Spatial analysis of Des Moines Lobe washboard moraines using LiDAR data

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Spatial analysis of Des Moines Lobe washboard moraines using LiDAR 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

Program of Study Committee:
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Chris Harding, Co-Major Professor
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ABSTRACT

Washboard moraines are a characteristic landform of the Des Moines Lobe. Primarily composed of late Wisconsinan till and oriented parallel to and up-glacier from more conspicuous end moraines, washboard moraines are of low relief (1-2m) and appear to be regularly spaced. These moraines have been assumed in Des Moines Lobe reconstructions to have formed subglacially as basal crevasse fills, with crests developing perpendicular to the ice-flow direction when the lobe was at its maximum extent. Alternatively, the moraines are push moraines formed by seasonal advances of the lobe during its overall recession. The veracity of geomorphic reconstructions of the lobe’s thickness relies upon the former hypothesis being correct.

The morphologies and spatial patterns of the moraines may help reveal their origin but are poorly characterized, owing to the topographic subtlety of the moraines. The acquisition of 1 m LiDAR over the Des Moines Lobe’s footprint allows washboard moraines to be spatially characterized over broad areas for the first time. After mapping LIDAR-derived elevation data and identifying suitable tracts of moraines, spatial analysis techniques are applied to study moraine spacing and cross-sectional profiles. Using a chi-square test with a significance level of 95%, Fourier analysis of 400 topographic profiles constructed perpendicular to moraine trends reveals a dominant, statistically significant wavelength of 90-110 m. Uniform moraine spacing is expected for crevasse-fill ridges but not for end moraines. The cross-sectional profiles of individual, de-trended moraines are “stacked” to characterize the average moraine shape. This exercise indicates that they lack the systematic asymmetry typically displayed by push-style end moraines, which are generally steeper on their down-glacier sides. Analysis of abrupt changes in moraine trend, called “cusps,” indicates that they occur preferentially in the vicinity of outwash trains of sand and gravel: all cusps point up-glacier, and 62.7% are coincident with surface
outwash trains. Importantly, well logs indicate that remaining cusps are coincident with subsurface outwash overlain by till, indicating that the outwash pre-dates the last glacier advance and lending support to the hypothesis that subglacial outwash controlled the positions of cusp axes. Outwash trains may have supported anomalously low subglacial water pressures, thereby slowing basal slip in their vicinity and rotating basal crevasses to form the ridge cusps after glacier stagnation. These findings are consistent the Des Moines Lobe undergoing surge-like motion, with longitudinal extension creating transverse crevasses and stagnation allowing weak basal till to intrude upward into them.
CHAPTER 1: INTRODUCTION

A. Washboard moraines

Washboard moraines are a characteristic landform of the Late-Wisconsinan Des Moines Lobe of the Laurentide Ice Sheet. These moraines are especially prevalent in Iowa (Fig. 1.1). Referenced in past studies as swell and swale pattern (Gwynne, 1942), minor moraines (Gwynne, 1951), corrugated moraines (Prest, 1968, Stewart et al, 1988), and aligned hummocks (Colgan, 1996), these ridges form tracts of parallel ridges that resemble an antique clothes-cleaning “washboard” when viewed from altitude (Fig. 1.2). They typically consist of moderately deformed basal till with interbedded sands (Foster, 1969; Kemmis et al., 1981; Ankerstjerne, 2010). Ridges have amplitudes of 1-5 m and are superimposed upon larger undulations; even a trained eye struggles to identify the moraines from ground level (Kemmis et al., 1981). Post-glacial erosion and re-deposition has dampened the original relief by 1-4 m, resulting in the muted topographic variation observed today (Daniels & Handy, 1966; Burras, 1984; Burras & Scholtes, 1987). Varying between 20 m and 2 km in length, washboard-moraine crests trend perpendicular to the reconstructed Des Moines Lobe flow direction and generally parallel the larger, more conspicuous end moraines of the lobe (Fig. 1.1) (Kemmis et al., 1981; Clark, 1992). Washboard ridges appear to be periodically spaced with reported wavelengths of 30-200 m (Gwynne, 1942; Foster, 1969; Foster & Palmquist, 1969; Stewart et al., 1988; Colgan, 1996). Their apparent periodicity has led to a range of hypotheses for their formation. Testing these hypotheses is vital for assessing the veracity of Des Moines Lobe reconstructions, which depends on the ridges having formed subglacially at the glacial maximum (e.g. Clark, 1992, Hooyer and Iverson, 2002).
Figure 1.1. Map showing the Iowa footprint of the Des Moines Lobe overlaying a shaded relief map created from LiDAR data. The relief’s contrast was enhanced to visually emphasize the differences in terrain. Darker blue areas show large moraine complexes and yellow lines represent approximate locations and trends of washboard moraine tracts. The black square in Story County displays the location of Figure 1.2.
Figure 1.2. Terrain map of inset from Figure 1.1, showing an example of a well-preserved washboard moraine tract between the cities of Ames, IA and Nevada, IA. LiDAR data were used to create a 1 m resolution Digital Elevation Model, which was hill-shaded and colored according to elevation. The shaded relief’s contrast was enhanced to emphasize terrain details.

B. Transverse moraine classification

Tracts of moraines that lie transverse to glacier flow have been recognized worldwide and have been classified similarly, although they exhibit a wide variety of morphological characteristics. Despite attempts to distinguish transverse moraines (e.g. Elson, 1968; Prest, 1968), studies still commonly refer to transverse moraines of differing genesis in the same terms. The classification scheme of this thesis (Table 1) requires some discussion.
<table>
<thead>
<tr>
<th>Moraine Variety</th>
<th>Description</th>
<th>Glacier Environment</th>
</tr>
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| Push (annual)        | height: <5 m  
length: 200-5000m  
spacing: irregular  
Asymmetrical (steeper lee slope) | margin of retreating glacier                             |
| De Geer              | height: <10 m  
length: 50-1000m  
spacing: 400-1000 m  
Asymmetrical (steeper lee slope) | margin or subglacial crevasses of retreating, marine-terminating glacier |
| Rogen (ribbed)       | height: 5-20 m  
length: irregular  
spacing: 20->200 m  
Asymmetrical (steeper lee slope) | subglacial near ice divide or advancing glacial margin |
| Corrugation (submarine) | height: 1-25 m  
length: 1000-3000 m  
spacing: 60-200 m | grounding line of retreating, marine-terminating ice sheet |
| Washboard (minor)    | height: <5 m  
length: 20-2000 m  
spacing: 30-200 m | margin of retreating glacier or basal crevasses of stagnant glacier |

**Table 1.** Summary of transverse moraines and their properties (adapted from Ankerstjerne, 2010).

*Push (annual) moraines*

Push (or annual) moraines are small transverse moraines formed by annual glacial advances that push sediments into small ridges (Sharp, 1984). Generally less than 5 m in height, individual push moraines have asymmetrical profiles with distal slopes exceeding proximal slopes (Sharp, 1984; Bennett, 2001). Variations in the extents of seasonal margin advances dictate the uneven spacing of ridges (Fig. 1.3a). Arcuate in large-scale plan view, these moraines at smaller scales usually consist of multiple crests that are laterally traceable but very irregular (Benn & Evans, 1998). Moraines commonly are superimposed due to repeated marginal advances, further contributing to the irregularity of push-moraine terrain (Bennett, 2001).
Push moraines are formed primarily by a combination of compression and shearing of marginal ice and associated sediments (Bennett, 2001). The exact mode of deformation is dependent upon sediment characteristics but generally consists of coherent layers dislodging along a subglacial or proglacial décollement fault (Benn & Evans, 1998). These till layers are then stacked or thrust into the push moraine form as the margin advance progresses (Bennett,
Additional melt-out sediments may be draped over the moraine’s ice-proximal slope during the period of summer retreat (Benn & Evans, 1998). Substantial ice advances will tend to rework pre-existing push moraines, so those that are preserved most commonly reflect seasonal variations in margin position during the most recent period of net marginal retreat. The seasonal development of push moraines allows marginal retreat rates to be calculated (e.g. Gwynne, 1951; Boulton, 1986).

De Geer moraines

De Geer moraines are transverse moraines first described in Sweden in 1897 by Gerard De Geer (Hoppe, 1959). They are small, sharp-crested hills usually less than 10 m in height that commonly display an asymmetric profile with distal slopes exceeding proximal slopes. Individual De Geer moraine crests are lobate and may be traced laterally for hundreds of meters (Golledge & Phillips, 2008) (Fig. 1.3b). These moraines occur in swaths of closely-spaced ridges and consist largely of weakly-deformed glaciomarine sediments, with lesser amounts of till and stratified glaciofluvial deposits (Andrews & Smithson, 1966; Lindén & Möller, 2005). The predominance of glaciomarine sediments, which include clay and sand varves, indicates De Geer moraines are formed subaqueously by marine-terminating glaciers (Larsen et al., 1991).

Their genesis is controversial, but some consider them to be subglacial features. Transverse subglacial crevasses can form near the margin of advancing glaciers due to longitudinal ice extension (Golledge and Phillips, 2008). If these crevasses are just down-glacier from the grounding line of a marine-terminating glacier, fluctuations in water level may lower this previously floating ice onto the substrate (Zilliacus, 1989). The water-saturated substrate, consisting of stratified marine sediments, would then be squeezed upwards into the basal
crevasses (Hoppe, 1959; Lundqvist, 1989a; Zilliacus, 1989). An alternative hypothesis for subglacial deposition also cites transverse crevasses, but asserts that meltwater deposition of stratified glaciofluvial sediments in crevasses that extend upward to the glacier surface plays a larger role than squeezing of sediment from below (Beaudry & Prichonnet, 1991; Beaudry, 1994). Any subglacial origin for De Geer moraines requires sustained, rapid glacial recession to prevent reworking of the moraines by minor readvances (Golledge and Phillips, 2008).

In contrast, others consider De Geer moraines to be subaqueous push moraines. During a net glacial retreat, minor winter advances may deform proglacial stratified sand and clay deposits into small ridges (Boulton, 1986; Lindén & Möller; 2005). The characteristic asymmetrical profile, moraine truncation, and lobate form of De Geer moraines are also characteristic of terrestrial push moraines (Benn & Evans, 2008). Studies of submarine push moraines off the coast of Baffin Island lend support to the hypothesis that De Geer moraines may form subaqueously as annual winter push moraines (Boulton, 1986).

**Rogen (ribbed) moraines**

Rogen (or ribbed) moraines are transverse moraines thought to have formed beneath former ice divides of Northern hemisphere ice sheets (Boulton, 1987; Hättestrand, 1997). Recognized in Sweden, Finland, Norway, Canada, and the United States (e.g. Prest, 1968; Lundqvist, 1981), Rogen moraines have not been reported beneath the Greenland or Antarctic Ice Sheets (Hättestrand, 1997; Hättestrand and Kleman, 1999; Kleman and Hättestrand, 1999). Rogen moraines are sharp-crested, asymmetrical ridges with distal slopes exceeding proximal slopes (Aylsworth & Shilts, 1989; Bouchard, 1989). Varying in height between 5 and 20 m, they form in clusters of ridges that exhibit traceable crests up to kilometers in length (Bouchard, 1989;
Lundqvist, 1989b). Individual crests resemble barchan dunes, appearing concave in the down-glacier direction (Benn & Evans, 1998) (Fig. 1.3c). Composed of materials ranging from coherent bedrock blocks to stratified outwash, Rogen moraine internal structure varies widely but consistently contains steeply inclined layers and evidence of deformation (Cowan, 1968; Lundqvist, 1981; Bennett & Glasser, 2009).

