GLACIAL MORPHOLOGY OF THE CARY AGE DEPOSITS IN A PORTION

OF CENTRAL IOWA

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 Subject: Geology

Approved:

Signatures have been redacted for privacy

rsity

Ames, Iowa

1969

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ABSTRACT

Surface expression of the Cary Age Drift (Des Moines Lobe of Iowa) exhibits a pattern of intersecting linear ridges and depressions, previously termed swell-swale or "minor moraine" topography. Linear ridges, as mapped from air photos, are alligned approximately parallel or transverse (45 to 90^{o}) to associated end morainal systems.

Both parallel and transverse ridges appear genetically related, are composed predominately of till, range in height from five to twenty feet and have a mean spacing of 350 feet. Ridge intersections produce "T", "offset", "step" and "box" patterns. The irregular shape and high dip of cross-bedding of small sand bodies suggest a controlled ice disintegration origin. Allignment of till fabric with glacier flow (indicative of a lodgment till), the orientation of linear ridges and the apparent effect of the pre-Cary topography on the height and intensity of ridge formation suggest an ice flow control for their origin.

The current hypothesis that the ridges alligned approximately parallel to the margin represent "annual" recessional moraines does not explain the lack of outwash, the origin of transverse ridges, till fabric or the number of moraines and their geographic distribution.

Alternate hypotheses for the observed pattern are: 1) crevasse fill, 2) ice marginal thrust, 3) basal crevasse "squeeze", 4) inclusion of subglacial material by basal freezing and 5) boundary wave phenomenon.

INTRODUCTION

Glaciation is an integral part of the Pleistocene history of Iowa. Four periods of continental glaciation covered all or part of the state; these were the Nebraskan, Kansan, Illinoian and Wisconsin glaciers. Wisconsin glaciation, the most recent and less extensive than the Nebraskan and Kansan, is characterized in Iowa by two stages. Ice during the Tazewell stage (20,000 years b.p.[1]) terminated about 100 miles south of the Iowa-Minnesota border. Tazewell drift has been obscured, in part, by younger Cary drift. The Cary glacier (14,000 years b.p.) extended 135 miles into Iowa to its terminus at Des Moines (Ruhe 1969).

The Des Moines lobe, a product of Cary glaciation, exhibits a complex landform pattern of intersecting ridges, closed circular depressions and open linear depressions. The objectives of this study are 1) to map the distribution and orientation of the glacial landforms of the Des Moines lobe, 2) to determine the composition and variability of materials formin the various landforms, 3) to determine petrofabrics of the drift at selected sites, and 4) to critically evaluate the various hypotheses of origin for the landforms observed.

Landforms and deposits of the Des Moines lobe are well suited for genetic studies of glacial landforms for three reasons. First, the landforms can be assumed to have retained their original shape because little time has elapsed since deglaciation for erosion to have greatly altered the glacial landscape. The number of peat bogs, closed depressions and

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[1]b.p. indicates years before the present.

poorly integrated drainage systems attest to the youthful conditions of the Cary drift plain. Walker (1966) estimates that from 3-6 feet of sediments have been removed from the topographic highs. Second, the bedrock stratigraphy, structure and topography and the Pleistocene stratigraphy have been thoroughly investigated in the study area by other workers. Third, the only major study of the Des Moines Lobe landforms is that by Gwynne (1941, 1942a, 1942b). His conclusions are that the glacial landforms oriented parallel to the margin of the lobe represent "annual" recessional moraines.

This study indicates that Gwynne's hypothesis is inadequate to explain: 1) the lack of outwash on the upland, 2) the origin of non-parallel features and 3) the composition and fabric of the landforms. Ruhe, though, has mapped large areas of the Des Moines lobe as end moraine using swell-swale patterns as his criteria (Ruhe 1952). Similar landforms observed in North Dakota and Central and Western Canada have been described as ice stagnation features. The data from this study suggests that the orientation of linear elements is ice flow controlled but does not indicate whether they were formed at the time of glacial flow or during stagnation of the glacier. In light of this study a more thorough study of the processes of deglaciation and a reevaluation of Des Moines lobe glacial features is indicated.

Location

The area of study is located within the central part of Iowa (Figure 1). The area covers 400 square miles in northwest Story County, eastern

Boone County, southeast Hamilton County and the southwest portion of Hardin County, Iowa. The city of Ames lies approximately at the center of the study area.

Aerial photographs of the United States Department of Agriculture 1939 and 1953 series, exist for the entire study area at a scale of 1:20,000. Aerial photographs of the United States Corp of Engineers, 1967 series, cover the central part of the study area at a scale of approximately 1:12,000. The United States Geological Survey Ames and Boone quadrangles, at a scale of 1:62,500, covering the central and western portion of the study area have a contour interval of 20 feet.

