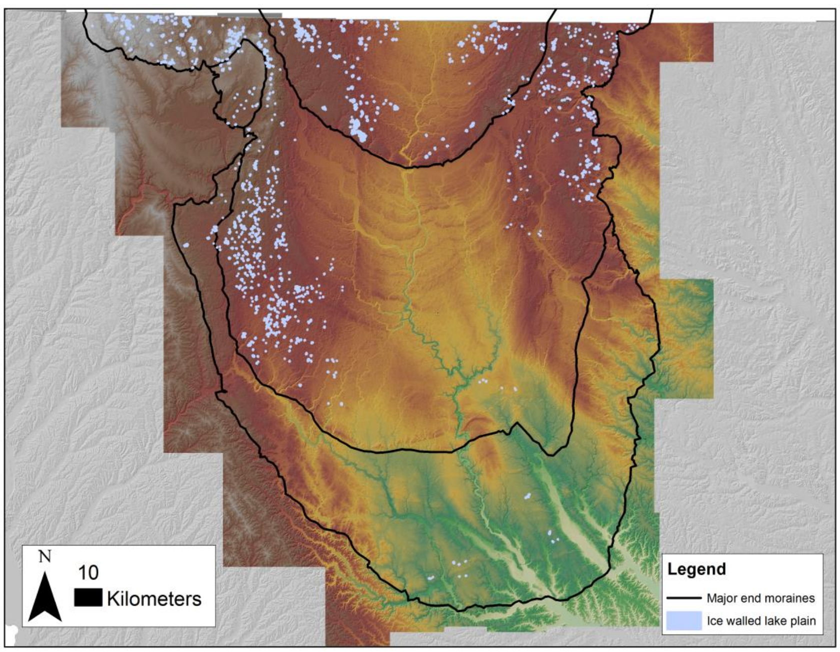


Figure 3.8: Map of areal extent of ice walled lake plains within the Des Moines Lobe footprint (blue). Black lines show the distal extent of the three major end moraines.

Eskers and tunnel valleys

Eskers and tunnel valleys have been extensively mapped in the northern portion of the Des Moines Lobe (Kemmis, 1991; Patterson, 1997). Four additional eskers and five tunnel valleys were identified and mapped in this study, largely on the basis of their morphology (Fig. 3.9). Eskers are conspicuously sinuous ridges that are generally perpendicular to the margin. Those mapped tend to have lengths of 1-20 km and heights of 0.5-5 m. Tunnel valleys (e.g., Benn & Evens, 2010), relatively linear channel segments of length 1-8 km that are inset into the till upland 2-15 m, are also generally perpendicular to the margin and either lack a modern stream drainage or contain an elongate lake (Fig. 1.10). The eskers and tunnel valleys are located most commonly within the Bemis-Altamont moraine complex and the three major end moraines (Fig. 3.9). A few of the newly mapped eskers and tunnel valleys are adjacent and

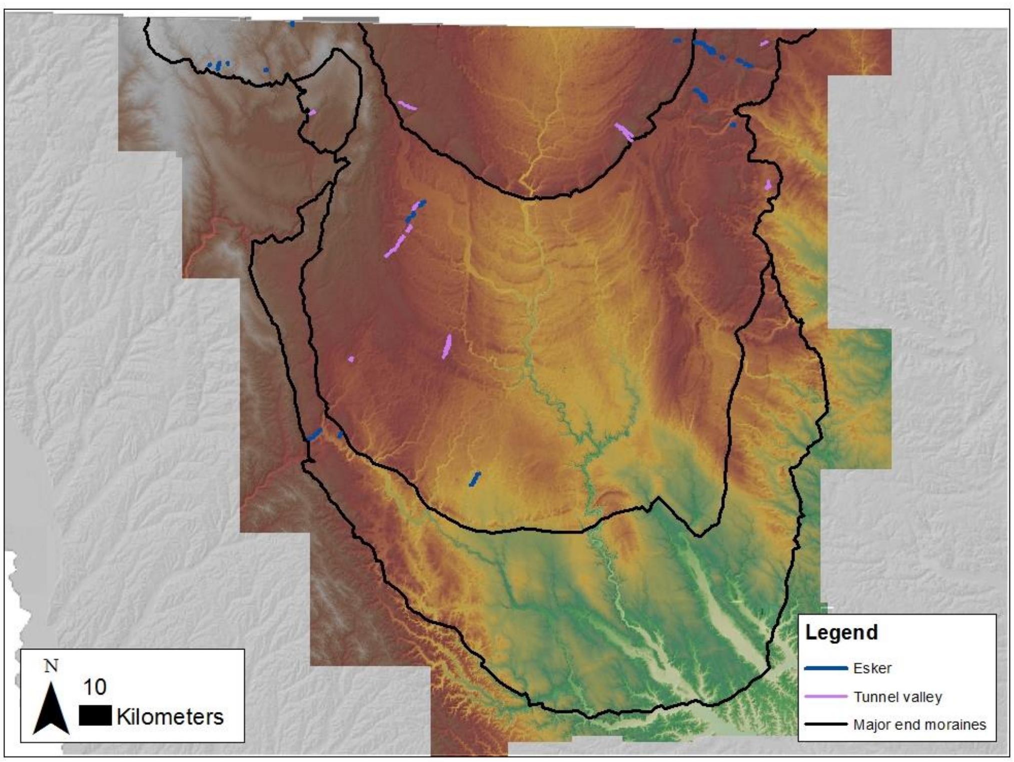


Figure 3.9: Eskers, including four newly identified, and tunnel valleys. Note only tunnel valleys without modern drainages have been included, due to the uncertainty of identifying tunnel valleys that contain a modern drainage.

perpendicular to some of the newly mapped end moraines between the Altamont and Algona moraines. Previously mapped eskers occur only in the northern portion of the map area, near the Iowa-Minnesota border. No tunnel valleys have previously been mapped south of the area mapped by Kemmis in 1991 (Fig. 1.10c).

B. Relationship of minor moraines to end moraines

Minor moraines commonly trend parallel to the nearest down-glacier end moraine. Where there are multiple sets of minor moraines with varying orientations, at least one set commonly lies parallel to the end moraine immediately down-glacier (Fig. 3.10a). In

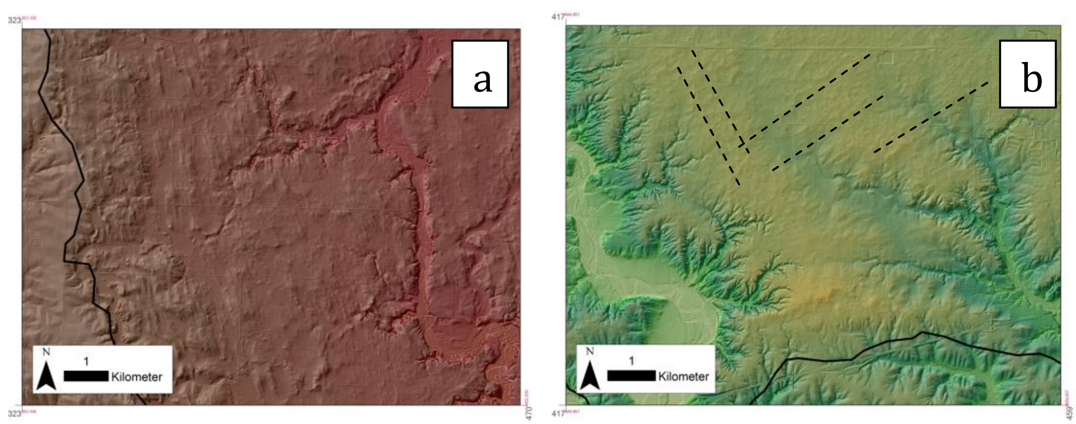


Figure 3.10: Minor moraines near the Bemis moraine. The black line is the distal edge of the moraine. **a.** Minor moraines parallel to the Bemis moraine on the western margin of the map area near Nemaha, Iowa. The glacier flow direction was to the west. **b.** Minor moraine sets, with trends marked by dashed black lines, at an oblique angle to the Bemis moraine west of West Des Moines, Iowa.

some places, however, there are no sets of minor moraines related to the down-glacier end moraine (Fig. 3.10b). Additionally, end moraines sometimes truncate minor moraines immediately down-glacier from them, with a large angle between the minor moraine and end moraine orientations (Fig. 3.11).

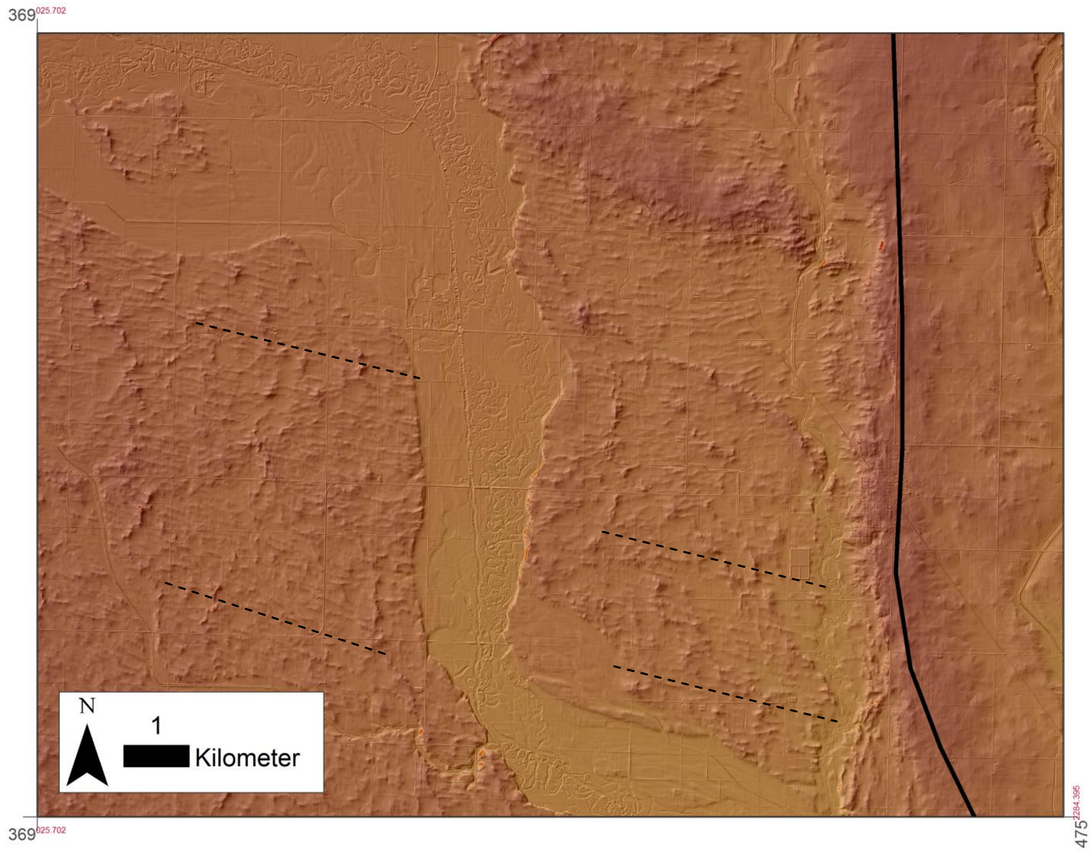


Figure 3.11: Minor moraines, with trends marked by dashed black lines, truncated by the western edge of the West Bend moraine (black line) west of West Bend, Iowa. The eastern side of the moraine is its up-glacier side.