The mechanism of Rogen moraine formation is widely debated. Early hypotheses were based upon annual end moraine deposition (e.g. Frödin, 1925). However, many recent studies cite the common spatial association of drumlins, eskers, and flutes with Rogen moraines as evidence for them having formed by subglacial deformation of the bed (e.g. Hoppe, 1968; Lundqvist, 1981). The three most prevalent hypotheses are the shear-and-stack hypothesis, the bed-deformation hypothesis, and the fracturing hypothesis.

The shear-and-stack hypothesis asserts that, due to localized longitudinal compressive stresses in ice near the bed, sections of debris-laden basal ice or subglacial till are sheared and stacked upon themselves (Shaw, 1979; Bouchard, 1989). The source of the compressive stress has been debated, with hypotheses that invoke, for example, frozen glacial margins or subglacial bedrock highs (Bouchard, 1989). Regardless of the source of compression, this hypothesis is supported by observations of thrust surfaces and compressive folds in moraine sediments (Benn & Evans, 1998).

Advocates for the bed deformation hypothesis suggest that Rogen moraines represent part of a continuum of bedforms that result from bed deformation (Boulton, 1987). The moraines form when pre-existing transverse ridges of sediment are mildly streamlined and thereby reshaped to the characteristic barchan dune form. If reshaping continues, the Rogen moraines are transformed to drumlins and flutes (Benn & Evans, 1998).
The fracturing hypothesis is predicated upon fracturing of subglacial sediment due to ice extension (Lundqvist, 1981). The basal ice extends due to tension associated with the transition from cold-based (non-sliding) to warm-based (sliding) basal motion (Hättestrand, 1997; Hättestrand and Kleman, 1999; Kleman and Hättestrand, 1999). This extension causes the frozen substrate to pull apart along a basal décollement, which Hättestrand (1997) likened to boudinage formation in extending rocks. The observation that Rogen moraine ridges appear to fit together like the pieces of a jigsaw puzzle (Bouchard, 1989; Kleman and Hättestrand, 1999) lends strong conceptual support to this hypothesis.

**Corrugation (submarine transverse) ridges**

Corrugation ridges are small, submarine transverse moraines identified on continental shelves using high-resolution swath-bathymetry techniques (Ottesen et al, 2005; Jakobsson et al., 2011) (Fig. 1.3d). Recognized in the high latitudes of both hemispheres, these ridges appear periodically spaced (60-200 m) and often form in association with mega-scale lineations (Shipp et al., 1999; Jakobsson et al., 2011). The few cores obtained from corrugation ridges consist of poorly-sorted till and glaciomarine sandy clays (Jakobsson et al., 2011). Technological advances in bathymetric imaging have only recently enabled the study of corrugation ridges, which are 1-25 m in height and occur in water depths between 270 m and 710 m (Dowdeswell et al., 2008; Winkelmann et al., 2010; Jakobsson et al., 2011). As refinement of sea-floor mapping techniques continues, corrugation ridges will likely garner additional attention.

Researchers have proposed three different mechanisms for the formation of corrugation ridges, all based upon the movement of the ice shelf grounding line. The ridges could be push moraines formed annually by minor grounding line advances during a period of overall
grounding-line retreat (Winkelmann et al., 2010). Corrugation ridges could also be recessional end moraines resulting from annual periods of stable grounding line position during a period of overall grounding-line retreat (Ottesen et al., 2005; Dowdeswell et al., 2008). Both of these mechanisms conveniently allow researchers to use the ridges to calculate rates of retreat. Alternatively, corrugation ridges could have formed following the catastrophic break-up of an ice shelf, as an upright mega-iceberg slowly drifted seaward (away from the calving front), grounding periodically due to tidal sea-level fluctuations (Jakobsson et al., 2011).

C. Hypotheses for washboard moraine formation

Modern hypotheses for washboard moraine formation fall into two broad categories: deposition as end moraines and deposition as subglacial crevasse fills.

End moraine hypotheses

Some end moraines are dump moraines that form during periods of stable margin position during an overall glacier retreat (Benn & Evans, 1998). Given enough time, sufficient supraglacial sediment may melt out of the glacier to form an ice-cored moraine ridge or complex of ridges (Boulton, 1972). Kemmis et al. (1981) suggested washboard moraines may reflect melt-out debris from the margin of a stagnant Des Moines Lobe. However, various till density and preconsolidation studies indicate washboard moraines in Iowa are composed primarily of basal till, rather than supraglacial till (Kemmis et al., 1981; Stewart et al., 1988; Ankerstjerne, 2010).

Thrusting of sediment-rich basal ice near the margin may also result in end moraines. Elson (1957, 1968) suggested that a washboard moraine ridge forms after a zone of debris-bearing
active ice is thrust over a marginal apron composed of stagnant ice that also contains debris. The moraine spacing was interpreted to indicate retreat of active ice due to annual thinning (Elson, 1957). Clayton and Moran (1974) hypothesized that washboard moraines formed near the margin when englacial sediment was concentrated along transversely striking shear zones. As the glacier longitudinally compressed, ice layers sheared upwards along thrust surfaces that penetrated to the glacier bed. This shearing accentuated melting, which increased lodgement deposition at the bed along the base of the shear plane and led to the gradual formation of the ridges (Sugden & John, 1976). This concept was expanded upon in later work, which invoked several surge-stagnation periods over the history of the Des Moines Lobe (Colgan, 1996). The zones of concentrated englacial sediment were deposited upon a layer of deformed basal till (Colgan et al, 2003). Similarly, Bennett (2006) studied transverse ridges at the surge-type glacier Kongsvegen in Svalbard and concluded that they formed by thrusting of basal ice and associated englacial sediment during longitudinal compression associated with a surge.

Others hypothesize minor marginal advances bulldoze proglacial sediments into small push moraines. This hypothesis was preferred by Gwynne (1942), one of the first to describe Des Moines Lobe washboard moraines. Gwynne’s hypothesis invoked summer deposition of melt-out till that was then pushed into ridges during the subsequent winter advance. He cited their periodic spacing, shape in relation to known margin positions, and subtle topographic variability as support for formation as annual push moraines (Gwynne, 1942, 1951). In Story County, Iowa, Gwynne (1942) observed “fifteen (washboards) to the mile,” consistent with a retreat rate of 107 m yr$^{-1}$ and inconsistent with surge of the lobe followed by its widespread stagnation. Similar transverse moraines in Wisconsin have been labeled as annual push moraines, exhibiting spacing that indicates a retreat rate of 37-82 m yr$^{-1}$ (Ham & Attig, 2001).
Crevasse-fill hypothesis

Washboard moraines may form as subglacial crevasse fills (Fig. 1.4). Rapidly moving glaciers sometimes undergo longitudinal extension near their margins, with development of transverse basal crevasses (Golledge & Phillips, 2008). Transverse crevasses on modern glaciers are commonly periodically spaced (Holdsworth, 1969; Colbeck & Evans, 1971; Lundqvist, 1989a; Garvin & Williams, 1993) and can create basal voids that cause local gradients in effective pressure that deform weak till upward into the voids (Hoppe, 1952; Stalker, 1960; Sharp, 1985). This “squeezing” of till upwards into basal crevasses was first proposed by Grippe (1929) and has been proposed for the Des Moines Lobe washboard moraines (e.g. Foster & Palmquist, 1969; Stewart et al., 1988). Analysis of pebble fabrics exhibited by washboard moraines in Story County, Iowa, indicates a preferred orientation perpendicular to ridge crests (Foster & Palmquist, 1969; Kemmis et al., 1981). Fabrics perpendicular to ridge crests, despite local deviations between ridge trends and reconstructed ice-flow direction, are evidence that the fabric resulted from flow associated with a local basal feature, such as basal crevasses, rather than more regional deformation of the bed by glacier flow (Hoppe, 1957).

Subsequent studies of the anisotropy of magnetic susceptibility (AMS) of till from washboard moraines have provided detailed information on moraine fabric and strain patterns not possible with clast analysis (e.g. Stewart et al., 1988; Ankerstjerne, 2010) (Fig. 1.5). AMS fabrics show tightly clustered susceptibilities, indicative of till deformation by simple shear (Ankerstjerne, 2010) (Fig. 1.5b). However, these data also indicate strain indicative of pure shear, consisting of longitudinal shortening perpendicular to the moraine trend with vertical and transverse extension (Ankerstjerne, 2010) (Fig. 1.5c). This state of strain is consistent with extrusion of till into a basal crevasse.
Figure 1.4. Crevasse-fill mechanism, showing upwards squeezing and associated shear planes (from Ankerstjerne, 2010).

Modern crevasse-fill ridges formed by squeezing of basal till have been documented in Glacier Bay, Alaska (Mickelson & Berkson, 1974; Goldthwait, 1974). Historic photographs match the locations of former crevasses with current crevasse-fill ridges and observations of ridges developing at the bases of modern crevasses at this location provide strong evidence for the crevasse-fill hypothesis (Mickelson & Berkson, 1974). Recently exposed crevasse-fill ridges formed by surge-type glaciers also correspond spatially to documented crevasse patterns (e.g. Sharp, 1985; Christofferson et al., 2005).
Figure 1.5. a. Sedimentological cross-section of a washboard moraine in Story County, Iowa. Arrows drawn from 1.5b and 1.5c indicate locations of multiple AMS fabrics consistent with the state of strain depicted. b. Diagram of simple shear and an AMS fabric stereoplot generated from washboard moraine till deformed by simple shear. Reconstructed glacier flow direction is from the northwest. Red dots correspond to orientations of $k_1$ (maximum) susceptibilities, green to $k_2$ (intermediate) and blue to $k_3$ (minimum) c. Diagram of pure shear and an AMS fabric stereoplot generated from washboard moraine till deformed via pure shear, with same coloring conventions as part b. Reconstructed glacier flow direction is from the northwest (adapted from Ankerstjerne, 2010).
D. Motivation

Spatial analyses of glacial landforms, including washboard moraines, are central to reconstructions of ancient ice sheets (Bennett, 2001). Moraine characteristics bear on retreat-rate calculations for ice sheets, reconstructions of glacier morphology, and glacier dynamics.

Retreat rate calculations

In the first studies of the Des Moines Lobe washboard moraines, they were considered to be proglacial features, created by a combination of annual melt-out till and bulldozing during minor seasonal advances throughout an overall period of lobe retreat (Gwynne, 1942). Their assumed annual genesis allowed glacier retreat rates to be calculated—an approach that clearly depends on the moraines forming at the lobe’s margin. Similarly, the corrugation ridges exhibited on the West Antarctic continental shelf have been widely invoked as a means of calculating grounding line retreat rates (Ottesen et al., 2005; Dowdeswell et al., 2008), which bear on the future stability of the West Antarctic Ice Sheet. This approach hinges on the assumption that one moraine forms at the grounding line every year. If these corrugation ridges actually formed subglacially, with spacing related to spatial rather than temporal factors, then their applicability to the past and future stability of the ice sheet is clearly not straightforward.

Reconstructions

In contrast, washboard moraines have also been deemed subglacial features, formed when the Des Moines Lobe was at its maximum extent, and used as flow-direction indicators in reconstructions of the lobe (e.g. Mathews, 1974; Clark, 1992; Hooyer & Iverson, 2002). Lobe geometry is reconstructed under the assumptions that flow-direction indicators formed at the same time as the terminal moraine, local ice surface elevation equaled the local terminal moraine
elevation, and elevation contours of the ice surface were perpendicular to the flow-direction indicators (Clark, 1992). The viability of washboard moraines as flow-direction indicators, and thus the strength of the reconstructions themselves, will be investigated through testing of the crevasse-fill hypothesis. Reconstructions, in turn, provide morphological characteristics that can then be used to help understand the lobe’s dynamics.