Drainage

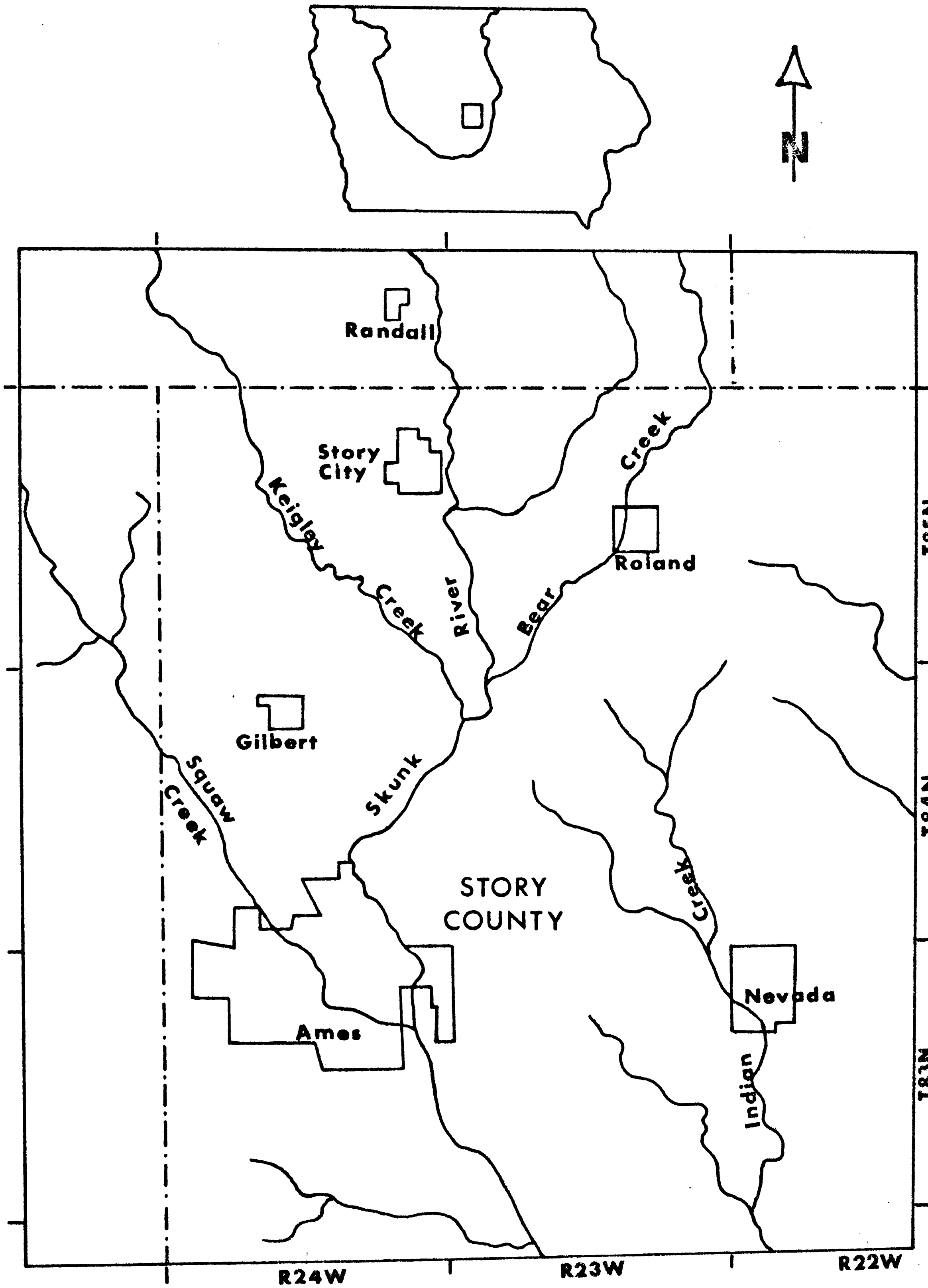
The study area lies within the Skunk River drainage basin, a tributary of the Mississippi River (Figure 1). Squaw Creek and Keigley Creek, flowing southeast, drain the western 1/3 of the area. Bear Creek, flowing southwest, drains the northeast 1/4 of the study area. East and West Indian Creek, flowing southeast, drain the southeastern portion of the area and join the Skunk River outside the area of study.