Along flow paths based on the most recent reconstruction of the Des Moines Lobe (Hooyer & Iverson, 2002), rose diagrams indicating moraine-set orientations illustrate the overall tendency for multiple moraine sets, sometimes at high angles to one another (up to 80°) (Fig. 3.12). Near the Bemis margin there is only one set of minor moraines that is parallel to the margin, albeit with one notable exception (Fig. 3.10).

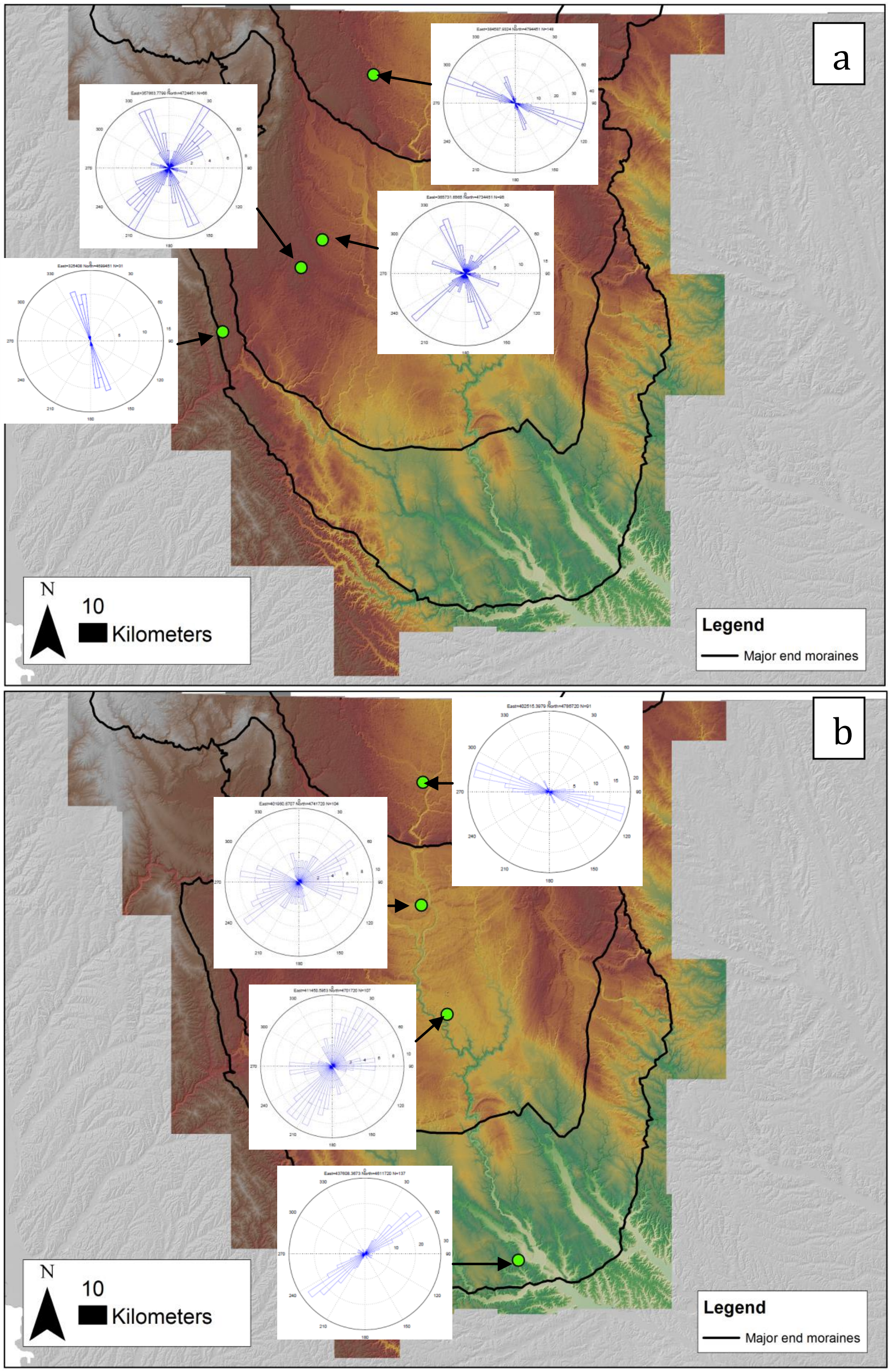


Figure 3.12: Rose diagrams from four positions along a **a.** western, **b.** central, and **c.** eastern flow path, depicting the variability of minor moraine orientations.

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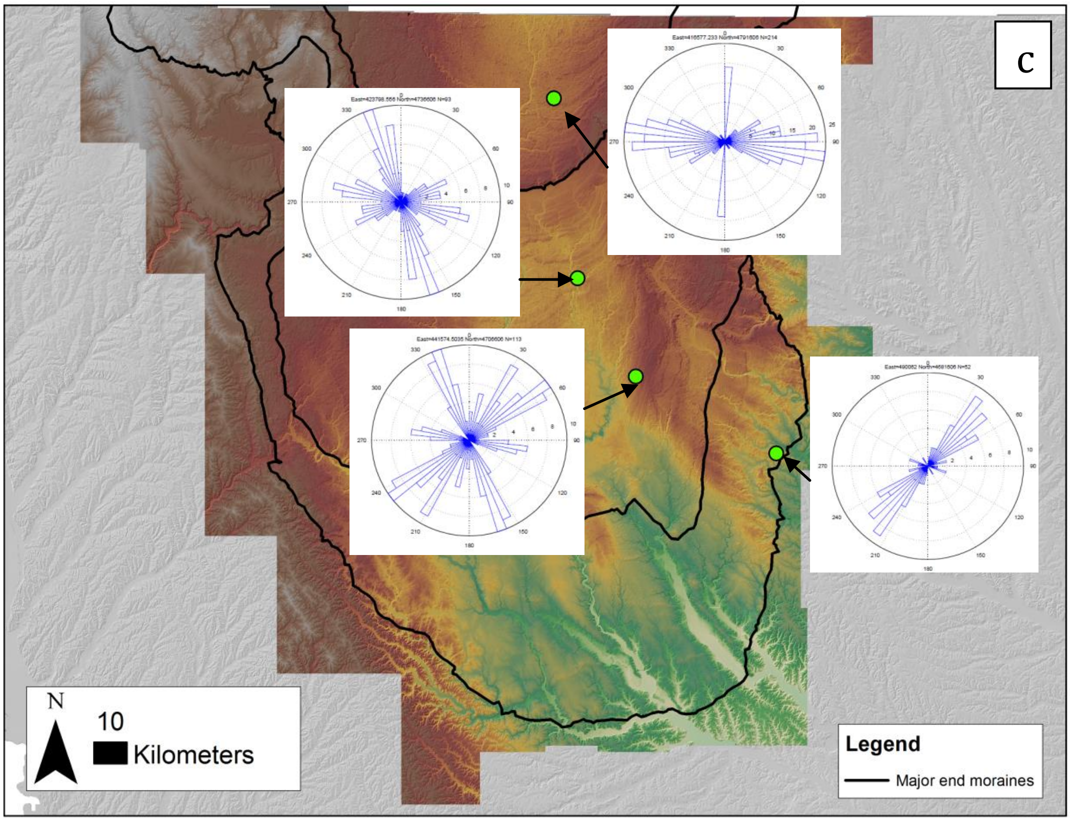


Flow paths based on the Hooyer and Iverson (2002) reconstruction (Fig. 3.13) were used to compare the angular differences between minor moraine orientations and end moraines immediately down-glacier. End moraines that were considered include both the three major end moraines and more minor end moraine ridges, many of which are identified for the first time herein. As noted in Chapter 2, the goal was to explore whether end moraines generally represent surge-type advances. These advances should have an associated minor moraine set that reflects filling of transverse crevasses formed during surge-related longitudinal extension. Alternatively, some end moraines may be recessional, without associated minor moraine sets.

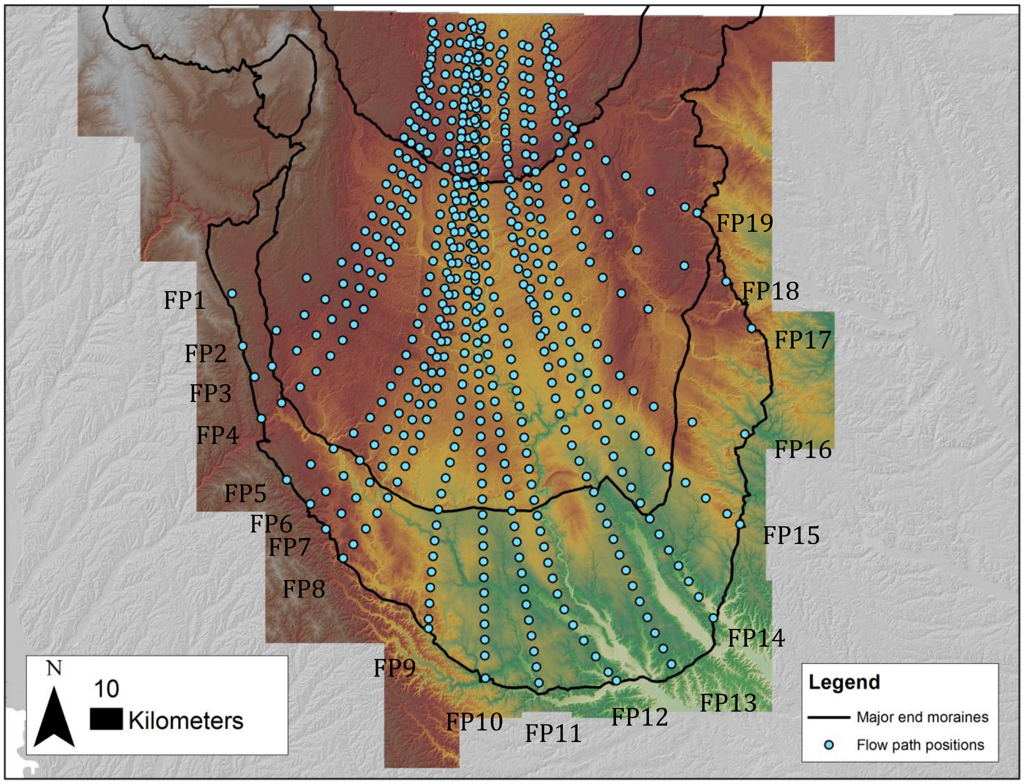


Figure 3.13: 19 flow paths across the Des Moines Lobe in Iowa along which orientations of minor moraines were determined. Blue dots indicate the center point of each sample area along the flow path.

The angular difference between the orientations of the nearest down-glacier end moraine and the sets of minor moraines was calculated at positions along each flow path (Fig. 3.14). Where there are multiple minor moraine sets, the angular differences between the minor moraine sets both most parallel (mode min) and least parallel (mode max) to the end moraine immediately down-glacier were calculated and plotted against the distance along the flow path, with end moraine positions noted and the Des Moines Lobe terminus at 0 km. Positions without data points do not have minor moraines or have only one set of them; in that case the angular difference was considered a minimum angle (mode min).

In general, the three major end moraines have a set of minor moraines immediately up-glacier that is approximately parallel, 0-15^{o}, to the end moraine. 15^{o} is chosen as a threshold herein, based on the typical variability of orientations within a minor moraine set and the curvature of flow paths, both of which tend to increase angular differences. For the Bemis moraine, nine of the 17 positions where there is a minor moraine up-glacier with no intervening end moraine have a minor moraine set approximately parallel to the Bemis moraine. At 11 of 16 such positions and 15 of 19 such positions for the Altamont and Algona moraines, respectively, a minor moraine set parallels them immediately up-glacier. In general, each end moraine within the Des Moines Lobe had one set of minor moraine orientations approximately parallel to it along some of the flow paths considered. In a few instances, however, there were no minor moraine sets along any flow path that were parallel to the nearest down glacier end moraine (e.g., EM17, see Fig. 3.14).