**Lobe dynamics**

Correctly determining how washboard moraines form will provide clues about the dynamics of the Des Moines Lobe. Gwynne (1942) proposed a steady advance and an “active” retreat consisting of a slow, annual marginal recession due to a consistently negative glacier mass balance. More recently, researchers have drawn upon the low driving stresses and high subglacial water pressure evident in reconstructions of the lobe as indicators that it advanced, not due to a positive mass balance but for internal dynamic reasons. Then the lobe stagnated, similar to a surge-type glacier (Clayton et al., 1985; Colgan, 1996; Colgan et al., 2003). Basal water pressure is thought to have been near the ice-overburden pressure, which reduced basal drag and allowed for the advance of the lobe despite its small driving stresses and the warming climate of ~15,000 radiocarbon years ago (Patterson, 1997; Hooyer & Iverson, 2002). The high basal water pressure could have also led to marginal longitudinal extension and associated transverse crevasses, instead of the marginal compression normally exhibited by glaciers in their ablation areas (Iverson, 2005). Observations in the forefields of modern surge-type glaciers have revealed transverse crevasse-fill moraines (e.g. Johnson, 1975; Clarke, 1984; Sharp, 1985). The ridges are preserved due to widespread, post-surge ice stagnation and down-wasting (Sharp, 1985). This ice-stagnation mode of retreat has been proposed for southern lobes of the Laurentide Ice Sheet (e.g. Gravenor & Kupsch, 1959; Palmquist & Connor, 1978; Colgan, 1996).
Washboard moraines formed by filling of basal crevasses would provide support for the surge-and-stagnate concept, but their formation as end moraines would not.

E. Objectives

The goal of this study was to use LiDAR-derived elevation data to try to answer three questions that may bear on whether the washboard moraines of the Des Moines Lobe in Iowa formed subglacially as crevasse fills or at the ice margin.

1) Is the flow-parallel spacing of well-developed washboard moraines statistically periodic, and if so, what is the dominant wavelength of the moraines? Flow-parallel periodicity is not a likely attribute of annual push moraines. Annual ablation would be expected to vary year to year, so that a constant recession rate necessary for uniform moraine spacing would be unlikely. Furthermore, the amount of seasonal advance during the winter, which would have pushed the moraines into ridges, would have likely been variable from one year to the next. Conversely, periodically-spaced transverse crevasses are observed on some modern glaciers (Holdsworth, 1969; Colbeck & Evans, 1971; Lundqvist, 1989a; Garvin and Williams, 1993). Therefore, evidence of periodicity of moraine spacing would support the crevasse-fill hypothesis.

2) What is the mean longitudinal profile of washboard moraines? An asymmetric profile, with the distal slope exceeding the proximal slope, is characteristic of push moraines. Any systematic asymmetry would agree with a push-moraine origin for washboard moraines. Conversely, the lack of any asymmetry would be evidence supporting washboard moraine formation as crevasse fills, provided that till intruded basal crevasses when there was little forward movement of the glacier.
3) How do abrupt changes in washboard moraine trend, called cusps, correlate to buried sand and gravel bodies? Cusps have been linked to buried valleys and are hypothesized to have formed due to local hydraulic conductivity differences in the glacier substrate (e.g. Stewart et al., 1988). Compared to clay-rich till, areas of sand and gravel substrate would have likely experienced lower subglacial pore water pressures because the water would have drained through the glacier substrate more easily. Lower pore pressures would have increased basal drag, slowing glacier flow locally and altering the trend of any crevasses in the vicinity of the slower ice (Fig. 1.6a). Upon glacier stagnation, the crevasses would have remained cuspat e and any subsequent upward squeezing of basal till into the crevasses, as required by the crevasse-fill hypothesis, would have generated washboard moraines reflecting the cuspat e form.

Conversely, sand and gravel deposits may not have been a cause, but rather a result of the cusp formation process. Cusps have been described as push moraine tracts along a lobate glacier margin, with cusps formed in areas of unusually rapid retreat caused by increased glacial runoff (Gwynne, 1942) (Fig. 1.6b). This increased runoff would have concentrated glaciofluvial sand and gravel in low areas between sub-lobes, resulting in outwash valley trains at the locations of cusps. Glaciofluvial deposition can occur both at the glacier margin and on the glacier surface up-glacier from the margin, so contemporaneous formation of the sand and gravel bodies with
the washboard moraines does not favor either hypothesis of washboard formation. However, evidence of sand and gravel bodies at cusp locations prior to the formation of washboard moraines would be consistent with the crevasse-fill hypothesis.
CHAPTER 2: METHODS

A. Introduction

LiDAR (Light Detection and Ranging) data were analyzed with GIS techniques to characterize well preserved washboard moraines within the Iowa footprint of the Des Moines Lobe. The crevasse-fill hypothesis was tested through analysis of a digital elevation model (DEM) that accurately portrayed the washboard moraine terrain. A high resolution DEM was created from the LiDAR data and elevation profiles of washboard moraines were extracted. Fourier analysis was used to investigate the profiles’ dominant wavelength. A representative moraine profile was created by normalizing and averaging the individual profiles. Also, abrupt changes in moraine trend were mapped, characterized, and compared with locations of outwash valley trains. Considerable detail is provided in parts of this chapter (and attached appendices) to enable subsequent students to perform similar data manipulations.

B. Study area

The Des Moines Lobe was the largest lobe along the southern margin of the Laurentide Ice Sheet (LIS). Within Iowa the lobe covered approximately 31,000 km² and stretched from the northern border south to Des Moines (Fig. 2.1). Reaching its maximum extent at the Bemis Moraine approximately 13,800 radiocarbon years ago (Clayton & Moran, 1982; Hooyer & Iverson, 2002), the Des Moines Lobe created hundreds of washboard moraines, as well as a series of end-moraine complexes.

This study focused on the Des Moines Lobe for multiple reasons. Washboard moraines are well-preserved in some areas within the Des Moines Lobe footprint; they were easily identifiable and post-glacial modification has been sufficiently limited to preserve many of their
morphological attributes. Iowa State University is located within the footprint of the Des Moines Lobe, so the moraines were of local interest. The Des Moines Lobe advanced late during the Wisconsinan glaciation, during a period of climatic warming unlike earlier advances of some LIS lobes at about the glacial maximum. The study of this particular lobe’s dynamics in the face of a
warming climate depends, in part, on understanding the origin of washboard moraines and may lend insight into the dynamics of modern glaciers faced with a warming climate. The Iowa DNR recently completed a state-wide LiDAR survey, which included the entire Iowa footprint of the Des Moines Lobe. As of 2010, Iowa was one of only six states with complete LiDAR coverage. The availability of LiDAR data was vital to this study because it enabled high-resolution spatial analysis of the topographically subtle washboard moraines.

The primary focus of this study was the washboard moraines of Story County (Fig. 2.2). Statewide LiDAR coverage was not complete at the onset of this project, limiting the area...
available for digital elevation analysis. However, all of Story County was available, and it contains some of the best-preserved washboard moraines within the footprint of the lobe. The washboard moraines of Story County have also been characterized by two sets of sedimentological analyses (Stewart et al., 1988; Ankerstjerne, 2010) which provided important insights not attainable through topographic analyses alone.

C. LiDAR

Digital elevation maps were created using LiDAR elevation data, which were collected by the Iowa DNR from 2006 to 2009. LiDAR (Light Detection And Ranging) or ALSM (Airborne Laser Swath Mapping) is a revolutionary remote sensing system used to sample a terrain’s shape, typically from an airplane. GPS instruments onboard the airplane calculate its exact lateral position and elevation at all times (a precisely known position of the emitter is critical for determining absolute elevation of the terrain beneath the airplane). As the plane flies over the target topography, the LiDAR system emits thousands of light bursts per second then measures the reflectance of each light burst as it returns (Measures, 1984). Similar to RADAR (Radio Detection and Ranging), a LiDAR system measures how the energy waves are reflected from a target, and the resulting lag times yield information about the distance from the emitter to the target (Collis, 1970; Cracknell & Hayes, 1991; Elachi & van Zyl, 2006). However, LiDAR pulses are emitted as near-infrared radiation (with a wavelength of 1064 nm), which is a much shorter wavelength than radar energy waves (~1 cm – 1 m) (Measure, 1984). As a result, LiDAR-generated data are much higher resolution than data generated by radar (Elachi & van Zyl, 2006) (Fig. 2.3). Washboard moraines are so small that the larger cell sizes of the now-obsolete 10 m DEM almost completely muted their subtle topographic expression (Fig. 2.3).
Figure 2.3.  

a. Map showing a 10 m resolution digital elevation model of the area between Ames, Iowa and Nevada, Iowa, as was available prior to the LiDAR survey. A hill-shaded relief map is used to accentuate the colored topography. 

b. LiDAR-derived digital elevation model (1 m horizontal resolution with vertical accuracy within 18.5 cm) of same area overlain with a hill-shaded relief map. Note the marked improvement in resolution.

As such, the 1 m resolution of the LiDAR DEM proved to be vital for the accuracy of this study, which was the first to use a LiDAR-derived digital elevation map to study washboard moraines.

LiDAR data include several sets of reflections, called returns, which must be sorted when analyzing the data. When flown over buildings, LiDAR records the roof elevations. Similarly, LiDAR collected over vegetation detects multiple reflections: reflections from the top of the tree canopy ("first returns"), reflections from leaves and branches inside the canopy, and finally reflections from the ground ("last returns") (Fig. 2.4). As this project was only concerned with modeling the ground, only the last returns were analyzed and any returns from buildings or vegetation were ignored. These last returns, with building removed, are called "bare-earth returns," which were used to create a digital elevation model of the topography (Fig. 2.5).
Figure 2.4. Diagram showing the LiDAR pulse reflection (returns) generated by vegetation. The “5th return” in the diagram represents the “last” return that would be used in this study. (image by Jason Stoker, USGS)

Figure 2.5.  

(a) Example DEM of “first” LiDAR returns, containing all buildings and vegetation.  
(b) Example DEM of “last” LiDAR returns, showing the ground surface and only buildings.  
(c) Example DEM of “bare-earth” LiDAR returns, as would be used in this study. Buildings and vegetation are removed.
D. Geographical Information Systems (GIS)

ArcGIS 9.3.1, by ESRI (Environmental Systems Research Institute), was used to produce the three-dimensional digital surface from LiDAR elevation data. These data consisted of an irregularly-spaced “cloud” of discrete points containing x, y, and z coordinates. Due to memory constraints and large downloading times, point clouds of data were downloaded as 2 x 2 km tiles from the Iowa DNR/UNI GeoTREE website. Each tile contained two to five million 3-D points and, in practice, these large numbers of irregularly-spaced points were not well suited for directly characterizing terrain. Using a converter script, the data were transformed into a regularly-spaced raster grid, which ArcGIS was able to more-efficiently process. This LiDAR converter, written by Chris Harding using the ArcGIS Python API (Application Program Interface), linked several ArcGIS tools together to create the DEM (see Appendix A). Although the sequence of tools needed could also be operated manually within ArcGIS, the Python script was written to save time by processing all the desired tiles in a batch without user interaction.

After creation by the processing program, the DEM raster was adjusted to enhance analysis. The raster was colored to display elevation differences: each DEM raster cell was colored based upon its elevation (Fig. 2.6a). A pixilation effect amongst these cells could be seen when zoomed into a small scale, as the raster contained elevation values at discrete 1 m intervals (Fig. 2.6a). However, viewing the terrain at larger scales presented a smooth view (Fig. 2.6b). The DEM was also used to create a separate hill-shade raster, which helped with the visual identification of washboard moraines (Fig. 2.7). The hill-shade raster did not contain any information about the absolute elevation, but contained only gray colors that mimicked the intensity of the sun’s light to create a 3-D effect and more effectively display subtle features.
Figure 2.6. a. Small-scale view of a raster image. Pixel color reflects elevation, increasing from green to red. b. Larger-scale view of the same raster image, with the location of 2.6a outlined by the black box. No pixilation is visible.