Geologic Description

Bedrock stratigraphy

Bedrock outcrops along the valleys of Skunk River, Bear Creek and Squaw Creek. Between Story City and Ames, in the Skunk River Valley are exposures of Pennsylvanian shales and Mississippian carbonates of the

Figure 1. Location of study area


N
Randall
Story City
Keigley
Creek
River
Bear
Creek
Roland
Gilbert
Squaw
Creek
Skunk
STORY
COUNTY
Creek
Nevada
Ames
Indian
T85N
T84N
T83N
R24W
R23W
R22W

Saint Louis and Warsaw formations (Zimmerman 1952). Along Bear Creek are exposed Pennsylvanian limestones, sandstones and shales. Subsurface studies indicate that the bedrock immediately below the drift consists of the Saint Louis, Warsaw, Keokuk, Gilmore City and the Hampton formations of Mississippian age and the Cherokee Group of Pennsylvanian age (Figure 2), (Sendlein and Dougal 1968).

Bedrock structure

The bedrock structure in the study area was first studied by McGee (1891) and Beyer (1898). From limited outcrop and well log information they established a northwest-southeast anticlinal flexure which they termed the "Skunk River Anticlinal". A revision of the earlier concepts was made by Zimmerman (1952), Zimmerman and Thomas (1953) and Huedepohl (1955). They established the major structure as a northeast-southwest trending, asymmetrical anticline, with the steeper dip to the east which they named the "Ames-Roland Anticline".

Staub (1969), using seismic and well log data, concluded that the major structure in western Story County was related to a series of northeast-southwest faults with a minimum of folding.

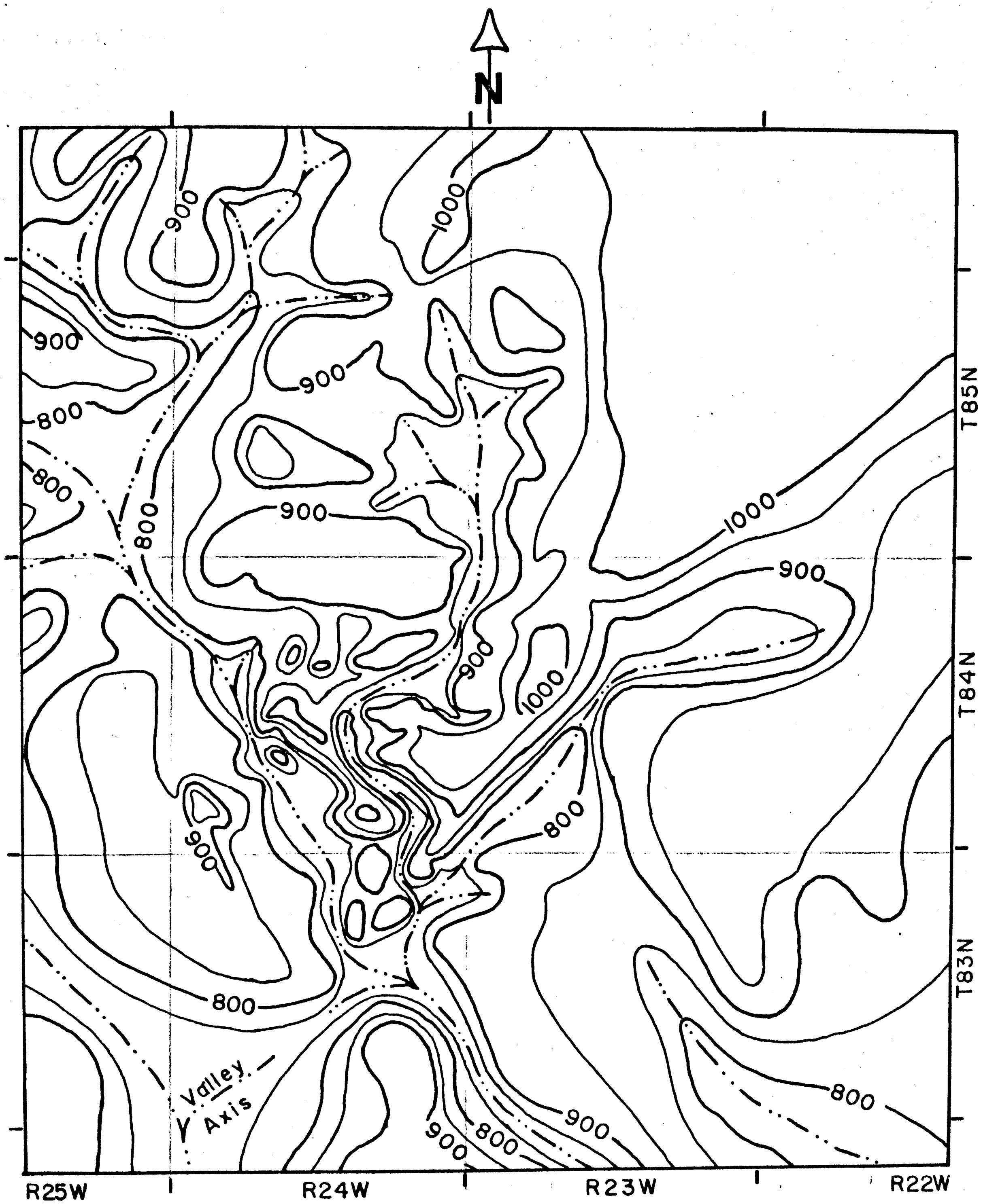
Preglacial Topography

The preglacial topography of Story County has been studied by Zimmerman (1952), Backsen (1963), Twenter and Coble (1965) and Schoell (1967). Two major bedrock channels were found underlying the modern valleys of the Skunk River and Squaw Creek (Figure 3). These bedrock channels are called the Skunk channel and Squaw channel respectively and have a relief of about