Data in Figure 3.14 are summarized in Table 3.1, in which the minimum (mode min) and maximum angles (mode max) between minor moraine sets and end moraines directly down-glacier are tabulated and averaged among the flow paths for each end moraine. Averages for the minimum angles illustrate that, when multiple flow paths are available for an end moraine, angular differences larger than 15° are relatively rare and have large standard deviations. Averages for maximum angles illustrate that every end moraine has at least one minor moraine set at a high angle to it (27-89°). The histograms of Figure 3.15 summarize the averages of Table 3.1.

A second way to summarize these data is to consider, not only the orientation of the minor moraine immediately up-glacier from an end moraine, but to consider the orientations of all minor moraine sets between the end moraine under consideration and the next end moraine up-glacier. Computing an average that includes all such minor moraines along all flow paths yields the average angular differences and standard deviations of Table 3.2. Although average minimum angular differences tend to be slightly larger than those of Table 3.1, angular differences from end moraines that include data from many flow paths tend to be below or at least near 15°. Larger values, particularly for the Bemis and Altamont moraines (22° and 23°), may reflect the curvature of flow paths and resultant non-parallelism that should increase with increasing distance up-glacier from the end moraines.

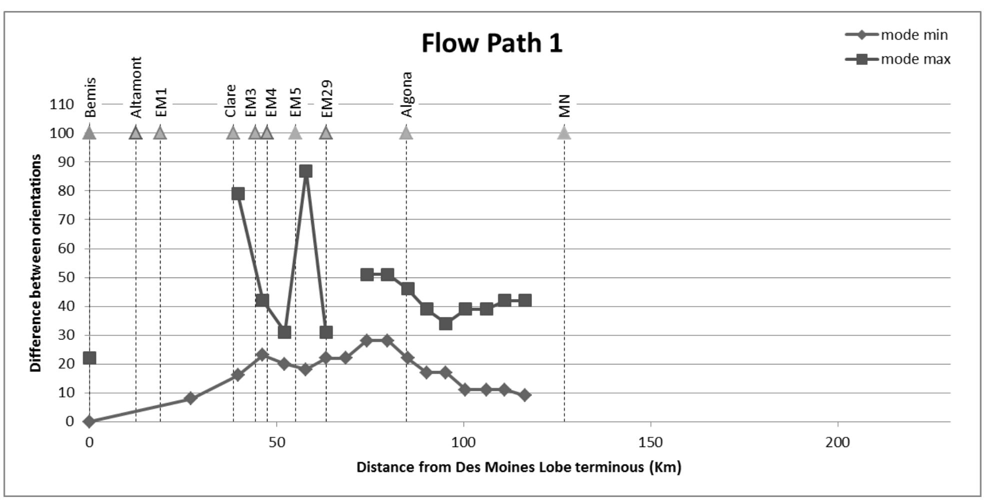
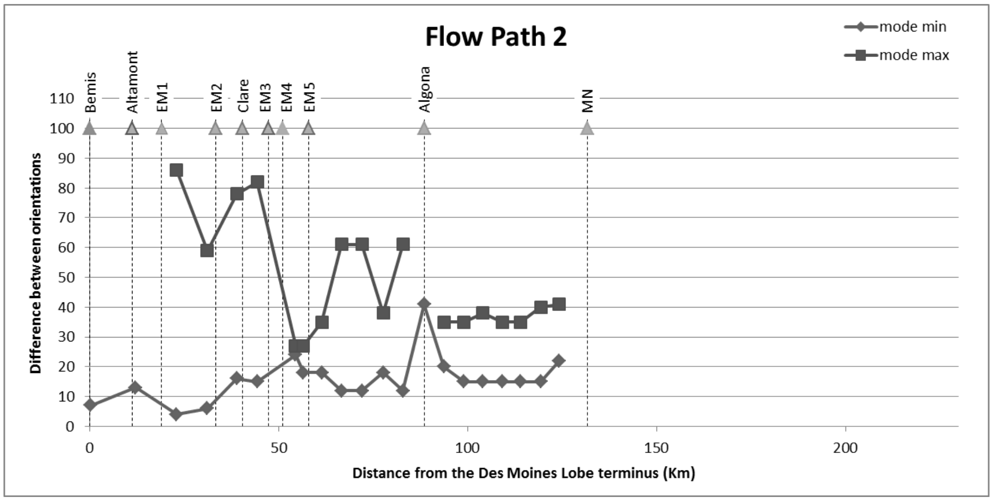
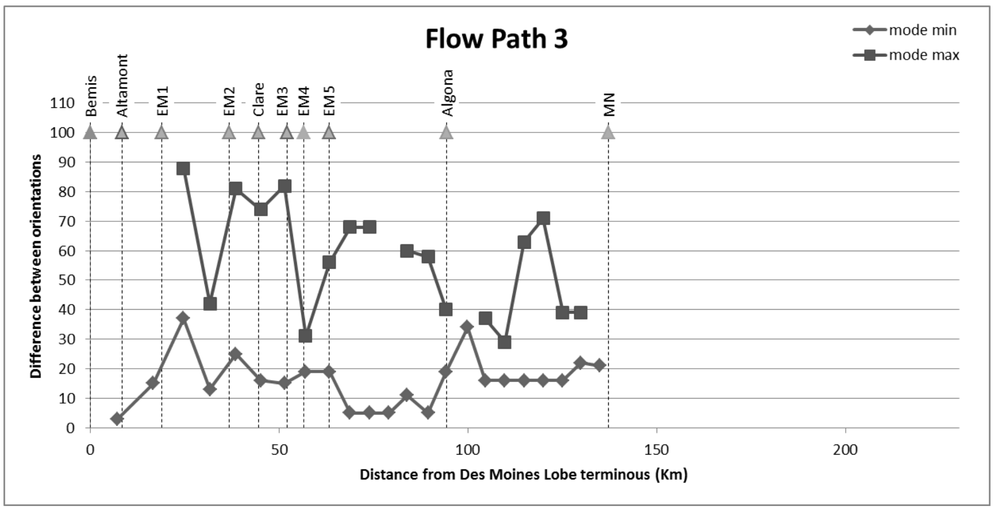
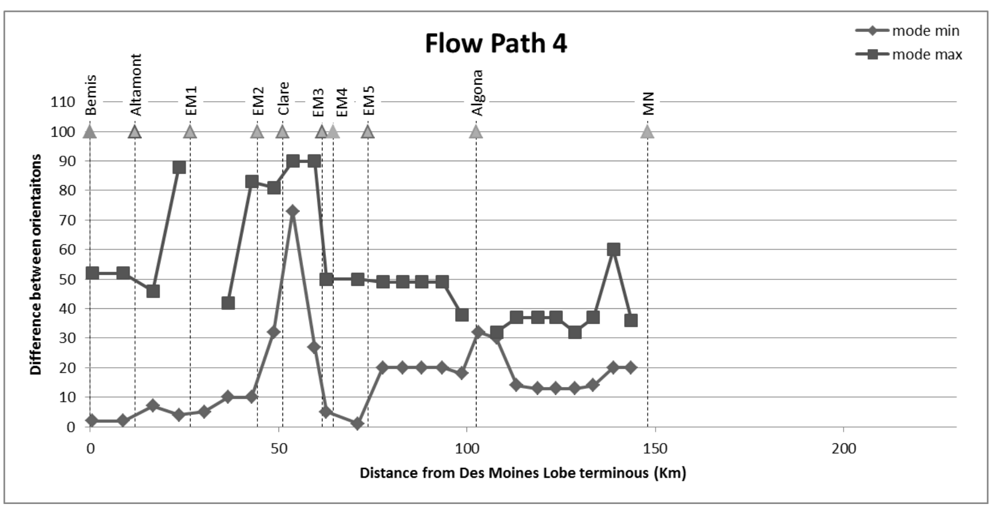


Figure 3.14: Minimum angular difference (mode min) and maximum angular difference (mode max) plotted along 19 flow paths. Each end moraine intersected is labeled, with the terminal moraine located at zero kilometers. Missing data points are from areas without a second set of minor moraines or without any minor moraines.

Figure 3.14 continued:







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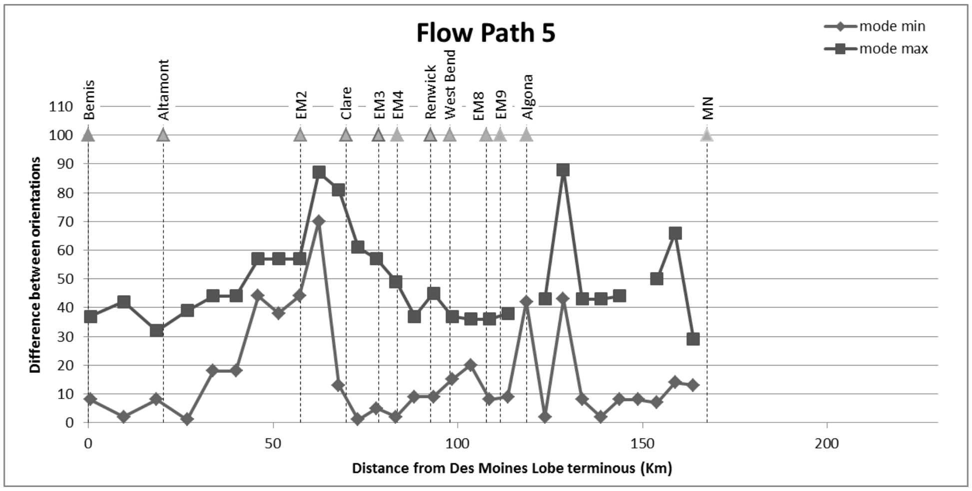