Figure 2.7. (left) Digital elevation model (DEM) representing a section of Squaw Creek, northwest of Ames, Iowa. (center) A hill-shade relief map, derived from the DEM, which displays shadows generated by the digital topography. (right) The hill-shade relief map, now partially-transparent, overlaying the DEM. The 3-D illusion improves topographic visualization.
Finally, all tiles were joined together into a larger map using the ‘Mosaic to New Raster’ tool (Fig 2.8). The result was a single raster file that allowed for a consistent color scheme and for areas larger than a single tile to be collectively analyzed.

Well-preserved tracts of washboard moraines were visually identified using the hillshade-overlain DEM mosaic. Automated delineation of washboard moraine tracts by a simple computer program would have been difficult due to variations in moraine trends and various post-glacial modifications of the moraines, such as their local erosion by post-glacial streams. Furthermore, the goal of this study was the spatial characterization of washboard moraines that were well-preserved, a subjective concept difficult to include objectively in a computer code.

**Figure 2.8.** *(left)* Digital elevation models (overlain by a partially-transparent hill-shaded relief maps) representing four individual tiles from the area surrounding Squaw Creek, Ames, Iowa. *(right)* The mosaic (also overlain by a hill-shade) created by combining the four tiles into one map.

**E. Profile generation**

Elevation profiles of washboard moraines were generated to enable the two-dimensional analysis of the three-dimensional digital terrain. Each profile was digitized (drawn digitally) in ArcGIS based on several criteria:
1) Profiles were confined to areas of well-developed washboard moraines. The aim of this project was not the characterization of all washboard moraines within the Des Moines Lobe, rather only those that were best preserved. This was the fundamental profile-selection criterion, as all subsequent criteria were dependent upon easily recognizable washboard moraines.

2) A single profile required a continuous tract of parallel moraines. Tracts were commonly bounded by areas devoid of washboard moraines. An elevation profile drawn spanning multiple tracts would have provided a skewed representation of moraine spacing.

3) Profiles were drawn within areas of limited alteration by natural drainage or human activity. Stream processes had completely erased washboard moraines from some areas, so elevation profiles were drawn to avoid these tract truncations. Road construction had significantly altered the land surface, so major roadways were avoided as much as possible. However, averaging of multiple parallel profiles during processing limited the influence of roads on the final elevation profile.

4) Profiles were drawn parallel to glacier flow direction, assumed to be perpendicular to the moraine crests (Clark, 1992; Hooyer and Iverson, 2002). Profile orientation was important because two of the research targets—the flow-parallel spacing and longitudinal moraine cross-section—would have become distorted if the profile were drawn obliquely (moraine spacing would be exaggerated and widths of individual moraines would be stretched).

Once delineated, each elevation profile went through a series of processing steps within ArcGIS to allow for further analysis with separate programs (see Appendix B).
F. Application to research objectives

Analysis of washboard moraine spatial characteristics was not possible without the creation of digital elevation models and elevation profiles. However, to glean information from these maps and profiles relevant to the research objectives of this thesis, further processing and analyses were required.

Regularity of washboard moraine spacing

The spacing of washboard moraines was studied by applying Fourier-analysis techniques to the washboard elevation profiles. Fourier analysis determines the principal components of complex waveforms and has been commonly used within various scientific disciplines for decades, including applications to topographic waveforms (eg. Pike & Rozema, 1975; Perron et al., 2008) (see Appendix C). However, Fourier analysis had not yet been applied to washboard moraines.

Fourier analysis, also known as harmonic analysis or spectral analysis, decomposes complex waveforms into simpler sine waves (Chatfield, 2004) (Fig 2.9). Fourier analysis is typically applied in the time domain, meaning the wave reflects variations of signal strength over time; Milankovitch cycles were detected in this manner (Hays et al, 1976) (Fig. 2.10). However, this project applied Fourier analysis to washboard moraines in the spatial domain, meaning the wave reflects changes in the elevation signal strength over distance (Fig. 2.10). Most commercially-available Fourier analysis software is in the time-domain; a custom script was adapted for this project to allow for Fourier analysis of spatial domain data (see Appendix D).

After Fourier analysis, a periodogram plots the results as variance against frequency (Fig 2.11). Originally described by Schuster (1898), a periodogram represents an estimate of
Figure 2.9. Example of decomposition by Fourier analysis. The complex (multi-frequency) wave at the top is decomposed into the three simple sinusoids.

Figure 2.10. a. Time-domain graph of the Milankovitch cycle reflecting Earth’s precession, or axis wobble. This wobble affects incoming solar rays, creating a cyclic climatic effect with a period of ~26,000 years. Fourier analysis of δ¹⁸O climate records contained within deep sea cores revealed this periodic variation (adapted from Hays et al, 1976). b. Spatial-domain graph of a washboard moraine elevation profile from Story County, Iowa, visually displaying a period of ~120 m.
Figure 2.11. a. Synthetic waveform, consisting of two waves (wave 1: $\lambda=50$ m, $A=2$ m; wave 2: $\lambda=10$ m, $A=1$ m), representing an example topographic elevation profile. b. Periodogram reflecting the spectrum obtained from the synthetic waveform subjected to an FFT. The red line represents the spectrum, the solid purple line represents the red noise null continuum, and the purple dashed line represents the 95% significance level. The two spectral peaks above the significance level, with wavelengths of 50 m and 10 m, correspond to the known wavelengths of the two synthetic constituent waves.
unknown periodicity strengths contained within a function (Chatfield, 2004). Statistically significant periodic spacings contained within each elevation profile were visually identified from the corresponding periodogram. Any spectral peak higher than the 95% confidence interval reflected significant periodicity at that particular wavelength. One periodogram reflects the spectrum obtained from a single profile swath, so this process was repeated for each profile swath generated within ArcMap. After the generation of all periodograms, statistically-significant moraine spacings were compiled and characterized. The wavelengths of significant periodicities were also included on the DEM for identification of spatial variations.

Profile stacking

The longitudinal symmetry exhibited by the profile of a representative washboard moraine can yield insight into moraine formation. A technique called stacking is commonly used to reduce waveform noise (e.g., Persh & Houston, 2004; Stilla et al., 2007; Abbott et al., 2009; Yao & Stilla, 2010). A similar method was used to average flow-parallel profiles of individual washboard moraines.

Single moraines were selected from the elevation profiles generated for Fourier analysis (Fig. 2.12). Using the Fourier analysis results as a guide, moraine wavelengths between 50 m and 200 m were chosen for stacking (see Chapter 3); this criterion ensured that only profiles representing washboard moraines were used in the averaging. Moraines were delineated through to trough from the detrended, swath-averaged profiles (Fig. 2.12). The swath-averaging again served to reduce data contamination from post-glacial surface modification and the detrending was crucial because most moraines were superimposed upon larger undulations, which could have created an artificially-skewed profile. However, the polynomial function used for detrending did not
perfectly remove the non-washboard landscape. The residual effect from a partially-detrended undulation caused some profiles to still begin and end at much different elevations (creating a skewed profile), so only detrended ridges with beginning and ending trough elevations within 0.5% of the total profile length were selected for stacking.

Detrended profiles were normalized to compare shapes of differently scaled moraines (Fig 2.13). A program written in Python by Chris Harding performed the normalization and stacking procedures. First, each profile length was normalized to the length of the single longest profile, while simultaneously stretching each profile to maintain the original width-to-height ratio of each ridge (Fig. 2.13b). After scaling both the x and y axes from 0.0 to 1.0, all ridge crested were aligned at y=1.0 (Fig. 2.13c). Then all y values at each position along the x axis were averaged to create the representative profile. The result was a compilation of profiles, normalized both horizontally and vertically, overlain by the average moraine profile, which was bounded above and below by error bars that represented the elevation variability (Fig. 2.13d).

**Figure 2.12.** A flow-parallel profile across a washboard moraine.
Figure 2.13. Stacking procedure.  

- **a.** Raw elevation profiles. Colored lines represent individual washboard moraines. 
- **b.** Profiles from 2.13a, now normalized horizontally and vertically. 
- **c.** Normalized profiles from 2.13b with crests aligned vertically. 
- **d.** Stacked-profile plot. The thick black line indicates the average of all individual hill profiles after stacking. The error bars extending above and below the average line represent ± 1 standard deviation.
Cusp-outwash correspondence

The relationship between cusps and valley trains of sand and gravel was investigated through cusp mapping and the inspection of corresponding subsurface records. Cusps, or scallops, are abrupt changes in the trend of washboard-moraine crests (e.g. Foster, 1969; Foster & Palmquist, 1969; Gwynne, 1942; Kemmis et al., 1981; Stewart et al., 1988) (Fig 2.14a).

Cusp limbs usually converge at modern drainages such as river valleys and the axes of these cusps are associated with modern sand and gravel deposits, which can be difficult to differentiate from older deposits (Fig. 2.14a). Furthermore, the cusp-convergence surface features at these localities are no longer present due to the stream erosion, obscuring conditions during cusp formation. To more clearly determine causation between the cusps and valley trains, special emphasis was put on locating cusp axes not associated with active drainage channels (Fig. 2.14b). Any sand and gravel associated with these particular cusps were covered by till, so this sand and gravel must have been overridden by the glacier. Historical well logs from local drillers were used to roughly characterize subsurface sediments near cusps not associated with modern streams (Fig. 2.15). Most logs were available online through the Iowa Department of Natural Resources. The basal Des Moines Lobe till can be up to 20 m thick (Quade & Seigley, 2006), so any sand and gravel would be reflected in the well logs below that depth. To account for the scarcity of well data in desired locations, any well drilled within one kilometer of the cusp axis was considered viable. Some strip logs were recorded by the Iowa DNR and contained detailed sediment descriptions. Other sediment descriptions, written by drillers, varied widely due to differing levels of education. However, the difference between till and sand/gravel is sufficiently obvious that their differentiation should have been straightforward.
Figure 2.14.  a. Cusp that converges on Squaw Creek valley, northwest of Ames. Yellow lines denote the trends of washboard moraine crests.  b. Cusp not associated with a modern stream, southwest of Stanhope, Hamilton County, Iowa. Yellow lines again denote washboard moraine crests. The blue dot displays the location of a farm well used for subsurface information (see Figure 2.15).

Figure 2.15. Driller’s log from well displayed in Figure 2.14b. Note the sand/minor gravel from a depth of 137-175 ft.
CHAPTER 3: RESULTS

A. Regularity of washboard moraine spacing

Fourier analysis was applied to 400 elevation profiles (80 swaths of five profiles each) within Story County, Iowa (Fig. 3.1). The profiles were largely in the central portion of the county, where washboard moraines are best preserved. Periodograms identifying statistically significant, periodic spacing of washboard moraines were constructed from the Fourier analysis results. Although all periodograms are available in digital format, representative profile swaths (Fig. 3.1) and their associated periodograms are shown in Figure 3.2.

Figure 3.1. Map of all profiles from Story County subjected to Fourier analysis. Each white line represents a swath of five elevation profiles. The red lines indicate locations of representative profile swaths (87A and 273A) whose Fourier analysis results are shown in Figure 3.2.
The periodogram created from the Fourier spectra of Profile 273A shows a strong peak at a wavelength of 110 meters (Fig. 3.2a). This peak was deemed statistically significant because it exceeds the 95% confidence interval (the dashed purple line). To simplify results, a single, discrete wavelength was identified for statistically significant peaks, and the peak widths were not considered. Elevation Profile 273A (Fig. 3.2a top) indeed shows moraine crest spacings of ~110 meters. This visual corroboration is a critical check when assessing the suitability of Fourier analysis for washboard moraine analysis.