Figure 2. Idealized bedrock stratigraphic column

SYSTEM	SERIES	GROUP	FORMATION	DESCRIPTION
Pennsylvanian	Des Moines			
		Cherokee	Undifferentiated	shale, sandstone, limestone, coal
Mississippian	Meramec		St. Louis	sandy limestone
	Osage		Warsaw	shale dolomite
			Keokuk	cherty dolomite and limestone
	Kinderhook		Gilmore City	oolitic limestone
			Hampton	limestone and dolomite

Figure 3. Bedrock configuration of the study area (map redrawn after Kent 1969, personal communication) (contour inte
50 feet)


N
900
1000
900
900
800
800
800
900
1000
900
900
1000
T85N
T84N
T83N
900
800
800
Valley Axis
900
800
900
800
R25W
R24W
R23W
R22W

200 feet whereas the present surface has a maximum relief of approximately 100 feet.

The Squaw channel, from its confluence with the Skunk River southeast of Ames, trends northwest passing under stratford (Hamilton County) and finally ends eight miles north of Fort Dodge. The Skunk channel first appears just north of Story City, trending northwest-southeast. At Soper's Mill (sec. 6, T84N, R23W) the channel swings to the southwest paralleling the north flank of the "Ames-Roland" structural high and exhibits a gorge-like channel. One mile north of Ames the Skunk channel breaches a saddle in the structural high and joins with the Squaw channel just south of Ames.

The greater depth and length of the Squaw channel relative to the Skunk Channel substantiates Beyer's (1898) hypothesis that the Squaw channel is the primary headward extension of the bedrock channel which occurs below the confluence of the two channels, and that the Skunk channel is a tributary to the Squaw channel. This is also described by Backsen (1963, p. 12):

> The bottom of the bedrock valley under Squaw Creek has a lower elevation than the bottom of the bedrock valley under the Skunk River. Maximum relief in the pre-Pleistocene(?) valley under Squaw Creek is approximately 180 feet, whereas, maximum relief in the pre-Pleistocene(?) valley under the Skunk River is about 100 feet. This would indicate, if the two valleys are the same age, then the bedrock valley under the Skunk River has a very steep gradient immediately upstream from the confluence with the valley under Squaw Creek. However, it seems unlikely that this steep gradient would have existed and that, more probably, the valley under the Skunk River is younger than the bedrock valley under Squaw Creek.

Pleistocene Stratigraphy

The sequence of regolith materials in Story County can be divided into five distinct units: 1) Nebraskan till, 2) Kansan till, 3) Wisconsin drift, 4) sand and gravel beds and 5) silt.