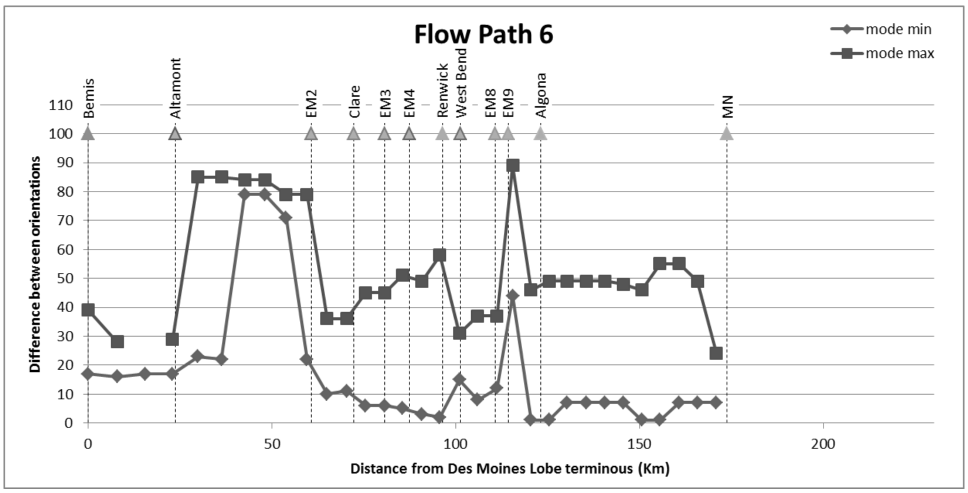

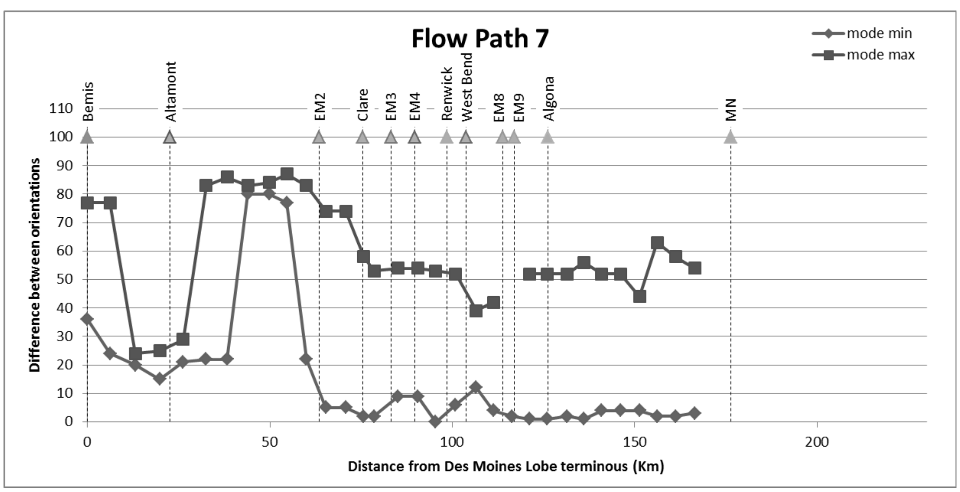

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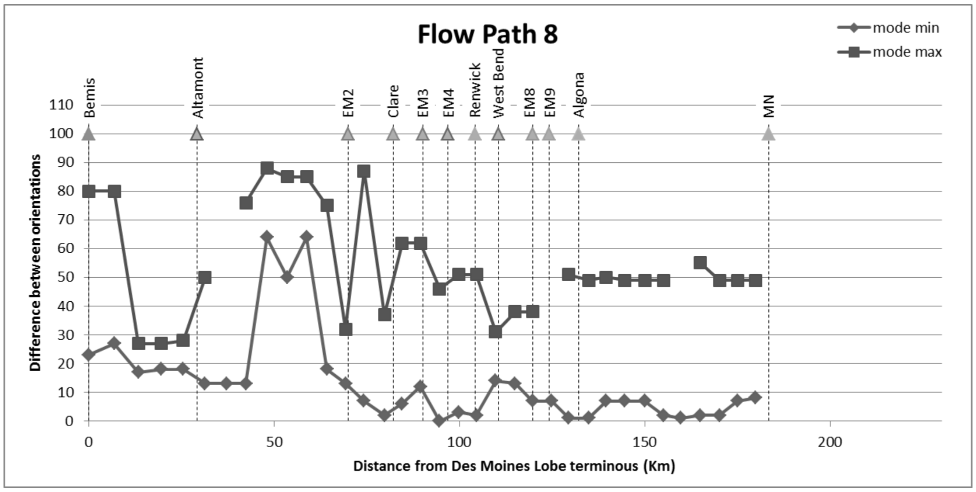

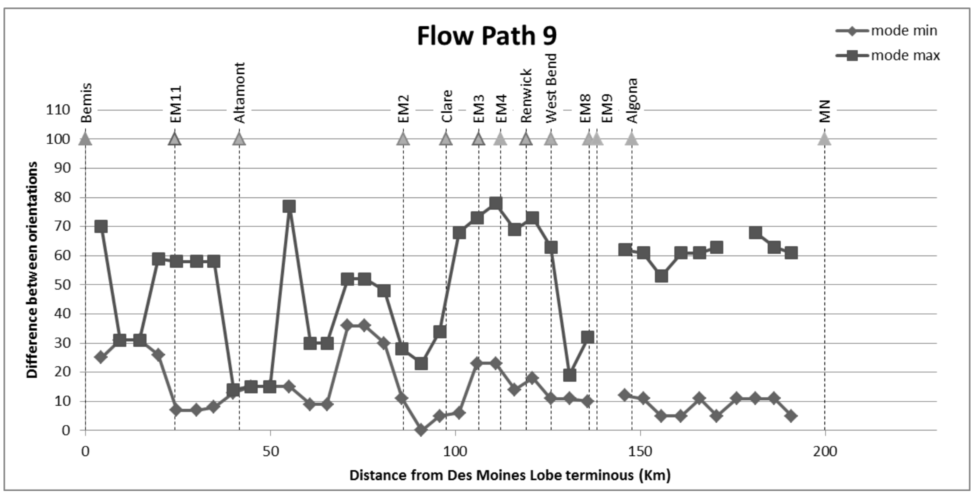

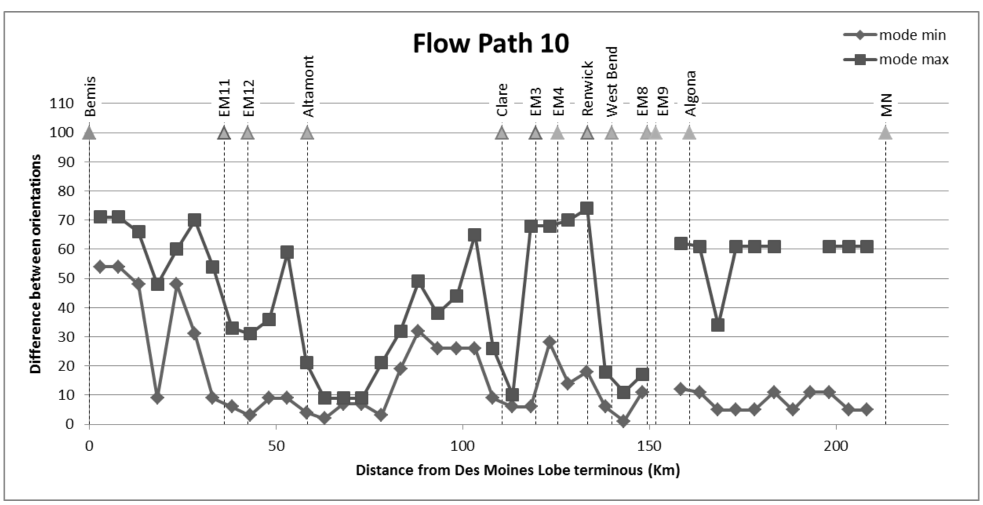

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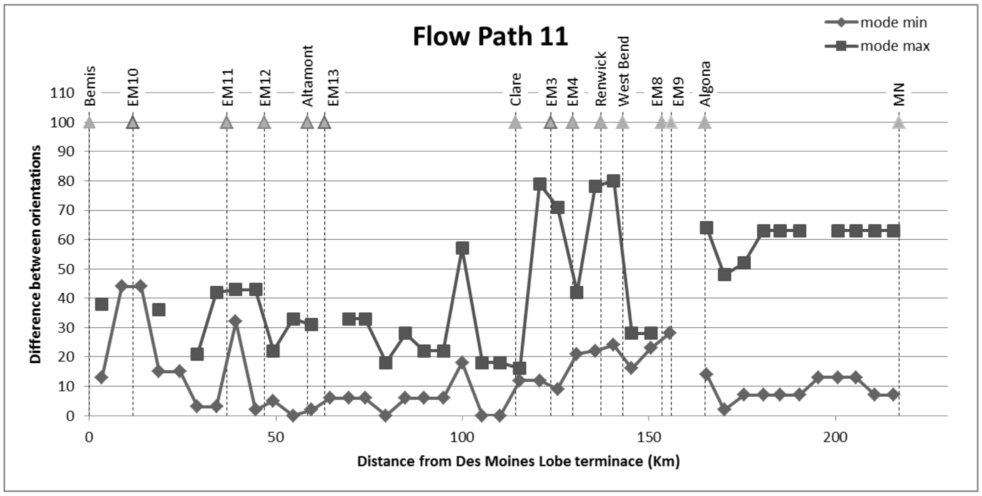

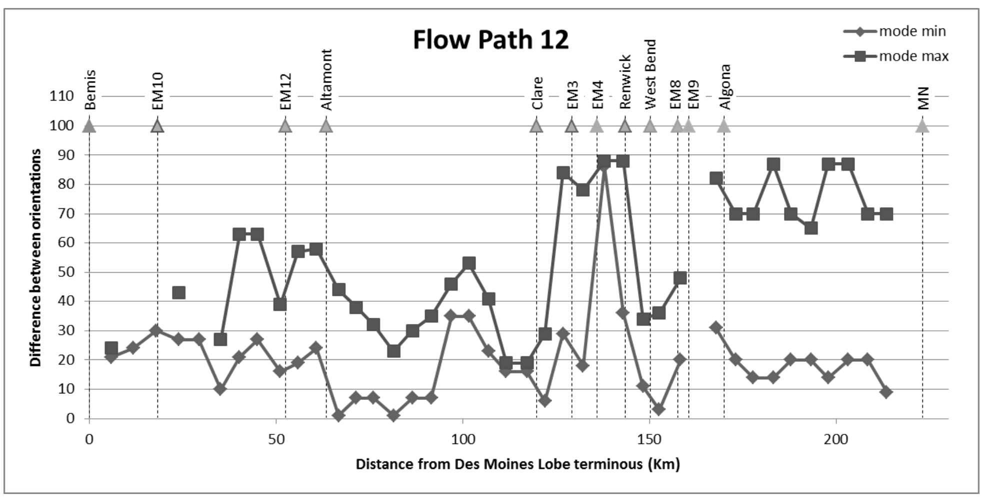

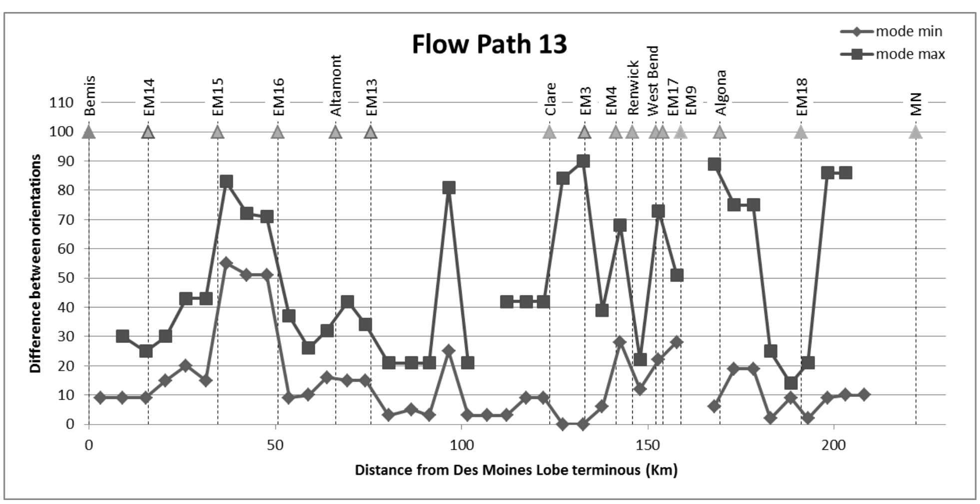

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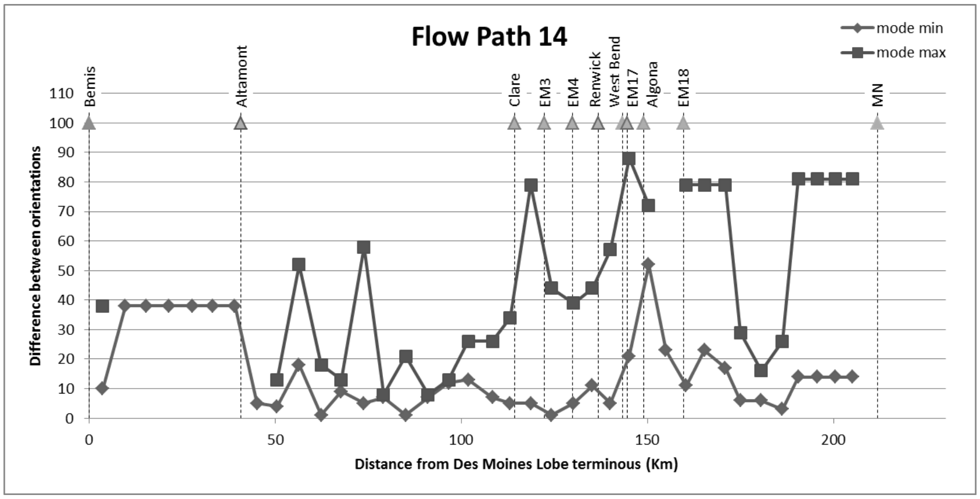