In contrast, the periodogram constructed from Profile 87A (Fig. 3.2b) contains no statistically significant periodicity. Although this profile swath was drawn following the same criteria as Profile 273A, no spectral peak reaches above the 95% confidence level. The non-significant wavelengths of ~77 m and ~115 m can be vaguely recognized in the associated elevation profile, but the variances (areas underneath the curve) encompassed by these peaks are not sufficient compared to the total spectrum variance to warrant designation as being ‘statistically significant.’

Most washboard moraines of the Des Moines Lobe display statistically significant, periodic spacing. Compilation of all periodogram results shows that 55% (44/80) of profile swaths subjected to Fourier analysis have statistically significant moraine-spacing periodicity at a 95% confidence interval (Table 3.1). Of the profiles with significant periodicity, 27% (12/44) contained multiple significant periodicities, resulting in the identification total of 59 statistically-significant moraine spacings. Using z-scores and the Grubbs test for detecting outliers (Grubbs, 1969), the wavelength of 400 meters was excluded from analysis, leaving 58 significant wavelengths that were identified. The exclusion of this outlier is logical because that particular profile (248A) contains a long-wavelength undulation (on which the washboard moraines are superimposed) that is visually identifiable but not completely removed by detrending.
Figure 3.2a. (top) Detrended elevation profile 273A. (bottom) Periodogram showing the Fourier spectra created from Profile 273A. The solid purple line is the red noise baseline, and the dashed purple line is the 95\% confidence interval. There is a strong, statistically significant peak at a wavelength of 110 meters.
Figure 3.2b. Profile 87A. (top) Detrended elevation profile 87A. (bottom) Periodogram showing the Fourier spectra created from Profile 87A. There are no statistically significant peaks observed above the dashed 95% confidence interval.
Table 3.1. Statistically significant wavelengths identified from each profile’s periodogram.

<table>
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Figure 3.3. Histogram displaying the distribution of statistically significant wavelengths identified from periodograms.
The dominant wavelength of moraines is between 91 and 110 meters; wavelengths within this range account for 34.4% of the total distribution. Those between 111-130 meters and 131-150 meters account for 17.2% and 15.5%, respectively. A histogram of statistically significant moraine wavelengths indicates a positively-skewed distribution (Fig. 3.3), with a skewness value of 1.68. As a result, the average wavelength (128.5 meters) is skewed to the right of the median (118 meters) and mode (110 meters).

Statistically-significant periodicities were not evenly distributed across the county: profiles in the northern third of Story County tended to less frequently display statistically significant periodicity than those farther south (Fig. 3.4). The majority (23/44 or 52.3%) of the statistically significant profiles were located in the relatively small area between Ames and Nevada, which represents only ~6% of the total area of Story County. Within this region, 23/28 (82.1%) of elevation profiles yielded statistically significant periodicity. Only 40% (21/52) of the profiles derived from other areas of Story County showed significant periodicity.

This general reduction in regularity of moraine spacing from south to north is also true over a larger area of the lobe and is well-illustrated by contrasting regularity of washboard moraines south and north of the Altamont Moraine (Fig 3.4). The Altamont Moraine, a widely-recognized end moraine many times larger than any washboard moraine, forms a boundary between areas of generally strong and weak periodicity within Story County: 34/52 (65.3%) profile swaths from south of the Altamont moraine yield statistically significant moraine spacing, whereas only 10/28 (35.7%) profile swaths from north of the moraine show statistically significant spacing. This overall tendency for moraine spacing to become less regular to the north extends generally over the full latitudinal variation of the Des Moines Lobe in Iowa, so much so that washboard moraine identification (let alone analysis) in far northern Iowa is very difficult.
Figure 3.4. Map displaying the location of profiles subjected to Fourier analysis, with profiles color-coded to indicate whether moraine spacing is periodic (Green = statistically-significant periodicity, Red = no significant periodicity). The blue line marks the approximate location of the down-glacier margin of the Altamont Moraine, which LiDAR data suggest extends through the city of Ames, rather than north of Ames as indicated in pre-LiDAR maps (Ruhe, 1969; Kemmis et al., 1981).
B. Profile stacking

The longitudinal profiles of 58 individual moraines, selected from 17 of the detrended elevation profiles used for Fourier analysis, were selected for stacking (Fig. 3.5). The 17 profiles that contained these moraines displayed statistically significant periodicity. Several profiles are located in the northern portion of the county, but the moraines are largely located in the center of

Figure 3.5. Map displaying the location of profiles from which individual moraine profiles were selected for stacking.
Figure 3.6. Moraine shapes with dimensions normalized. Glacier flow was from left to right. The thick, black line indicates the average moraine profile, which indicates no systematic asymmetry. Error bars indicate ±1σ.
the county. Most elevation profiles were ~1 km in length and contained one to eight suitable moraine ridges each, as dictated by the moraine selection criteria (see Chapter 2). Individual moraines varied in length from 65 to 185 m, whereas moraine height varied from 0.2 and 2.5 m.

No substantial evidence of systematic flow-parallel asymmetry can be identified after stacking individual washboard moraines (Fig. 3.6). Although individual moraines display varying geometries, including profiles that are asymmetrically steepened either up-glacier or down-glacier, the average profile shows no conclusive asymmetry. The ±1σ error bars indicate similarly that variability of moraine height is symmetrically disposed about moraine peaks.

C. Cusp-outwash correspondence

Abrupt changes in washboard moraines trend (cusps) were correlated with outwash within the Iowa footprint of the Des Moines Lobe. Of the 59 identified cusps, 37 (62.7%) were coincident with surface outwash (valley trains) (Fig. 3.7). Lines connecting the apices of cusps, which I call convergence axes, were delineated and varied in length from one to ~45 kilometers.

The remaining 22 (37.3%) of cusp convergence axes were hypothesized to be coincident with subsurface outwash. Toward testing that hypothesis, a survey of digital well records yielded 13 wells with adequate sediment logs in the vicinity of cusp axes without surface outwash (Fig. 3.8). These 13 wells corresponded to ten cusp convergence axes (some axes were surrounded by multiple suitable wells) and were widely-distributed across the Des Moines Lobe. Additional wells were located in prime locations near cusp convergence axes but lacked sufficient well-log information.
Figure 3.7. Map showing convergence axes of all washboard cusps within the Des Moines Lobe. Convergence axes are shown as colored lines, indicating those associated with surface outwash (red) and not associated with surface outwash (green). Convergence axes connect the apices of adjacent cusps.
Figure 3.8. Map showing convergence axes of cusps with no surface outwash (green lines), as well as the locations of wells adjacent to cusps (orange dots) and wells remote from cusps (red dots) with adequate sediment descriptions. See Table 3.2 for well descriptions.
Well logs indicated subsurface outwash at nine of the 13 well locations adjacent to cusp convergence axes (Table 3.2). The most commonly identified sediments were sand or a sand/gravel mix. Well 2 contained no sediment description, but the shallow production depth (24.4-33.5 m) indicated the presence of a near-surface aquifer. The depth to outwash varied between 1.0 and 53.4 m, and the thickness of the outwash layer varied from 3.0-21.1 m. Although the identified outwash thickness varied from well to well across the lobe’s footprint, the wells in Humboldt County generally yielded the thickest outwash layers.

Well logs were also used to classify the sediments deposited on top of the outwash (Table 3.2). Seven wells (Wells 1-7) indicated subsurface outwash predominantly overlain by till. Two wells (Wells 8 & 9) did not show any overburden at all but are not associated with any modern fluvial processes; the DNR tentatively labeled these sediments as the Pilot Knob member of the Dows Formation, which are usually recognized as kame/esker deposits (Kemmis et al., 1981). Well 10 did not reveal any outwash but did indicate fractured limestone, which may have a relatively high hydraulic conductivity (Freeze & Cherry, 1979). Although located within a kilometer of their respective cusp axes, Wells 11-13 did not reveal any outwash at depth.

The well logs from additional wells drilled farther from the cusp axes were analyzed to test the spatial continuity of the outwash overlain by till. Wells 1a-7a were located near the respective cusp axes of Wells 1-7 (Figure 3.8). The axis-remote wells showed that the axis-adjacent deposits of subsurface outwash observed in Wells 1-7 were absent farther away from the cusp axes: the vertical profiles of Wells 1a-7a were all dominated by till (Table 3.2).
Table 3.2. Well logs used to evaluate stratigraphy near to and remote from cusps. Wells 1-13 are located near the axes of cusps with no surface outwash. Wells 1a-7a (red) correspond to Wells 1-7 (orange), respectively, but are located slightly further away from each respective cusp axis. Note that logs from Wells 1-7 (near the cusp axes) indicate subsurface outwash, and logs from Wells 1a-7a (further from cusp axes) do not.

<table>
<thead>
<tr>
<th>Well</th>
<th>Well ID</th>
<th>County</th>
<th>Distance from cusp axis (km)</th>
<th>Outwash depth [thickness] (m)</th>
<th>Substrate description</th>
<th>Overburden description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38317</td>
<td>Hamilton</td>
<td>0.25</td>
<td>41.8-53.4 [11.6]</td>
<td>sand and gravel</td>
<td>clay w/sand lenses (till)</td>
</tr>
<tr>
<td>1a</td>
<td>38316</td>
<td>Hamilton</td>
<td>1.2</td>
<td>-</td>
<td>sandy clay w/sand lenses (till)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>31393</td>
<td>Hamilton</td>
<td>0.3</td>
<td>(24.4-33.5) [9.1]</td>
<td>no description (very shallow production)</td>
<td>-</td>
</tr>
<tr>
<td>2a</td>
<td>44762</td>
<td>Hamilton</td>
<td>2.05</td>
<td>-</td>
<td>clay w/sand lenses (till)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5094</td>
<td>Humboldt</td>
<td>0.2</td>
<td>15.5-19.8 [4.3] / 19.8-36.6 [16.8]</td>
<td>gravel / sandstone</td>
<td>till</td>
</tr>
<tr>
<td>3a</td>
<td>10114</td>
<td>Humboldt</td>
<td>2.05</td>
<td>-</td>
<td>till w/gravel lenses</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4624</td>
<td>Humboldt</td>
<td>0.95</td>
<td>9.1-15.2 [6.1]</td>
<td>very coarse sand to gravel</td>
<td>till</td>
</tr>
<tr>
<td>4a</td>
<td>36189</td>
<td>Humboldt</td>
<td>1.7</td>
<td>-</td>
<td>clay w/sand lenses (till)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>38388</td>
<td>Humboldt</td>
<td>0.8</td>
<td>22.9-35.7 [12.8]</td>
<td>fine sand</td>
<td>clay w/gravel lenses (till)</td>
</tr>
<tr>
<td>5a</td>
<td>59520</td>
<td>Humboldt</td>
<td>2.6</td>
<td>-</td>
<td>clay (till)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>11935</td>
<td>Palo Alto</td>
<td>0.7</td>
<td>42.1-48.2 [6.1]</td>
<td>sand</td>
<td>clay (till)</td>
</tr>
<tr>
<td>6a</td>
<td>62416</td>
<td>Palo Alto</td>
<td>1.15</td>
<td>-</td>
<td>clay (till)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>65497</td>
<td>Cerro Gordo</td>
<td>0.55</td>
<td>10.7-13.7 [3] / 32-36.6 [4.6]</td>
<td>sand / gravel</td>
<td>clay w/sand lenses (till)</td>
</tr>
<tr>
<td>7a</td>
<td>17294</td>
<td>Cerro Gordo</td>
<td>1.4</td>
<td>-</td>
<td>till w/sand and gravel lenses</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>52404</td>
<td>Palo Alto</td>
<td>0.4</td>
<td>1.2-4 [2.4] / 2.4-10.1 [7.7]</td>
<td>sand / gravel</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>58501</td>
<td>Kossuth</td>
<td>0.9</td>
<td>0-8.2 [8.2]</td>
<td>stratified sand</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>30042</td>
<td>Story</td>
<td>0</td>
<td>10-</td>
<td>crevassed limestone</td>
<td>sandy clay (till)</td>
</tr>
<tr>
<td>11</td>
<td>43739</td>
<td>Greene</td>
<td>1</td>
<td>-</td>
<td>sandy clay (till)</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>51016</td>
<td>Greene</td>
<td>0.75</td>
<td>-</td>
<td>sandy clay (till)</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>29112</td>
<td>Palo Alto</td>
<td>0.8</td>
<td>-</td>
<td>sandy clay (till)</td>
<td>-</td>
</tr>
</tbody>
</table>
CHAPTER 4: DISCUSSION