Nebraskan till

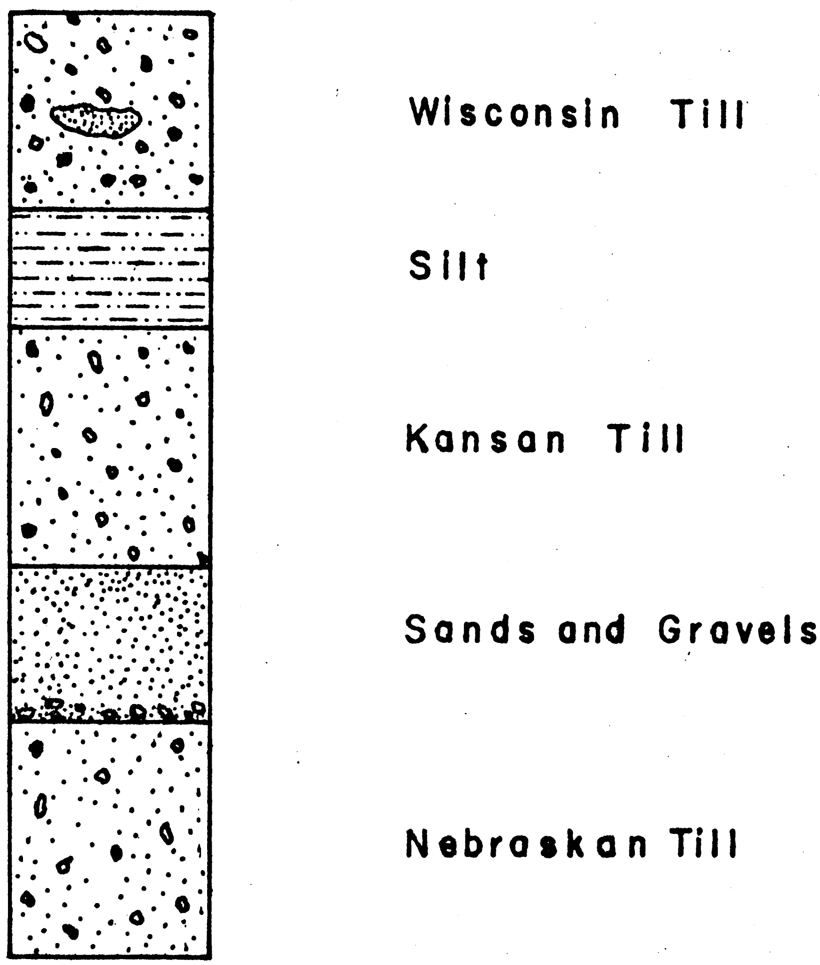
Nebraskan till has been found only in limited amounts and then only as the basal deposit of the Squaw Creek bedrock channel. Here the till ranges in thickness from less than 10 feet to over 100 feet with an average thickness of 60 feet (Backsen 1963). The till thins progressively to the north. The oxidized zone of the till appears yellow-brown in color while the unoxidized zone is gray in color. The limited amount of Nebraskan till within the area, thinning of the till to the north and lack of an oxidized zone probably results from erosion subsequent to deposition.

Sand and gravel beds

The buried sands and gravels have been studied by Beyer (1898), Simpson and Norton (1912), Hershey and others (1957), Backsen (1963), Twenter and Coble (1965), Schoell (1967) and Kent.[1] The sands and gravels represent a filling of the Skunk and Squaw channels, probably as a proglacial outwash. This composite body is known as the "Ames Aquifer". In the vicinity of Ames, the sands and gravels are stratigraphically above the Nebraskan till and below the Kansan till. North of Ames this unit rests directly on the bedrock and is overlain by progressively younger

[1]Kent, Douglas C., Ames, Iowa. Subsurface configuration, Story County Private communication. 1969.

alized Pleistocene stratigraphi


Wisconsin Till
Silt
Kansan Till
Sands and Gravels
Nebraskan Till

deposits. At Story City the sequence of Pennsylvanian shales, sands and gravels and Wisconsin till suggests that this unit might be of Wisconsin age (Schoell 1967, p. 43). It can be shown, therefore, that material of different ages constitutes the "Ames Aquifer" and in some cases it is difficult if not impossible to differentiate them by age.

Kansan till

Kansan till is much more extensive than Nebraskan till. Though limited in the number of outcrops within the study area the till subcrops in many wells (Beyer 1898, Simpson and Norton 1912, Backsen 1963 and Schoell 1967). The till averages 60 feet in thickness (Backsen 1963) of which 25 feet may represent a gray-brown oxidized zone. When unoxidized the till appears gray in color. In many cases a ferretto zone can be found associated with the Kansan till (Beyer 1898, Smith 1921).

Silt

Wisconsin silt, including alluvium, loess and loessoid deposits, has been observed in limited outcrops along Squaw Creek, Onion Creek, Bear Creek, Near Roland, and subcropping in many wells within the study area (Beyer 1899, Simpson and Norton 1912, Smith 1921, Ruhe 1950, Ruhe and Scholtes 1955, Thomas, Hussey and Roy 1955, and Schoell 1967). The composition of the silt is quite variable ranging from fine silt to fine and medium sands and varying from yellow-brown to blue-gray in color. Backsen (1963, p. 15) found that the silt was as much as 60 feet thick in places though the average was near 30 feet and was found to thin considerably as the Skunk River is approached. The gradational relationship between loessoid deposits and Wisconsin till suggests that these were deposited, in part, contemporaneously with Cary glaciation (Thomas, Riggs and Tench 1953).

Wisconsin drift

Wisconsin age deposits occur as stratified drift and till. Stratified drift is associated with the present stream systems as channel fill or terrace deposits. Upland stratified drift is limited to an area east of Randall ½ mile wide and 4 miles long trending toward the southeast or within short sinuous glacial meltwater channels found throughout the area.

Till is by far the most prominent Wisconsin deposit in the study area and completely blankets the upland except where removed by modern streams. The thickness of the Wisconsin till ranges from 10 feet to more than 100 feet thick over some preglacial channels.