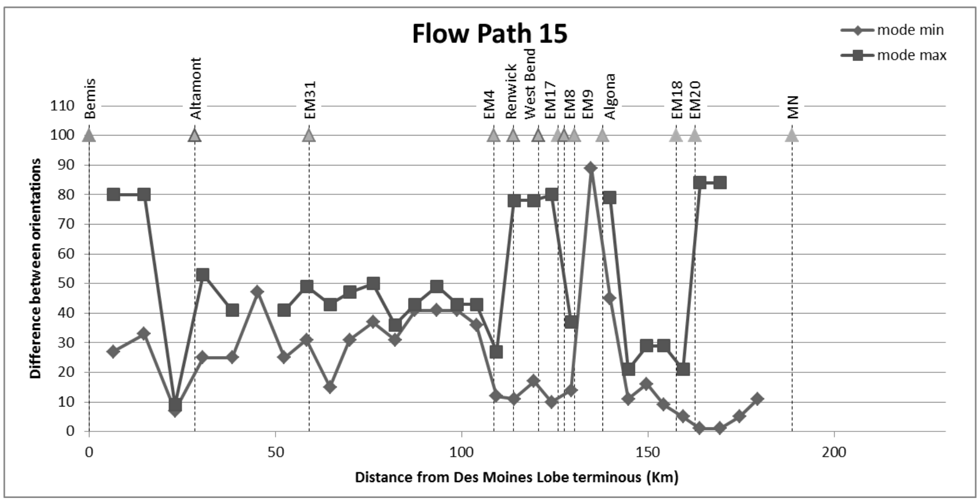

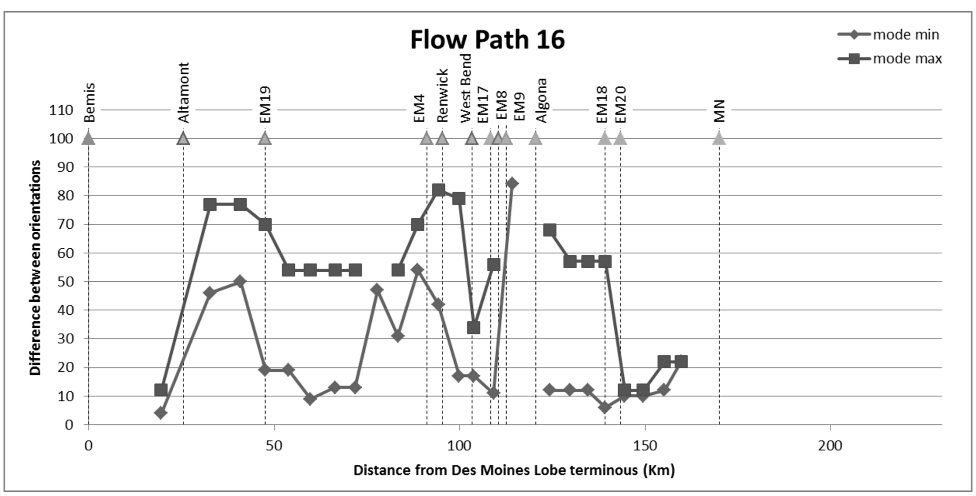

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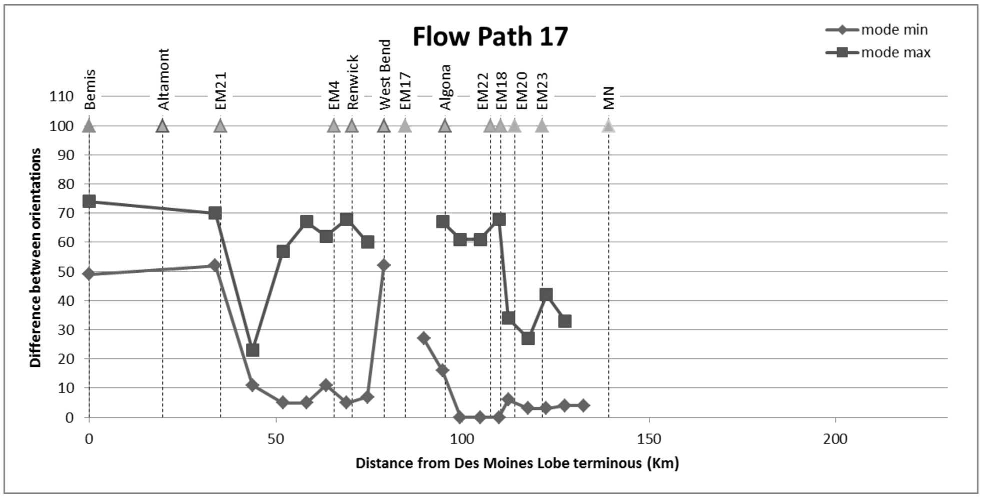

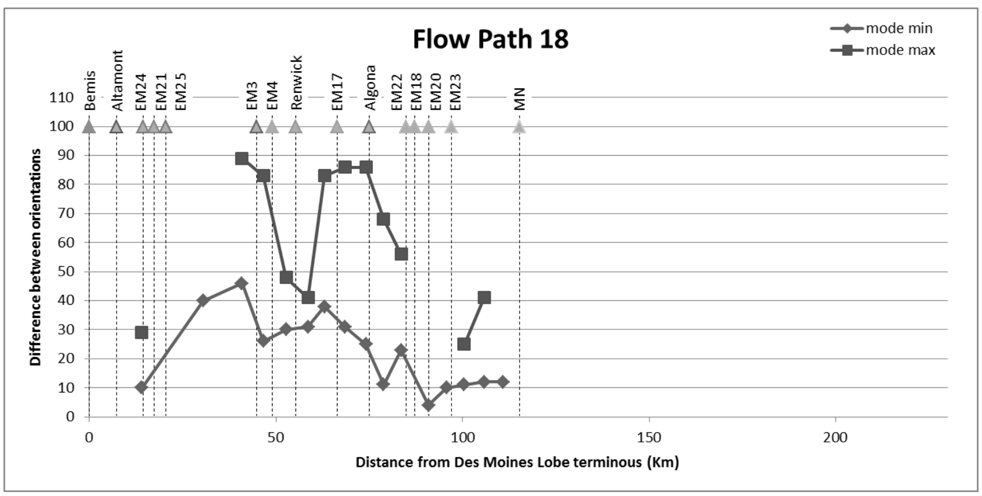

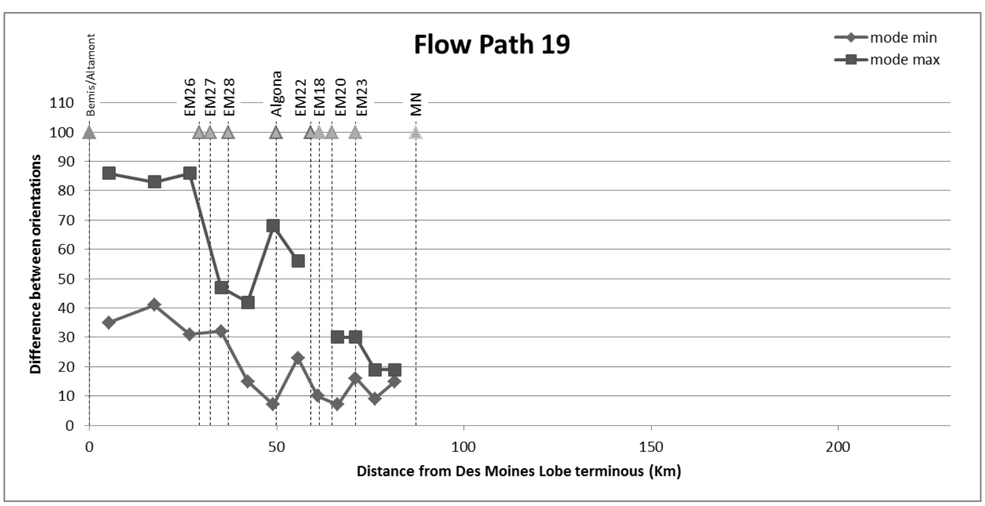

Table 3.1: Minimum (top) and maximum (bottom) angular differences for each flow path (fp) between the trends of end moraines and orientations of minor moraine sets immediately up-glacier. Averages and standard deviations for each end moraine are also listed. Note that the blank spaces indicate that the flow path does not cross that moraine.

Mode Min - Immediately Up Glacier from End Moraine																						
		Flow Paths (west to east)																				
		fp1	fp2	fp3	fp4	fp5	fp6	fp7	fp8	fp9	fp10	fp11	fp12	fp13	fp14	fp15	fp16	fp17	fp18	fp19	Ave	std. dev
End Moraines	Bemis	0	7	3	2	8	17	36	23	25	54	13	21	9	10	27	4	49			18.11765	15.60122
	Altamont		13	15	7	1	23	21	13	13	4	2	1	15	5	25	46	52			16	14.51723
	Algona	17	15	16	13	8	7	1	7	5	5	7	14	2	6	16	12	16	11	7	9.736842	4.929419
	Clare	16	15	16	73	1	6	2	6	6	6	12	6	0	5						12.14286	17.63866
	Renwick					9	15	6	14	18	18	24	11		5	11	17	7	31		14.30769	7.1617
	West Bend					15	8	4	13	11	1	16	3				17	52			14	13.76227
	EM1	8	4	37	5									12							13.2	12.22129
	EM2		16	25	32	70	10	5	7	11				22							22	18.9385
	EM3	23	24	19		2	5	9	0	23	28	9	18	6	1				26		13.78571	9.806547
	EM4	20	18		5	9	3	0	3	14	14	22	86	28	5	12	42	5	30		18.58824	20.12917
	EM5	18	12	5	20																13.75	5.847008
	EM8					8	12			10											10	1.632993
	EM9					9	44	1	7	12	12	14	31	6		14	84				21.27273	23.00629
	EM10											15	27								21	6
	EM11									7	6	32									15	12.02775
	EM12										3	5	19								9	7.118052
	EM13											6		3							4.5	1.5
	EM14													15							15	0
	EM15													55							55	0
	EM16													9							9	0
	EM17													28	5	10	11	27	31		18.66667	10.24153
	EM18													2	3	5	6	6	4	10	5.142857	2.415934
	EM19																19				19	0
	EM20															1	10	3	10	7	6.2	3.655133
	EM21																	11			11	0
	EM22																	0			0	0
	EM23																	3	11	16	10	5.354126
	EM24																		10		10	0
	EM25																		40		40	0
	EM27																			32	32	0
	EM28																			15	15	0
	EM29	22																			22	0
	EM31															31					31	0

Table 3.1 continued:

Mode Max - Immediately Up Glacier from End Moraine																						
		Flow Paths (west to east)																				
		fp1	fp2	fp3	fp4	fp5	fp6	fp7	fp8	fp9	fp10	fp11	fp12	fp13	fp14	fp15	fp16	fp17	fp18	fp19	Ave	std. dev
End Moraines	Bemis	22			52	37	39	77	80	70	71	38	24	30	38	80	12	74			49.6	22.84674
	Altamont				46	39	85	29	50	14	21	31	44	42	13	53	77	70			43.85714	21.34699
	Algona	46	35	40	32	43	49	52	49	61	61	48	70	75	79	79	68	67	68	68	57.36842	14.33145
	Clare	79	82	74	90	61	45	58	62	68	10	16	29	84	34						56.57143	24.96201
	Renwick					45	31	52	31	73	74	80	34	22	57	78	79	60	41		54.07143	19.674
	West Bend					37	37	42	38	63	11	28	36	73			34				39.9	16.37345
	EM1		86	88	42																72	21.22891
	EM2		78	81	81	87	36	74	87	28											69	21.82888
	EM3	42	27	31		49	51	54	46	73	68	71	78	39	44				83		54	17.08801
	EM4	31	27		50	37	49	53	51	69	70	78	88	68	39	27	82	68	48		55	18.724
	EM5	87	61	68	49																66.25	13.77271
	EM8					36	37			32											35	2.160247
	EM9					38	89	52	51	62	62	64	82	89		37					62.6	18.11187
	EM10											36	43								39.5	3.5
	EM11									58	33	43									44.66667	10.27402
	EM12										31	22	57								36.66667	14.83989
	EM13											33		21							27	6
	EM14													30							30	0
	EM15													83							83	0
	EM16													37							37	0
	EM17													51	88	80	56		86		72.2	15.57434
	EM18													21	26	21	57	34			31.8	13.467
	EM19																70				70	0
	EM20															84	12	27		30	38.25	27.2798
	EM21																	23			23	0
	EM22																	68			68	0
	EM23																	42	25	30	32.33333	7.133645
	EM24																		29		29	0
	EM25																		89		89	0
	EM27																			47	47	0
	EM28																			42	42	0
	EM29	31																			31	0
	EM31															49					49	0

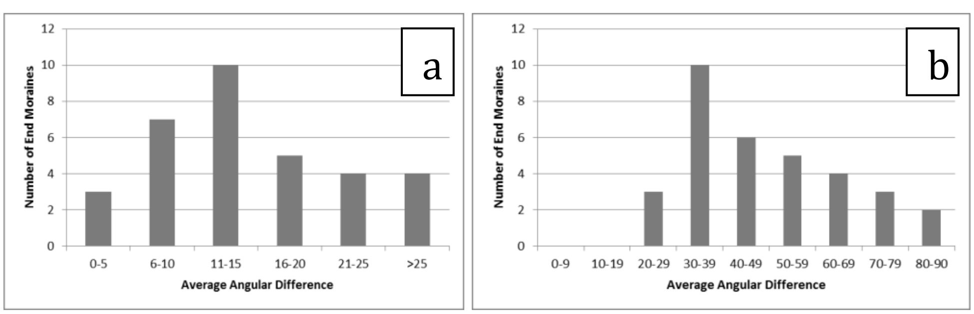

Figure 3.15: Histograms of **a.** the average minimum (mode min) and **b.** maximum (mode max) angular differences for the end moraines studied.

Table 3.2: Averages and standard deviations like those listed in Table 1 but considering the orientations of all minor moraine sets between the end moraine under consideration and the next end moraine up-glacier.

Mode Min				Mode Max			
End Moraine	Average Angular Difference	Standard Deviation	Number of Sample Positions	End Moraine	Average Angular Difference	Standard Deviation	Number of Sample Positions
Bemis	22.32727273	15.15862136	55	Bemis	46.64102564	21.72495573	39
Altamont	23.27380952	20.94684383	84	Altamont	46.98734177	25.46006735	79
Algona	11.57251908	8.371188808	131	Algona	52.40495868	15.53964725	121
Clare	11.48	14.60169853	25	Clare	63.24	22.41299623	25
Renwick	15.05555556	8.51451194	18	Renwick	54.16666667	21.54646143	18
West Bend	14.94736842	11.4729599	19	West Bend	36.5625	15.18621394	16
EM1	11.625	9.986709919	8	EM1	66.66666667	19.88019673	6
EM2	15.14285714	17.38988681	14	EM2	59.78571429	24.26984776	14
EM3	14.72222222	9.18214182	18	EM3	54.77777778	16.33182155	18
EM4	16.69565217	18.64178286	23	EM4	54.82608696	18.20093685	23
EM5	13.4	5.953150426	15	EM5	56.85714286	12.47200948	14
EM8	10	1.632993162	3	EM8	35	2.160246899	3
EM9	23	27.41350032	16	EM9	60.33333333	17.33653817	12
EM10	16.4	8.731551981	10	EM10	41.75	14.11338018	8
EM11	10.33333333	9.877021593	6	EM11	48.83333333	9.753916592	6
EM12	9.857142857	8.043250434	7	EM12	42.28571429	14.17960594	7
EM13	6.157894737	5.96713065	19	EM13	31.76470588	16.47646954	17
EM14	16.66666667	2.357022604	3	EM14	38.66666667	6.12825877	3
EM15	52.33333333	1.885618083	3	EM15	75.33333333	5.436502143	3
EM16	11.66666667	3.091206165	3	EM16	31.66666667	4.496912521	3
EM17	25.33333333	11.63328558	9	EM17	74.14285714	14.02475945	7
EM18	8.642857143	4.185129164	14	EM18	59.54545455	26.96247775	11
EM19	25.625	15.70778072	8	EM19	58.57142857	7.228063223	7
EM20	8.363636364	5.756778254	11	EM20	36.625	27.98632479	8
EM21	8	3	4	EM21	52.25	17.25362281	4
EM22	0	0	1	EM22	68	0	1
EM23	9.555555556	4.597369081	9	EM23	29.85714286	8.790068607	7
EM24	10	0	1	EM24	29	0	1
EM25	43	3	2	EM25	89	0	1
EM27	32	0	1	EM27	47	0	1
EM28	15	0	1	EM28	42	0	1
EM29	25	3	4	EM29	44.33333333	9.428090416	3
EM31	33.77777778	7.799968344	9	EM31	44.77777778	4.184037863	9

CHAPTER 4: DISCUSSION

A. Evidence of stagnation

There are two contrasting hypotheses of the Des Moines Lobe advance and retreat. The leading hypothesis is that the lobe underwent surge-like advances, to build its three major end moraines, with stagnation after each advance (Clayton et al., 1985; Kemmis, 1991). Alternatively, the lobe may have experienced active retreat (Gwynne, 1942; Gwynne, 1951; Lawrence & Elson, 1953), such that negative mass balance and recession were accompanied by active ice flow. The results of this project indicate that 90% of the Des Moines Lobe landscape in Iowa, not considering modern drainages, comprises stagnation landforms, including minor moraines, hummocky moraines, and ice-walled lake plains (Fig. 3.1). The prevalence of stagnation landforms across most of the lobe's area suggests that the lobe underwent surge-like advances and stagnation.

Minor moraines cover 60% of the Des Moines Lobe footprint (Fig. 3.1), and diverse data indicate that they formed by filling of crevasses that extended to the bed. Ankerstjerne (2010) studied a cross-section through a minor moraine in Story County, Iowa, and concluded that the moraine formed by crevasse filling. Preconsolidation and density data indicated that the till of the moraines had been deposited under the glacier, rather than at its margin. Moreover, till fabrics based on anisotropy of magnetic susceptibility (e.g., Shumway and Iverson, 2009) indicated upward shear in the proximal side of the moraine, with longitudinal shortening and upward extension just down-glacier from the moraine crest where till was squeezed upward into the crevasse (Fig.

4.1). Earlier less comprehensive sedimentological work but on several minor moraines

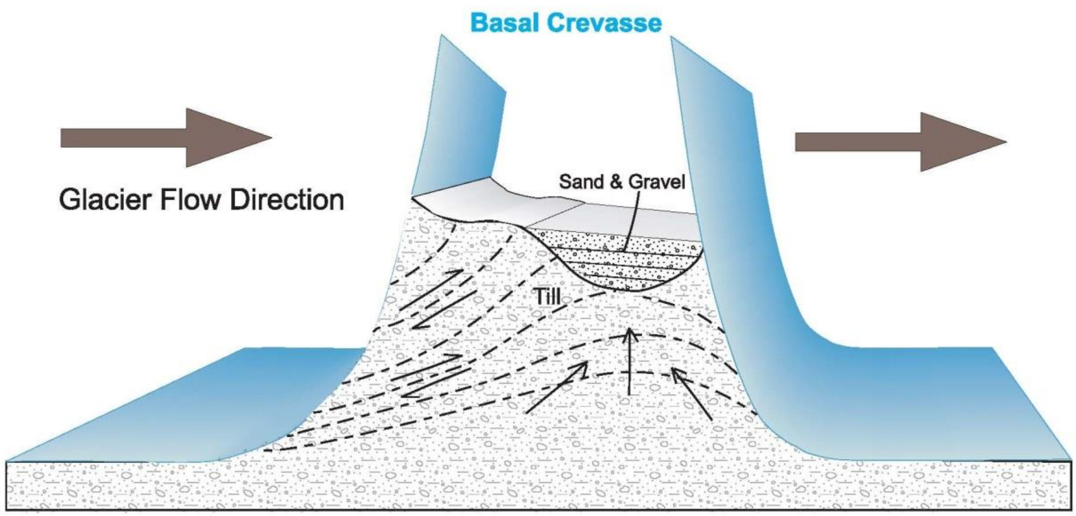

Figure 4.1: Conceptual model of minor moraine formation due to filling of crevasse that extends to the bed (from Ankerstjerne, 2010)

in Story County led Stewart et al. (1988) to also conclude the moraines were crevasse-fill ridges. Cline (2011) studied the geometric attributes of the minor moraines of Story County and found that they are most commonly both symmetrical parallel to ice flow and periodically spaced consistent with crevasse-fill moraines associated with surge-type glaciers (Sharp, 1985b; Herzfeld & Mayer, 1997; Evans et al., 1999; Herzfeld et al., 2004; Molnia, 2004; Schomacker & Kjær, 2007; Evans et al., 2009; Johnson et al., 2010).

Crevasse-fill ridges are uniquely associated with the forefields of surge-type glaciers and are thought to form at the end of the surge phase during stagnation (e.g., Sharp, 1985a; Rea and Evans, 2011). Thus, the abundance of minor moraines within the area of

Des Moines Lobe reinforces the conclusion that the lobe underwent surge-like advances followed by stagnation.

Hummocky moraines develop in stagnant ice environments as ice-cored moraines begin to down-waste (Benn, 1992). Hummocky moraine development associated with surge-type glaciers is well documented; after the glacier surges, stagnant debris-laden ice at the glacier margin down-wastes (Kjær & Krüger, 2001; Evans & Rae, 2003; Schomacker & Kjær, 2007). 31% of the footprint of the lobe is characterized by hummocky moraines. The Altamont moraine (Fig. 2.3, 4.2) is one of the best examples within the Des Moines Lobe. Hummocky end moraines are thus additional evidence of stagnation, a point also emphasized by others (e.g., Kemmis, 1991).