A. Regularity of washboard moraine spacing

The flow-parallel spacing of washboard moraines is consistent with the hypothesis that they formed as subglacial crevasse fills, rather than as ice marginal dump or push moraines. Past studies have described washboard moraines as evenly-spaced, but without quantitative support (i.e. Gwynne, 1942; Foster, 1969; Stewart et al., 1988; Colgan, 1996). Fourier analyses of elevation profiles clearly show statistically significant periodicity amongst the washboard moraines of Story County with dominant periodicities of 91-110 m (Fig. 3.3). Periodic spacing of moraines is evidence against their formation on an annual basis at the glacier margin, as some have suggested (Gwynne, 1942, 1951), which would produce irregular spacing due to yearly temperature variations and resultant variability of margin retreat rates (Sharp, 1984; Bennett, 2001). In contrast, tracts of regularly-spaced crevasses have been identified by applying Fourier analysis of transverse crevasses of modern glaciers (Garvin and Williams, 1993). These periodic crevasses studied by Garvin and Williams (1993) were within a Greenlandic ice stream and Icelandic surge-type glaciers characterized by longitudinal extension within 15-30 km of the margin. Similarly, the Des Moines Lobe is hypothesized to have been in a state of extension and thin (Patterson, 1997; Hooyer & Iverson, 2002), with preconsolidation data indicating basal water pressures approaching the ice overburden pressure (Hooyer & Iverson, 2002). These factors would have favored the development of transverse crevasses that extended to the bed (Christofferson et al, 2005; Luckman et al, 2011). Spacing of moraines formed by squeezing of subglacial sediments—weakened by high pore-water pressure and pushed laterally and upward into crevasses by the effective normal stress gradient along the bed near crevasses—would mimic the periodic crevasse spacing.
Statistically-significant moraine spacings are not evenly distributed across Story County but are concentrated in the area between Ames and Nevada (Fig 3.4). Moraines north of the Altamont moraine appear to be spaced irregularly, perhaps as a result of post-glacial modification not experienced by the washboard moraines south of the moraine. This is consistent with the prevailing hypothesis of separate, surge-like advances of the Des Moines Lobe (Clayton et al., 1985; Colgan, 1996; Colgan et al., 2003): the Altamont Moraine represents the terminal moraine for an advance post-dating the original deposition of the washboard moraines of Story County (which were formed during the earlier Bemis advance). As a result, the washboards overridden by the more recent Altamont advance would now display less uniform properties than those to south of the Altamont moraine that were unaltered.

Although intriguing, the spatial distribution of statistically significant moraine spacing periodicity could reflect factors unrelated to glaciation. Areas with regularly spaced moraines were also the areas containing washboard moraines that were easiest to identify, suggesting a correlation between moraine preservation and statistically uniform spacing. Post-glacial processes may have modified moraine spacing more in some areas than in others. Soil studies quantifying post-glacial moraine modification indicate the original washboard relief has been reduced by 1-4 m by slope processes (Daniels & Handy, 1966; Burras, 1984; Burras & Scholtes, 1987), although why these processes should degrade the regularity of moraine spacing more in some areas than in others is unclear.

The Bering Glacier, a surge-type glacier in Alaska, presents a modern analog of the Des Moines Lobe. Characterized by large fields of transverse crevasses during and immediately after surge periods, the Bering Glacier’s last major surge occurred from 1993-95 (Herzfeld & Mayer, 1997; Roush et al., 2003) (Fig 4.1). Similar to the prevailing hypothesis for the Des Moines
Figure 4.1. (top) Transverse crevasses formed during the 1995 surge of the Bering Glacier, Alaska (photo by Bernhard Edmaier). (bottom) Transverse crevasses formed on the Bering Glacier during a minor surge in 2011 (photo by Chris Larsen).
Lobe advance (Clayton et al., 1985), surge-type glaciers, such as the Bering Glacier, periodically accelerate, without a change in mass balance, due to transiently high subglacial water pressures (Kamb et al., 1985; Kamb, 1987; Boulton et al., 1996).

The consequences of a rapid glacial advance associated with a surge are numerous, but three are of particular interest to this thesis. First, the swift advance gives rise to widespread longitudinal extension, opening large swaths of transverse crevasses (Boulton et al., 1996; Herzfeld & Mayer, 1997; Herzfeld et al., 2004). Second, the subglacial water pressure that is near the ice overburden reduces ice closure rates that can keep basal crevasses open, despite the overburden pressure of the ice (Golledge & Phillips, 2008; Luckman et al., 2011). These basal crevasses serve as voids into which sediments can upwardly deform as crevasse fills (Grippe, 1929; Foster & Palmquist, 1969; Stewart et al., 1988; Boulton et al., 1996; Evans & Rea, 1999). Third, after the surge termination, the glacier has extended well beyond the extent supported by the glacier’s prevailing mass-balance. This overextension leads to widespread stagnation and down-wasting (Sharpe, 1988; Boulton et al., 1996). This stagnation is important because it limits the modification of crevasse fills by active ice movement during net retreat of the glacier margin (Evans & Rea, 1999).

The Bering Glacier is particularly important to this study because it provides an example of modern crevasse-fill formation. During the most recent surge, transverse crevasses were well-documented across large portions of the glacier (e.g. Herzfeld & Mayer, 1997; Herzfeld et al., 2004) (Fig. 4.1). Upon surge termination, the glacier largely stagnated. Melting ice revealed crevasse-fill moraines in the vicinity of the crevasses (Molnia, 2004) (Fig. 4.2). The similarity between washboard moraines of Story County and transverse crevasse-fill moraines formed underneath the surging Bering Glacier is striking (Fig. 4.2). Crevasse-fill moraines, preserved
after surging, have been documented in the forefields of other glaciers (e.g. Sharp, 1985; Boulton et al., 1996; Christofferson et al., 2005). The Bering Glacier analog demonstrates that if the Des Moines Lobe stagnated following a surge-like advance (with an abundance of regularly-spaced transverse crevasses), sediments squeezed upwards into those crevasses could have been preserved as moraine ridges.

**Figure 4.2. (top)** Near-vertical aerial photograph of a 1 x 1.5 mile area recently exposed by the retreat of the Bering Glacier. The elongate ridges oriented vertically in the photo are crevasse-fill moraines formed during the latest major surge event (photo by Bruce Molnia). **(bottom)** Hill-shaded relief map of washboard moraines of Story County, oriented with north to the lower right to align the washboards with the crevasse-fill moraines shown from Bering Glacier. Note the similar moraine spacings and morphologies. The more rounded crests of those in Story County likely reflect post-glacial diffusive hillslope processes.
B. Flow-parallel profiles

The longitudinal profiles of washboard moraines also help reflect how they formed. Moraines that have been exposed to shear, such as annual push moraines or basal crevasse-fill moraines formed beneath an actively sliding glacier, are characterized by an asymmetrical profile (Sharp, 1984; Bennett, 2001). Lack of asymmetry supports washboard moraine formation as crevasse fills intruded into basal crevasses of a stagnant glacier.

Systematic asymmetry could not be identified after stacking 58 individual washboard moraines in Story County (Fig 3.6). Annual push moraines would be expected to display asymmetrical profiles with distal slopes exceeding proximal slopes (Sharp, 1984; Bennett, 2001) (Fig. 4.3). The steeper distal slope would result from shearing and stacking of marginal ice and associated sediments (Bennett, 2001). Similarly, sediment deformed upwards into an active-ice basal crevasse would be sheared into an asymmetric form during advance of the crevasse’s trailing edge (Sharp, 1984) (Fig. 1.4).

Figure 4.3. Diagram of a typical annual push moraine. The distal slope exceeds the proximal slope (from Bennett, 2001).
The lack of washboard moraine asymmetry is consistent with washboards forming subglacially and underneath stagnant ice. These conclusions support the prevalent hypothesis that the Des Moines Lobe stagnated after advancing quickly to its maximum extent (e.g. Clayton et al., 1985). While the surge-like motion would have produced transverse crevasses associated with longitudinal extension as the lobe advanced, the lack of moraine asymmetry shows that the crevasse-fill process did not take place until largely after the time of ice stagnation. Post-stagnation subglacial formation is also supported by observations of modern crevasse-fill ridges, formed after a surge of the Eyjabakkajökull glacier in Iceland, which lack systematic asymmetry (Sharp, 1985).

One complicating factor when analyzing hill morphologies is modification by normal slope processes. The washboard moraines of Story County have been continually modified for ~13,000 radiocarbon years since glaciation, which has undoubtedly had a large effect, as noted, on their relief and perhaps on the measured regularity of their spacing. Many slope evolution studies characterize sediment movement on gentle, soil-mantled slopes as a linearly diffusive process (Hanks et al., 1984; Heimsath et al., 2005) (Fig. 4.4), in which the flux of sediment transported is considered to be proportional to slope. Also characterized as “slope decline” with basal deposition, erosion would tend to occur more readily on the steeper face of a washboard moraine ridge, resulting in the face becoming progressively lower and more gently sloping (Ritter et al., 2002), thereby reducing asymmetry. Studies quantifying erosion rates of Des Moines Lobe washboard moraines have demonstrated the net movement of sediment from ridge crests to intervening lows, a process intensified by post-settlement farming (Daniels & Handy, 1966; Burras, 1984; Burras & Scholtes, 1987). However, if hillslope diffusion/slope decline is an accurate description of washboard moraine evolution, some remnant of original moraine
asymmetry would persist with time, albeit in a progressively less pronounced form. As noted, when moraine ridge profiles are averaged through stacking, no such asymmetry is observed (Fig. 3.6).

**Figure 4.4.** Idealized example of hill-slope diffusion. The original slope (thin line) had sediment eroded from the top and deposited at the bottom to form the new slope (thick line) (adapted from work by Chuck Connor, University of South Florida).

C. **Correlation between cusps and outwash**

Coincidence of so-called washboard moraine “cusps” and outwash deposits provides information about the washboard moraine formation mechanism. Cusps may represent annual push moraines formed along a lobate margin, with glaciofluvial processes concentrating outwash where supraglacial glacier drainage channels developed in the low areas on the glacier surface between lobes (Lawrence & Elson, 1953). Conversely, the outwash may have pre-dated cusp formation, thereby lowering subglacial water pressure there and locally slowing glacier slip (causing the deflection of crevasses) as the lobe advanced over the more-hydraulically conductive outwash (Stewart et al., 1988). After subsequent glacier stagnation, the deflected crevasses would have then been subjected to filling from below by weak sediments.

Coincidence of washboard moraine cusps and local outwash deposits, particularly those that can be shown to pre-date glacial advance as indicated by burial beneath late Wisconsinan till, provides evidence supporting the crevasse-fill hypothesis.
Most mapped cusps correspond to surface occurrences of sand and gravel in the form of modern alluvial surfaces. This is expected, as many of Iowa’s modern streams follow the buried valleys of ancient streams (Prior, et al., 2003). For example, the alluvium of Squaw Creek (which is bordered by strongly-cuspate washboard moraines) (Fig. 2.14a) is deposited upon pre-glaciation alluvium/outwash (Nicklin, 1974; Seidel, 1991) (Fig. 4.5). However, the surface outwash could have been coincidentally deposited above older sand and gravel. As a result, such occurrences of sand and gravel provide no definitive support for either mechanism of moraine formation.