Cary till appears as a sandy to silty clay-till which is calcareous except for the upper 1 to 3 feet. The oxidized till is gray-brown to yellowish-brown in color while the unoxidized till is dark-gray in color. Grain size analysis (Ruhe and Scholtes 1955) indicate 50-60% sand, 25-35% silt and 15% clay. Pebble suites include granite, quartzite, basalt, greenstone, limestone and dolomite. The characteristics of the Wisconsin drift will be treated in detail in this report.

Acknowledgments

I gratefully acknowledge my debt to Dr. Robert Palmquist for his willing assistance and encouragement during my course of study at Iowa State University. I am also grateful to my committee, composed of Dr.

Mickle (Civil Engineering) and Drs. Hussey and Sendlein (Geology), for their constant readiness to discuss and criticize various aspects of this paper. The drilling program during the summer of 1968, which provided critical subsurface information, could not have been undertaken without the financial assistance from the University Small Grants Committee. Without the encouragement and moral support of my wife, Linda, and her willingness to assist, the writing of this paper would have been more difficult to complete.

GLACIAL GEOLOGY

General Description

The Cary Drift Plain, covering approximately 12,300 square miles in north central Iowa, exhibits a lobate configuration skewed somewhat east of south (Figure 5). The lobe extends 135 miles from the Iowa-Minnesota border to its terminus at Des Moines.

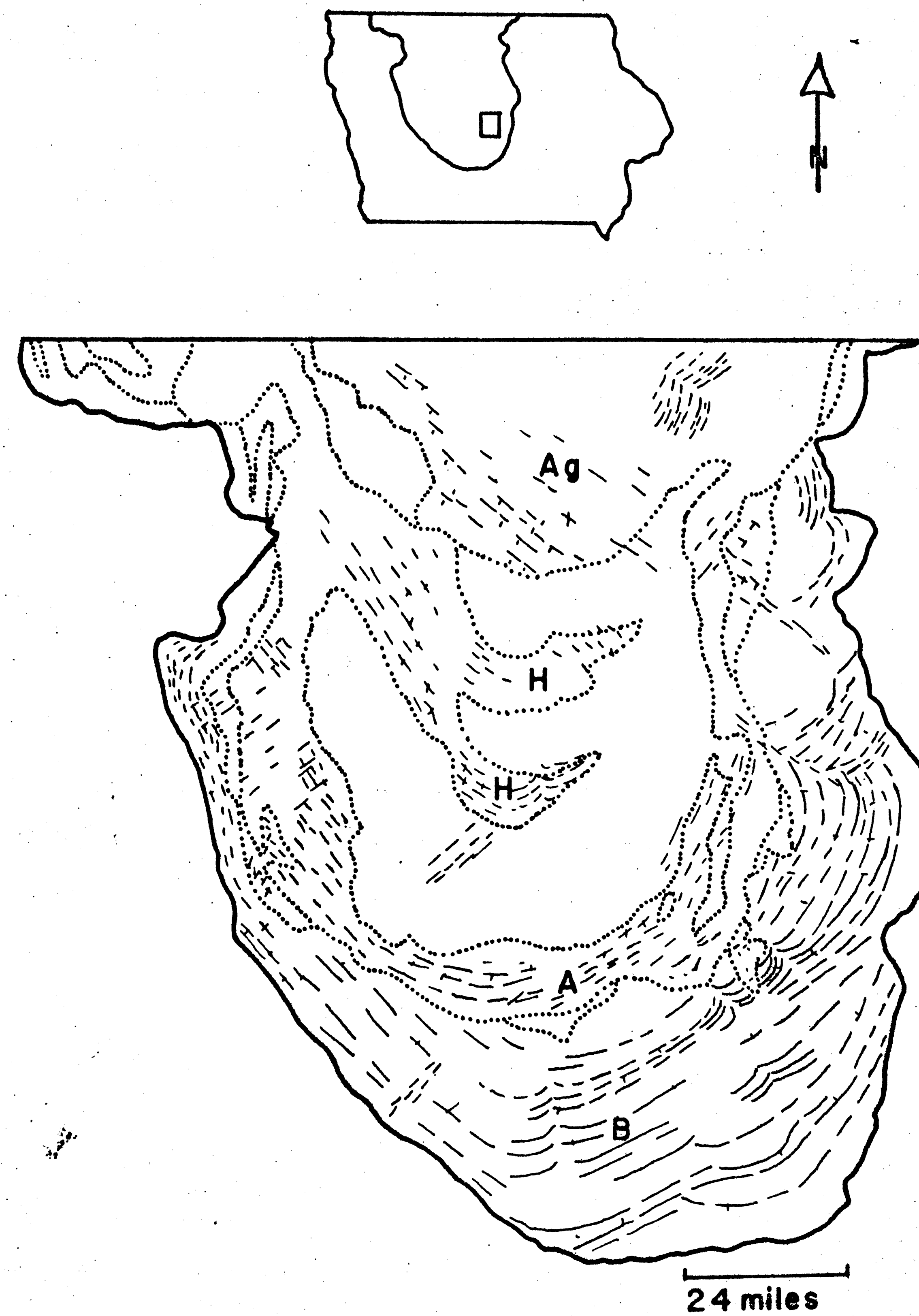
Four distinct and easily mapped morphostratigraphic units have been identified with the Des Moines lobe, with each unit reported to represent a separate readvance of the Cary glacier (Ruhe 1969). A morphostratigraphic unit refers to a unit "composed of a body of till and stratified drift that is identified primarily from the surface form [expression] that it displays. Each unit contains the end moraine and ground moraine, and the continuation of the body beneath the surface where it can be recognized" (Ruhe, p. 57). The morphostratigraphic units are the Bemis, Altamont, Humboldt and Algona systems (Figure 5).