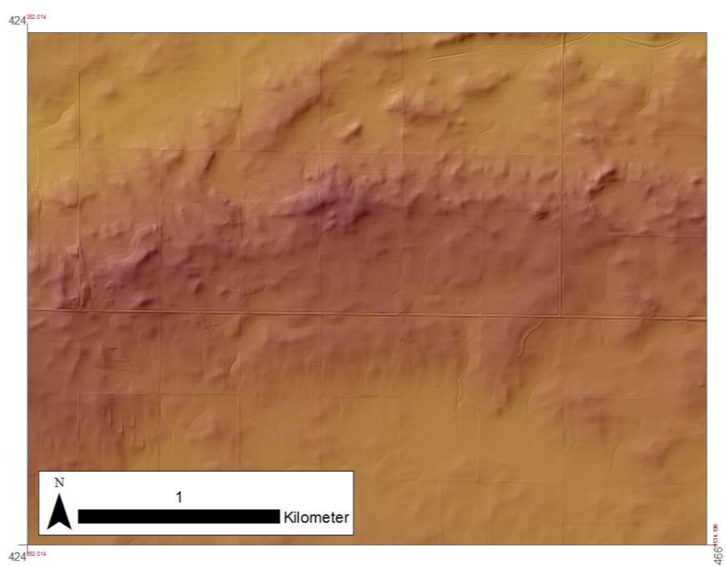

Figure 4.2: Hummocky topography of the Altamont moraine, north of Boone, Iowa, with flow direction indicated.

Newly mapped ridges, 5-10 m high, with a width of ~1 km. (Fig. 2.4b, c) are assumed to be end moraines. This assumption is based on the lateral continuity of the ridge and its sub-parallel relationship to the previously identified end moraines. These ridges likely formed by processes similar to those that formed the broad hummocky end moraines. Differences in geometry between these two styles of end moraines may be explained by the number of times the glacier advanced to a given location. Low amplitude, ~5 m high, ridges may reflect a single advance, whereas broad hummocky moraines with till thicknesses of ~10-15 m may reflect multiple advances to approximately the same position (Kjær & Krüger, 2001; Evans & Rea, 2003; Schomacker & Kjær, 2007). Alternatively, lower amplitude ridges may reflect a margin position that did not persist for an extended period. Although the origin of these ridges is uncertain, their morphology suggests that they likely formed along the surging margin of the glacier and can thus be considered end moraines.

Although less prevalent than minor moraines or hummocky end moraines, ice-walled lake plains cover 6% of the map area and also develop in stagnant ice environments. Supraglacial lakes develop as debris and melt water accumulate in depressions on the stagnant ice surface. The sediment collected in the lakes is deposited on the ground surface when the stagnant ice melts (Ham & Attig, 1996; Johnson & Clayton, 2003; Clayton et al., 2008). Ice-walled lake plains, therefore, also indicate that the Des Moines Lobe was characterized by stagnant ice.

The observation that 90% of the Des Moines Lobe landscape in Iowa consists of stagnation landforms does not provide information regarding the number of surges or relative timing of stagnation over different parts of the map area. Moreover, newly identified end moraine ridges without stagnation topography leave open the possibility that that parts of the lobe's margin left recessional moraines formed during active retreat. Minor moraine orientations can provide relevant information on these issues.

B. Significance of minor moraine orientations

Nearly all of the end moraines studied—the three major hummocky end moraines, other previously mapped end moraines, and the 25 newly mapped end moraine ridges—have a set of moraine ridges immediately up-glacier that are parallel or sub-parallel to them. Given that minor moraine ridges are likely transverse crevasse-fill ridges that formed immediately after surge-like advances, most end moraine ridges can be interpreted as being the result of surge-like advances. Thus, the likelihood that there were many more than three surge-like advances seems high. This conclusion is supported by the observation that in most areas and for every end moraine there is more than one set of minor moraines, with some of those sets having orientations that deviate greatly from the orientation of the nearest end moraine down-glacier. Minor moraines at a significant angle to the adjacent end moraine down-glacier correspond to end moraines farther down-glacier and have been presumably overridden by a later surge. This sort of re-advance over previous surge-type topography is common in modern surge-type glacier forefields (Kjær & Krüger, 2001; Evans & Rea, 2003; Schomacker & Kjær, 2007) and supported by the observation that minor moraines are sometimes truncated by end moraines (Fig. 3.11). Surge-like re-advance is also supported by the superposition of minor moraines on ice-walled lake plains (Fig. 3.5). The alternative—that most end moraine ridges are recessional and that glacier flow during recession was in the same direction as surge motion—seems unlikely given the diversity of flow directions indicated by minor moraine orientations. Moreover, the spatial prevalence of stagnation features, together with their tendency to be focused relatively near modern glacier margins, argues for multiple surge events to multiple locations to progressively build stagnation landforms spread over 90% of the lobe's landscape.

Minor moraines have previously been used to reconstruct flow paths and the ice surface of the Des Moines Lobe (Clark, 1992; Hooyer & Iverson, 2002). Reconstructions have involved making the assumption that minor moraines were perpendicular to flow when the lobe was at its maximum extent building the Bemis moraine, so that all of the minor moraines formed during the Bemis phase. However, multiple minor moraine orientations within the same area suggest that minor moraines did not form during the Bemis phase and that different sets reflect separate surge-like advances of the lobe. Thus, the extent to which minor moraines, particularly those moraines well up-glacier from the Bemis moraine, can be used to infer flow direction during the lobe's maximum extent is uncertain. Minor moraines far up-glacier that are best preserved and hence chosen for reconstructions are most likely to be associated with end moraines that are well up-glacier from the Bemis moraine. In contrast, far up-glacier from the Bemis moraine, minor moraines associated with the Bemis moraine advance are likely to be either poorly preserved or destroyed due to multiple overriding episodes. Also possible is that transverse crevassing required for minor moraine formation did not extend many tens of kilometers up-glacier from the glacier margin, such that all moraines far up-glacier from the Bemis moraine reflect later advances. Given the strong likelihood that most minor moraines well up-glacier from the Bemis moraine are associated with later advances of the lobe, a useful exercise would be to assess the sensitively of Des Moines Lobe reconstructions to disregarding minor moraine orientations that extend a threshold distance up-glacier from the Bemis moraine.

C. Lack of flow-parallel features

Flow-parallel features such as drumlins or flutes are characteristic of some surge-type glaciers (Evans et al., 2009; Johnson et al., 2010). Flow-parallel features are rare but present within the footprint of the lobe. Some of these features connect segments of minor moraines and are best interpreted as flow-parallel crevasse fills (Fig. 4.3). During surges, crevasses commonly form at roughly right angles, with one set parallel to flow (Fig. 4.4). Other rare flow-parallel features are less discrete lineations, extending ~500 m and superimposed across multiple washboard moraines (Fig. 4.5). These could also be a consequence of longitudinal crevasse fills, although their poor continuity along their lengths makes that interpretation uncertain. Drumlins and flutes are absent in the map area, and although one or both of these landforms can be absent from the forefields of modern surge-type glaciers (e.g. Loken, 1969; Holdsworth, 1977; Roberts et al., 2009; Evans et al., 2010), their absence from the Des Moines landscape is puzzling.

A leading hypothesis for drumlin formation requires a partially frozen bed (Whittecar & Mickelson, 1979; Stanford & Mickelson, 1985; Colgan & Mickelson, 1997; Hooke & Medford, 2013). As a glacier flows over partly thawed permafrost, thawed zones are eroded, with some sediment deposited at the crests and lee sides of the frozen zones (Stanford & Mickelson, 1985; Hooke & Medford, 2013). The Des Moines

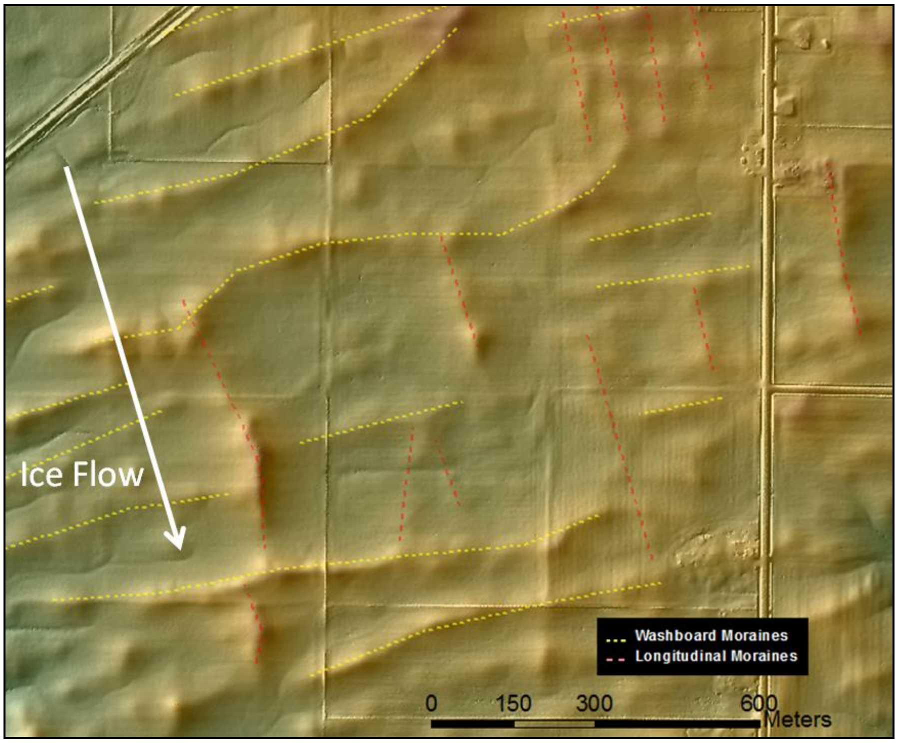

Figure 4.3: Longitudinal moraines (red dashed lines) interpreted as longitudinal crevasse fills. Yellow dashed lines indicate minor moraines (from Cline, 2011).

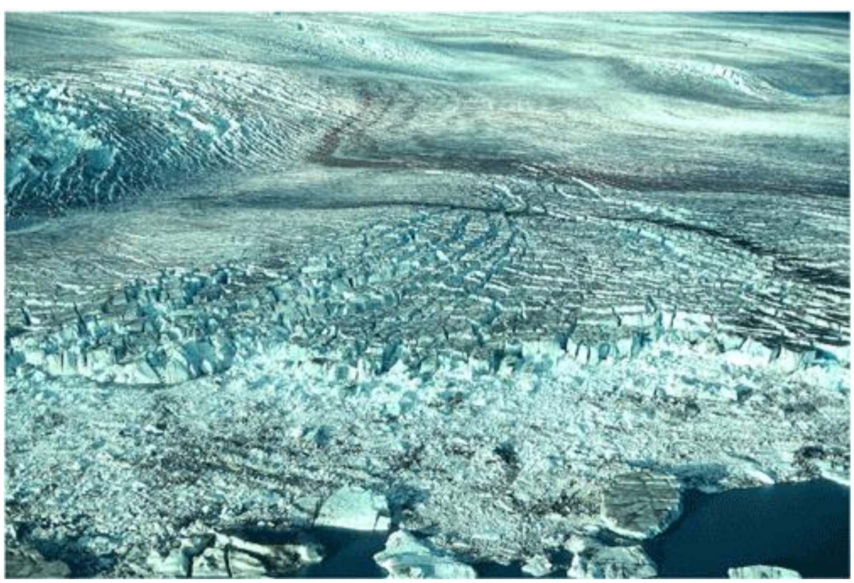

Figure 4.4: Photograph of the surge-type Bering Glacier, Alaska, in 1993 (USGS) showing prominent flow-parallel crevasses.