In contrast to cusp axes coincident with alluvium at the surface, other cusps do not exhibit surface outwash along their axes. These cusps are usually coincident with buried outwash overlain by till (Fig. 4.6), indicating that the glacier advanced over the sand and gravel. This observation precludes the hypothesis that the outwash resulted from concentrated glaciofluvial deposition on the glacier surface during retreat. Also, where outwash coincident with cusps is overlain by till, the outwash lacks lateral continuity (perpendicular to the cusp axis)—a requirement for locally low water pressures in the substrate that could have led to locally slower slip and subsequent cusp formation. The weight of evidence, therefore, favors outwash valley trains controlling the location of cusps, through crevasse deflection and filling, rather than a cuspate glacier margin controlling the location of outwash trains. Absence of cusps in other areas within the footprint of the Des Moines Lobe does not, of course, constitute evidence of homogeneous drainage conditions. Washboard preservation is not adequate to define cusps in many areas. Also, washboard moraines elsewhere, such as in parts of northern Iowa are especially difficult to recognize because there are multiple orientations of washboard moraines (Fig. 4.7).
Figure 4.5. (top) Cross-section showing the Squaw Creek substrate. Note the Squaw Creek alluvium overlaying older outwash sand and gravel (from Nicklin, 1974). (bottom) Bedrock topography DEM overlain by the surface topography-derived hill-shaded relief map. Note the deepest bedrock is approximately underneath Squaw Creek (based on work by Christianson, 2008 and Simpkins, 2011).
Figure 4.6. Simplified block diagram showing an outwash substrate (valley train) overlain by cuspatc washboard moraines (yellow lines).

Figure 4.7. Digital elevation map of north-central portion of Kossuth County, Iowa. There are three distinct washboard moraine trends.
D. Corroborating data

Previous studies provide corroborating evidence that washboard moraines formed as crevasse fills from basal till beneath largely stagnant ice.

Till density and preconsolidation studies indicate washboard moraines in Iowa are composed primarily of basal till, rather than of supraglacial till (e.g. Kemmis et al., 1981; Stewart et al., 1988; Ankerstjerne, 2010). In one particularly well studied washboard moraine in Story County, densities of till samples were plotted against known density distributions of Des Moines Lobe supraglacial till (generally lower density) and basal till (generally higher density) (Ankerstjerne, 2010) (Fig. 4.8). Washboard tills match the density distribution of the basal till, showing that the till was compacted by overlying ice (Ankerstjerne, 2010). Furthermore, preconsolidation pressures obtained from washboard till samples indicate an overburden pressure of 67 – 390 kPa (Ankerstjerne, 2010) (Fig. 4.9). This is significantly higher than modern overburden pressure of 20-57 kPa exerted by overlying glacial sediments and soil, showing that the washboard moraines were at one time beneath the glacier.

Anisotropy of magnetic susceptibility (AMS) studies of washboard moraine tills have provided detailed information on moraine fabric and strain patterns (e.g. Stewart et al., 1988; Ankerstjerne, 2010). AMS fabrics show tightly clustered susceptibilities, indicative of till deformation by simple shear (Stewart et al., 1988; Ankerstjerne, 2010) (Fig 1.5b). However, some of these data also indicate strain indicative of pure shear, consisting of longitudinal shortening perpendicular to the moraine crests with vertical and transverse extension (Ankerstjerne, 2010) (Fig. 1.5c). These data support the moraine-forming sequence of events described within this thesis: basal ice motion by simple shear of the bed—slowed where cusps eventually form in areas of outwash-controlled drainage—would cause tightly clustered
Figure 4.8. Washboard moraine till densities (blue) superimposed upon typical density distributions of supraglacial (gray) and basal (black) tills (from Ankerstjerne, 2010).

Figure 4.9. Pre-consolidation pressures obtained from washboard moraine sediments compared to the modern overburden pressure (red line) (from Ankerstjerne, 2010).
AMS fabrics. After ice had completely stagnated, upward and lateral extrusion of till into crevasses would locally yield girdle fabrics (Fig. 1.5c), indicative of pure shear.

Widespread deformation of subglacial till by stagnant ice has been hypothesized to account for the genesis of many of the landforms formed beneath the soft-bedded portions of the southern Laurentide Ice Sheet (Eyles et al., 1999). This hypothesis was originally described as the “pressing” model (Stalker, 1960). Using sedimentological characteristics obtained from primarily Canadian tills, Eyles et al. (1999) suggested that so-called “hummocky” terrain is not a result of thick, supraglacial and englacial till deposition (as suggested by Clayton et al., 1985), but rather the result of water-saturated weak till squeezing upward into voids beneath the disintegrating ice mass (Fig. 4.10). Pressing of soft till is hypothesized by Eyles et al. (1999) to have formed many glacial landforms of the southern Laurentide Ice Sheet, varying from random hummocks, to so-called “humdrums” (hummocky drumlin features), to washboard moraines. Similarly, it is quite likely that in addition to longitudinal extension, transverse extension opened longitudinal crevasses into which soft till could be squeezed. Evidence of the resulting longitudinal crevasse fills is indeed seen throughout Story County (Fig. 4.11).

![Diagram showing the “pressing” of soft basal till by stagnant ice](image-url)
Figure 4.11. Map showing area 1 km southwest of Nevada, IA. Longitudinal crevasse-fill moraines (red) are among washboard moraines (yellow).

E. Inferred genesis of washboard moraines

In Story County, well-preserved washboard moraines provide insight into the sequence of events required for moraine formation. Most fundamental of these was the surge-like advance of the Des Moines Lobe.

In the face of widespread warming, the Des Moines Lobe (circa ~14-15 k radiocarbon years) rapidly advanced in a surge-like state (Clayton et al., 1985; Patterson, 1997). Although strict classification of the Des Moines Lobe as a “surge-type” glacier is unwarranted because the term implies periodic rapid motion, surge-like behavior is indicated. Radiocarbon dates show the lobe advanced very swiftly at a rate of ~ 1700 m/yr (Clayton et al., 1985). Reconstructions
demonstrate that the lobe was thin and low-sloping, associated with very small basal shear stresses (Mathews, 1974; Clark, 1992; Hooyer & Iverson, 2002). Small basal shear stresses are usually characteristic of slow-flowing glaciers, but pre-consolidation data indicate the lobe was nearly floating (similar to modern glaciers when surging) (Hooyer & Iverson, 2002; Ankerstjerne, 2010). Pore-water pressure near the ice overburden pressure at the base of the lobe allowed it to quickly advance despite low basal shear stresses (Clayton et al., 1985).

The advancing Des Moines Lobe extended longitudinally, similar to modern surge-type glaciers, which resulted in transverse crevasses. Transverse crevasses that extend to the bed require longitudinal extension and basal water pressures close to the overburden pressure (Christofferson et al., 2005; Golledge & Phillips, 2008; Luckman et al., 2011). The crevasses that formed at the base of the Des Moines Lobe, which were uniformly spaced (Fig 3.4), served as the voids into which sediment could intrude. The average spacing of the crevasses in Story County (91-110 m) was comparable to the reconstructed ice thickness in the area (Hooyer and Iverson, 2002). Aspects of basal crevasse morphology were then preserved as washboard moraines. For example, heterogeneity beneath the glacier led to the up-glacier deflection of crevasses in areas where the substrate was composed of hydraulically conductive sediment (sand/gravel) (Fig 4.6), which slowed local ice flow by lowering pore-water pressure in the substrate. Crevasses formed in these areas of slower flow were deflected to form cusps.

Washboard moraines were formed as crevasse fills after surge stagnation. Contrary to previous studies (e.g. Gwynne, 1942, 1951; Stewart et al., 1988), the Des Moines Lobe did not “actively” retreat like a typical glacier; forward ice movement during an active retreat would have likely destroyed any existing washboard moraines. Upon stagnation, water-saturated till was extruded into the stationary crevasses (Foster & Palmquist, 1969; Stewart et al., 1988). This
upward “squeezing”, as indicated by evidence of pure shear (Ankerstjerne, 2010) and a lack of asymmetry (Fig. 3.6), was a likely a result of local gradients in effective pressure created by the weight of the adjacent ice.

F. Implications

The washboard moraines of Story County cannot be used to infer annual retreat rates. Annual moraines formed proglacially during an active retreat would allow for retreat rate determination by simply counting moraines (Gwynne, 1941, 1952; Lawrence and Elson, 1953). However, calculations of the Des Moines Lobe retreat rate based upon washboard moraines are incorrect because the moraines formed neither annually nor proglacially, but rather concurrently and subglacially. These results bear on the similar use of West Antarctic corrugation ridges to calculate ground line retreat rates (Ottesen et al., 2005; Dowdeswell et al., 2008); this thesis disputes the assumption that transverse moraines must form at an ice margin. As a result, additional study of basal processes in Antarctica is necessary to further qualify statements on grounding line retreat because basal crevasses could lead to similar features.

The crevasse-fill origin of washboard moraines supports their use in reconstructions of the Des Moines Lobe’s morphology. Washboards have been used as the primary flow-direction indicator in reconstructions. They have been assumed to have developed transverse to flow, to have formed subglacially, and to have formed when the lobe was at its maximum extent (e.g. Mathews, 1974; Clark, 1992; Hooyer & Iverson, 2002). The crevasse-fill hypothesis, advocated herein, provides support for these assumptions.

Finally, the characterization of the Des Moines Lobe as surge-like (Clayton et al., 1985; Colgan, 1996) is supported by the conclusion that washboard moraines formed as subglacial
crevasse fills. The high water pressures that weakened the till (enabling upward deformation) also allowed the lobe to surge in spite of low driving stresses (Kamb et al., 1985; Kamb, 1987; Boulton et al., 1996). The basal crevasses, into which sediment extruded to form the washboard moraines, are characteristic of surge-type glaciers undergoing longitudinal extension (Boulton et al., 1996; Herzfeld & Mayer, 1997). The Des Moines Lobe also advanced out of balance with climate forcing and stagnated upon reaching its maximum extent, as would be expected from a surge-type glacier (Sharpe, 1988; Boulton et al., 1996). This stagnation allowed time for till to squeeze upward between blocks of stagnant ice and also prevented resultant ridges from being destroyed by slip at the glacier base.
CHAPTER 5: CONCLUSIONS

The spacings of the washboard moraines of Story County indicate they formed as subglacial crevasse fills and not as annual push moraines at the lobe margin. The ridges are evenly-spaced, with an average spacing of 90-110 m. This suggests washboard moraines formed in crevasses, as periodic crevasse patterns have been observed on modern surging glaciers and ice streams (Garvin & Williams, 1993). Annual push moraines would not be periodically spaced, as seasonal mass balance forcing would vary from one year to the next.

The average flow-parallel profile of Story County washboard moraines also favors the crevasse-fill hypothesis. The profile displays no asymmetry, consistent with subglacial formation beneath stagnant ice. Moraines formed by pushing at the margin would be asymmetrical, with distal slopes exceeding proximal slope, and crevasse fills formed beneath actively sidling ice would be asymmetrically sheared by the crevasse’s trailing edge. Furthermore, the preservation of washboard moraines is also dependent upon stagnation, as forward ice movement during an active retreat would have modified or erased the moraine ridges.

Cusps, with outwash at their axes, formed as crevasse-fill ridges in deflected transverse crevasses and not as push moraines along a retreating lobate margin. The outwash supported lower pore-water pressures, locally slowing glacier slip and deflecting the crevasses. Till commonly overlies the outwash at cusp axes, indicating that the glacier advanced over the outwash and precluding supraglacial outwash deposition (and associated push moraine formation) at a retreating lobate margin.