Distinction of the morphostratigraphic units is based on recognizing low-relief end moraines and angular topographic discontinuities (a change in landform patterns) across these moraines (Ruhe 1952). The low relief and lateral discontinuity of the end morainal systems suggests that the glacier did not remain in marginal equilibrium for any length of time.

Glacial Geology of the Study Area

For this study the distribution and orientation of glacial landforms were mapped for the Des Moines lobe in Iowa (Figure 35) and for the study

Figure 5. Map of the Des Moines lobe in Iowa, after Ruhe (1952), showing the generalized lineament trends (The morphostratigraphic units are B = Bemis, A = Altamont, H = Humboldt, Ag = Algona)


N
Ag
H
H
A
B
24 miles

area (Figures 6A and B). Figure 35 was compiled from county air photo mosaics and therefore does not depict exactly the number of linear features in any one area but is representative only of their approximate density and orientation and is a more detailed version of the map by Gwynne (1942a) The regional patterns shown by this map will be discussed later. The landform patterns within the 400 square mile study area (Figures 6A and B) depict quite accurately the occurrence of linear ridges, undrained to poorly drained depressions and glacial drainageways.

Based upon Figures 6A and B, the physiography of the study area may be divided into two parts, 1) flat to gently rolling uplands and 2) river and stream cut valleys 50-100 feet below the upland. This report is concerned only with the characteristic glacial topography of the upland phase. The morphology and stratigraphy of the valley phase have been treated in detail by Schoell (1967), Backsen (1963), Versteeg (1968), Noble and Palmquist (1968) and Sendlein and Dougal (1968).

The upland phase exhibits two distinct geomorphic surfaces which in many cases appear as end members in a continuum from nearly level, featureless surfaces to distinctly lineated surfaces. These surfaces can be isolated on the basis of topography and characteristic tone and texture on aerial photographs.

A lineated geomorphic surface exhibits a distinct topography of intersecting lineaments and also includes transitional topographies where linear elements predominate. The Bemis morphostratigraphic unit consists almost exclusively of a lineated geomorphic surface. Likewise, the marginal portion of each successively younger and less extensive morphostratigraphic

Figure 6A. Map of glacial landforms for the northern half of the study area

Figure 6A

Map of Glacial Landforms for the Northern Half of the Study Area

Scale 1:20,000

KEY

Outline of glacial landform

Axis of linear ridge

Undrained depression

Glacial drainageway

Auger hole site ○ 3-70

Figure 6B. Map of glacial landforms for the southern half of the study area (see Figure 6A for kcg) unit exhibits a lineated surface which grades into a transitional then to a featureless or non-lineated geomorphic surface at the interior of the unit. In Figure 5, the lineated surfaces were shown as end moraines by Ruhe (1952), whereas the non-lineated surfaces were shown as being ground moraine. Lineated geomorphic surfaces will be discussed in detail later in this report.