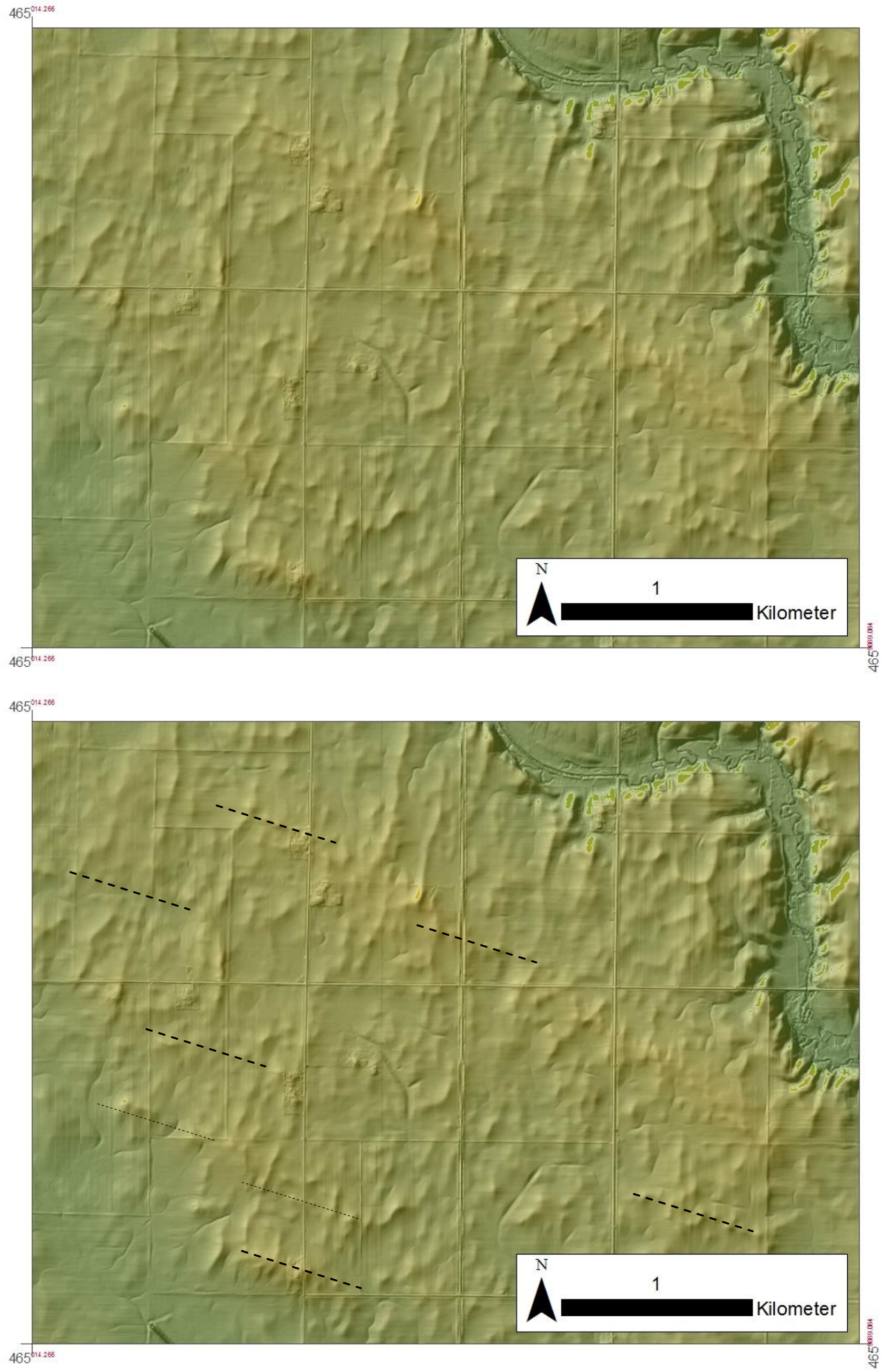

Figure 4.5: Area with flow-parallel ridges northeast of Nevada, Iowa.

Lobe did not have a frozen bed as it advanced out of balance with the climate into Iowa (Clark, 1994; Hooyer & Iverson, 2002; Mickelson & Colgan, 2003), so if this hypothesis is correct it could explain the absence of drumlins in Iowa and their ubiquity beneath some more northerly Midwest lobes of the Laurentide ice sheet (Whittecar & Mickelson, 1979; Stanford & Mickelson, 1985; Sharp, 1988; Colgan & Mickelson, 1997). On the other hand, several other popular hypotheses for drumlin formation do not require a frozen or partly frozen bed (Boulton, 1987; Hindmarsh, 1998; Fowler, 2009)

Flutes, a few decimeters to a few meters high and hundreds of meters long, are a common flow-parallel landform in the forefields of modern surge-type glaciers (Evans & Rea, 2003). Their absence from the Des Moines Lobe landscape may reflect their tendency to be readily eroded by post-glacial processes (Benn & Evans, 2010).

D. Modern analog

The multiple advances of the Des Moines Lobe—probably well in excess of the three surge-like advances into Iowa that have been typically postulated—invites comparisons with modern surge-type glaciers that repeatedly and periodically re-advance across their forefields (Evans et al., 1999; Schomacker & Kjær, 2007; Fleisher et al., 2010). Although there is no evidence for *periodic* advance of the lobe and thus describing it as a surge-type glacier would be overreaching, as noted in Chapter 1, many of the lobe's characteristics invite comparisons with surge-type glaciers and identification of a modern analog.

The Bering Glacier (Fig. 4.4), the largest surge-type glacier in North America (5200 km^2 and 190 km long), is perhaps the best analog, although imperfect. During its last surge from 1993 to 1995 it advanced at a rate of 365-2700 m yr^{-1}, thus spanning the 2000 m yr^{-1} advance rate of the Des Moines Lobe determined by Clayton et al. (1985) using the radiocarbon chronology of the lobe. The Bering Glacier rests on a soft bed and during its last surge was under high basal water pressure (Fleisher et al., 2010; Molnia & Post, 2010) similar to the inferred basal dynamics of the Des Moines Lobe's advance into Iowa (Fig. 1.4, Clark, 1994; Hooyer & Iverson, 2002). Transverse crevassing was pervasive on the surface of the Bering Glacier during its last surge (Fig. 4.6a). These crevasses locally extended to the bed and produced moraines remarkably similar in shape and scale to the minor moraines of the Des Moines Lobe (Fig. 4.6c). Sudden release of pressurized water from the bed at the end of the Bering Glacier surge locally resulted in scoured channels and eskers, features also associated with Des Moines Lobe (Fleisher et al., 2010). In other ways the comparison breaks down. Bering Glacier is confined by valley walls along most of its length, and over some of its margin, terminates in a large lake. End moraine ridges are not as prominent as in the Des Moines Lobe footprint. Moreover, some of the Bering Glacier forefield is mantled by flutes and poorly developed drumlins (Fleisher et al., 2010).

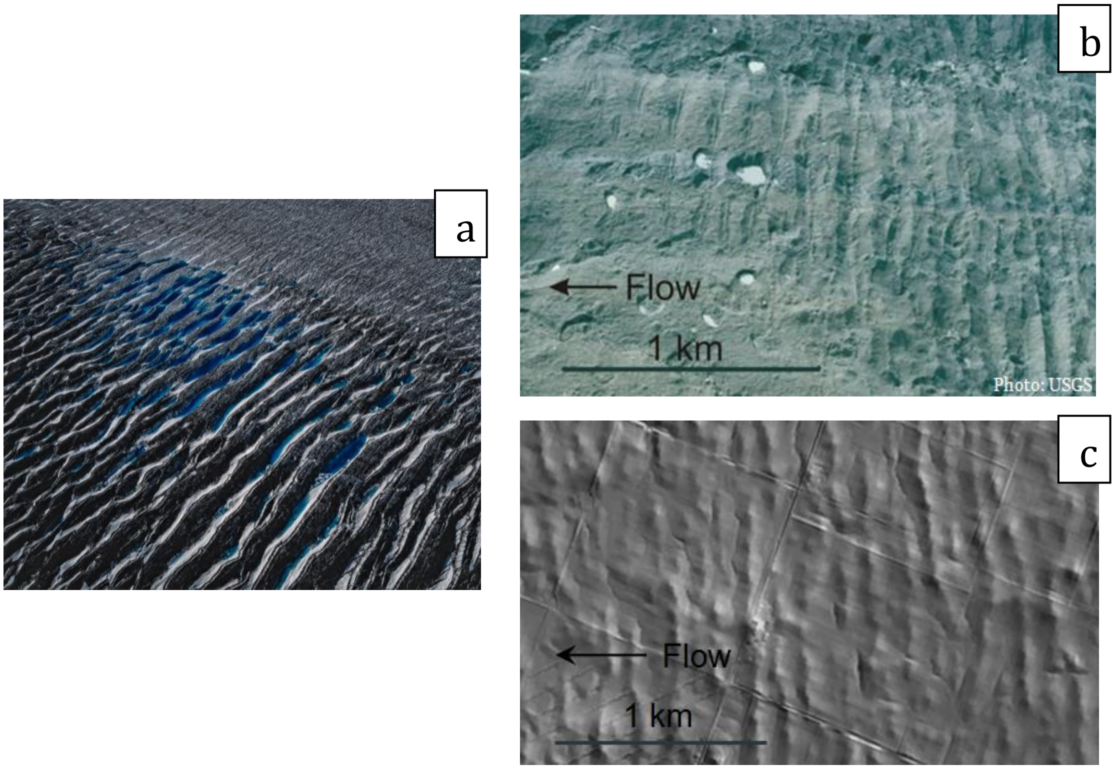

Figure 4.6: a. Transverse crevasses formed during the 1993-1995 surge of the Bering Glacier, Alaska (photo by Bernhard Edmaier; Cline, 2011). **b.** Aerial photograph of a ~4 km^2 area exposed by the retreat of the Bering Glacier following the 1993-1995 surge (Molnia, 2004). **c.** Minor moraines of the Des Moines Lobe at about the same scale as in **b.** (from Cline 2011).

CHAPTER 5: CONCLUSIONS

Stagnation landforms covering 90% of the Des Moines Lobe's footprint in Iowa, including minor moraines (60%), hummocky topography (31%), ice-walled lake plains (6%) and doubly blown-out donuts (3%), indicate that the glacier underwent widespread stagnation at multiple times. The extent of minor moraines, only associated with surge-type glaciers (e.g., Sharp, 1985), suggests that episodes of stagnation were preceded by surge-like advances of the lobe.

Multiple orientations of minor moraines at most locations indicate that most of the lobe's landscape reflects the action of two or more advances. Of the approximately 30 end moraines mapped, most of them, over at least part of their lengths, have a parallel ($<15^{o}$) set of minor moraines indicating that most moraines are likely the result of a surge-like advances. Additionally, all moraines have at least one secondary set of minor moraines at a high angle to the margin. These observations, considered collectively, indicate that there were multiple surge-like advances of the Des Moines Lobe—likely many more than the three advances thought to have formed the Bemis, Altamont, and Algona moraines (Clayton et al., 1985; Kemmis, 1991). Minor moraines that are both far from the Bemis moraine and well preserved are probably associated with later advances of the lobe and should not be used as flow direction indicators when the lobe was at its maximum extent building the Bemis moraine.

The surge-type, Bering Glacier, is a good, albeit imperfect, modern analog for the Des Moines Lobe, with speeds during surges, basal conditions, and crevasse-fill ridges similar to those inferred for the lobe. Unlike the Bering Glacier, however, the Des Moines Lobe in Iowa was not confined along it lateral margins and left no flutes that have been preserved or drumlins.

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