The spacing, shape, and locally-cuspate characteristics of washboard moraines indicate that they formed as subglacial crevasse fills after the stagnation of a surge-like Des Moines Lobe
advance. Longitudinal ice extension, caused by the rapid advance of the lobe on a bed under high pore-water pressure, created large tracts of transverse crevasses. In some locations, the glacier advanced over outwash, locally slowing slip and deflecting the crevasses. After surge stagnation, till weakened by high pore-water pressure was deformed by the weight of adjacent ice into the transverse crevasses. The ridges were then exposed as the surrounding stagnant ice melted.

The conclusion that washboard moraines formed as crevasse fills has diverse implications. The hypothesis of a surge-like Des Moines Lobe advance, as advocated by Clayton et al. (1985), is supported by evidence of rapid advance and stagnation associated with crevasse-fill moraine shape and preservation. A crevasse-fill origin for washboard moraines improves the veracity of lobe reconstructions dependent upon washboard moraine formation being both subglacial and perpendicular to flow (e.g. Clark, 1992; Hooyer & Iverson, 2002). The existence of transverse crevasse-fill moraines also prompts reassessment of conclusions regarding transverse moraines in other areas of the world, particularly those on the sea floor adjacent to ice sheets (e.g. Ottesen et al., 2005; Dowdeswell et al., 2008): the assumption that these moraines formed sequentially at the grounding line by seasonal or tidal forcing, rather than simultaneously in transverse basal crevasses, may prove to be invalid.
APPENDIX A: LIDAR DATA CONVERSION

The LiDAR converter script, written by Chris Harding in the coding environment Python and available for download on Google Code (code.google.com/p/geoinformatics), linked together several ArcGIS tools (Fig. AA.1). Elevation points representing each LiDAR tile were downloaded and stored locally in a binary file format called LAS (Log ASCII Standard). The ArcGIS tool ‘LAS to Multipoint’ was used to read the bare earth returns from the LAS file and then store them as a 3-D multi-point shapefile. The 3-D points were then converted into a surface of irregular, non-overlapping triangles called a TIN (Triangulated Irregular Network) (Lee, 1991) using the ‘Create TIN’ and the ‘Edit TIN’ tools (Fig AA.2). Each triangle corner within the TIN, called a “node”, contained the x,y and z coordinates of a single LiDAR elevation point.

Figure AA.1. Visual representation of the Python script used to process LAS files. The input LAS file is blue, ArcMap tools used by the script are yellow, and output files are green.

Figure AA.2. (left) Example LiDAR points superimposed upon a 1 m grid. (right) The same LiDAR data points connected into triangles to form a TIN.
This TIN surface was then converted into a raster with a 1 m cell size using the ‘TIN to Raster’ tool. In general, raster cells of a digital elevation map reflect the z (elevation) value of their center point. The ‘TIN to Raster’ tool interpolates the elevation value for each cell center using the natural-neighbors interpolation algorithm, which weights the elevations of the closest TIN nodes by the cell area covered by each respective triangle (Fig. AA.3). The final product is a DEM raster with a 1 m resolution. Although this sequence of tools could have been operated manually using the ArcMap interface, the Python script was written to process all .LAS files with limited user input.

**Figure AA.3.** Maps displaying a location on the west side of the Squaw Creek river valley, northwest of Ames, Iowa. **a.** TIN surface, as generated from the bare-earth returns. The surface, made entirely of triangles, is almost recognizable as topography. **b.** Raster image with 1 m resolution, as generated from the TIN (Fig AA.3a). Pixel color reflects elevation, increasing from green to red.
APPENDIX B: PROFILE CREATION

After the locations of the profiles were finalized following the delineation criteria (see Chapter 2), each elevation profile went through a series of processing steps within ArcGIS to allow for further analysis with separate programs. First, a separate shapefile for each profile was created from the delineation template. Individual profiles (and all associated files) were named based upon the profile’s starting position within the county’s PLSS (Public Land Survey System, grid, which is downloadable from the Iowa DNR (Fig. AB.1a).

![Profile creation diagram](https://via.placeholder.com/150)

**Figure AB.1.** a. Single profile, drawn in Story County PLSS grid 298. b. Profile swath consisting of five parallel profiles spaced 20 m apart. c. Line graph of the 3-D profile swath derived from b., as generated within ArcMap. Note the sinusoidal nature of the washboard moraines and the difference between the scales of the axes; elevation varies only ~2 m over the ½ km long profiles.
Additional profiles, spaced 20 m and 40 m away from the initial profile, were generated on both sides of the original profile using the ‘Copy Parallel’ tool within the Editor Toolbar. This created sets of five parallel profiles within a single shapefile, referred to herein as swaths (Fig. AB.1b), which were later averaged for analysis. The averaging of the profiles contained within a swath reduced data contamination from post-glacial surface modification; a topographic anomaly contained within a lone profile was buffered by averaging with the other four swath profiles.

Elevation data were then added to the profile swaths using the ‘Convert Features to 3D’ tool within the 3D Analyst Toolbar (in ArcGIS 10, the tool is referenced as Functional Surface – Interpolate Shape). During execution of this tool, elevation values from the DEM were added to the profiles, raster cell by raster cell, along the entire length of each profile to create 3-D profiles.

After each profile swath was created, it was exported for analysis outside of ArcGIS. Using the ‘3D Analyst – Create Profile’ tool, each swath was exported into a spreadsheet file (.csv). For each elevation point along the profile, the exported file contained an x value (corresponding to the horizontal distance of each point from the start of the profile) and a y value (corresponding to the elevation of each data point). The result was a file containing the x and y values for the five profiles of a swath, which was then compatible with any basic plotting software.
Fourier analysis determines the principal components of complex waveforms and has been commonly used within various scientific disciplines for decades, including applications to topographic waveforms (e.g., Pike & Rozema, 1975; Perron et al., 2008). The wave decomposition process involves a Fourier transform that converts data from the spatial (or time) domain to the frequency domain. The complex waveform is fit by least squares to sinusoidal waves of varying wavelength and orientation phase, and then ‘transformed’ from the original x-y array to a new array (Chorley, 1972). The new array, called the spectrum, is the frequency-domain representation of the original complex wave and is the same size as the original array, but now reflects the amplitude and phase of the fitted constituent sine and cosine functions (Chorley, 1972).

The finite lengths of the elevation profiles described within this study required the use of a specific type of transform, called a discrete Fourier transform (DFT). A DFT requires at least one full period of the waveform to compute its spectrum (Jenkins & Watts, 1968). However, data covering multiple periods typically improve the quality of the analysis. The elevation profiles analyzed in this thesis contained 4-20 periods, and thus were well-suited for a DFT.

A discrete Fourier transform is efficiently calculated by a fast Fourier transform (FFT) algorithm, such as the Cooley & Tukey FFT algorithm (Cooley & Tukey, 1965). Normally, a discrete Fourier transform is computed with a single but often cumbersome series of operations. A fast Fourier transform breaks down a large DFT into smaller, more easily-computable DFTs; computing the regular DFT for a data set with N number of points requires $N^2$ operations, whereas computing the same DFT with the FFT algorithm requires only $N \log N$ operations (Cooley & Tukey, 1965). Depending upon the size of the data set, this can reduce the number of
required operations by an order of magnitude or more (Chatfield, 2004). The only caveat with using the FFT is that the number of data points within the waveform’s data set must be equal to a power of two (256, 512, 1024, etc.), so profiles with less samples must, therefore, be padded to the next higher power of two with zero-value samples.
APPENDIX D: FOURIER ANALYSIS MATLAB SCRIPT

A MATLAB script performing spatial domain Fourier analysis was written by Chris Harding, based upon code written by Perron et al. (2008) and Meko (2011). This script created a smoothed periodogram from a swath of five elevation profiles in five steps:

1) Detrending
2) Padding
3) Tapering
4) Fast Fourier transform computation
5) Smoothing

1) Detrending

A basic assumption when using a Fourier transform is that the mean, variance and frequency of the waveform are constant throughout the entire profile. In order for this assumption to hold, any background trend present within the data must be removed by detrending. As a result, detrending effectively serves as a high-pass filter to remove low-frequency artifacts that would clutter the Fourier spectrum.

After calculating an average profile from the five profiles of the swath, the MATLAB script fits a series of polynomial functions to the average profile to approximate large-scale variations and isolate the washboard moraine undulations. Once the best-fitting polynomial is determined by the user, it is applied to the profile as a detrending function; the program subtracts the polynomial function from the profile. The result is a “detrended” waveform that is devoid of the large-scale polynomial (Fig. AD.1).
2) Padding

Before performing the Fourier transform, it is necessary to “pad” the data with zeros so that the total number of samples is the next higher power of two (e.g. 947 samples would need to be padded up to 1024 samples) (see Appendix C). The detrended elevation data are already centered about 0, so adding 0-elevation samples does not change the character of the data and does not alter the resulting spectrum (Bloomfield, 2000). The power of 2 also determines the precision of the Fourier analysis by increasing resolution: padding to even higher powers of 2 (e.g. padding 947 to 2048 or 4096 samples, instead of 1024) may result in a more detailed spectrum.

3) Tapering

A technique called “tapering” was used to reduce the effects of profiles with an incomplete cycle at either end. Sometimes profiles were generated a few samples too short or long, which convoluted the resulting spectrum with “spectral leakage” (Fig AD.2). Tapering minimized the
leakage by multiplying the data by a Hanning window (basically the positive portion of a cosine wave), ultimately serving to sharpen the Fourier spectrum.

![Waveform and Spectrum](image)

**Figure AD.2.** (left) An example waveform with an incomplete cycle at the right end of the wave (blue) and the same waveform after being tapered with a Hanning window (green). (right) The spectrum computed from the untapered waveform (blue) and the spectrum computed from the tapered waveform (green). The tapered spectrum has much less leakage on either side of the peaks.

4) **Fast Fourier transform computation**

The script next calculated the Discrete Fourier transform (DFT) using the Fast Fourier Transform method (FFT). The result was a frequency domain plot called a periodogram (Fig 2.11b). A periodogram shows the strength of periodic components (spectral power) (y-axis) over distance (x-axis) (Chatfield, 2004). The unit on the y-axis is mean squared-amplitude of the variance; it has been normalized so that the sum of the spectral power of all components corresponds to the variance of the data.
In addition to plotting the periodogram, a baseline was required for determining which peaks were sufficiently high to be statistically significant. Red noise (Brownian noise) is the integral of white noise and displays increasing power with decreasing frequency (Torrence & Compo, 1998); generally, increasing power with decreasing frequency characterizes topographic variations (Perron et al, 2008). The spectrum of red noise can thus be used as a baseline, or null continuum, to indicate which peaks are high enough to be non-random. Assuming that the spectral power follows a chi-square distribution with 2 degrees of freedom, a 95 % confidence interval was constructed from the variance (total area under the curve) of the washboard-derived spectrum and plotted as a line above the baseline (Perron et al, 2008). This 95 % confidence line parallels the red noise baseline and represents a significance boundary: any washboard-derived spectral peak above the significance level represents only a 5 % probability to exist purely by chance (Fig. 2.11b).

5) **Smoothing**

Periodograms created from real-world waveforms are typically less clear than the periodograms generated from synthetic waveforms, and therefore require smoothing to clarify results. Smoothing (filtering a raw periodogram with a low-pass filter) removes high-frequency variations, serving to reduce the overall spectral variance and remove minor peaks (Fig. AD.3). Repeated filtering and/or wider filters increase the degree of smoothing. Through trial and error, sufficiently-smoothed periodograms (for the purposes of this thesis) were obtained after 5 passes with a binomial filter of size 3. The resulting smoothed periodograms clearly identified the statistically significant length(s) of the wave components that were present in the elevation profile. This multi-step process was performed for each profile, ultimately leading to the visual
Figure AD.3. Periodogram showing the effects of smoothing. The x-symbols show the raw spectral power for each spectral frequency and the red line shows a smoothed version of those raw data.
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