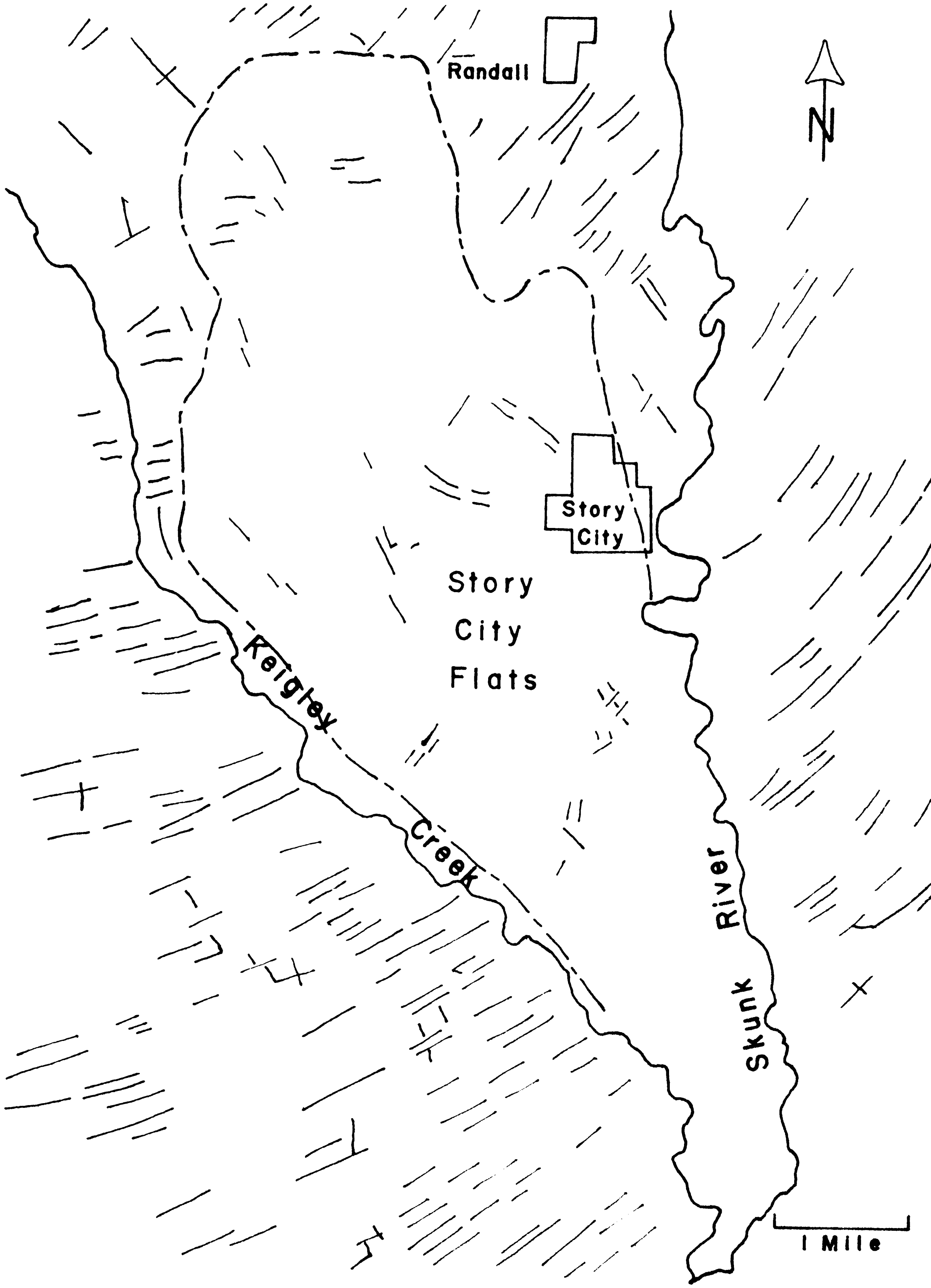
Non-lineated topography

Areas classed as nonlineated are characterized by 1) a low surface slope and subsequently poor drainage, 2) a lack of relief, 3) poorly defined linear elements and 4) dark tones and a smooth, even texture on aerial photographs. Ruhe (1952, 1969) has previously mapped non-lineated topographies as ground moraine.

The Story City Flats, covering approximately 20 square miles in the north-central part of the study area (Figure 6A and Figure 7), is typical of a non-lineated geomorphic surface. This roughly triangular shaped area is bounded on the east by the Skunk River and to the south and west is isolated from Keigley Creek by a 20-30 foot topographic high. To the north, near Randall, the Story City Flats grades into characteristic lineated topography.

Near Randall, the transitional portion of the nonlineated Story City Flats is at the same elevation as the surrounding lineated surfaces. Further south the area becomes progressively lower than the level of the lineated surfaces. At the southern tip of the area there is a difference of 30 feet between the level of the Story City flats and the lineated up-

Figure 7. Detailed sketch of the Story City Flats non-lineated geomorphic surface (dashed lines trace ridge axes)


Randall
N
Story City
Story City Flats
Keigley Creek
Skunk River
1 Mile

lands south of Keigley Creek and east of the Skunk River.

On aerial photographs the Story City Flats may be isolated from the surrounding lineated surfaces by its darker photographic tones and lightly mottled, random texture (Figure 8). The mottled texture is produced by soil and moisture variations resulting from the gentle 2-5 feet of relief. Intersecting linear elements appear randomly distributed throughout the area but do not dominate the topographic pattern. Two sets of orthogonal ridges can be isolated and are oriented northeast-southwest and northwest-southeast (Figure 9). Figure 9 also shows the difference in the photographic appearance of lineated and non-lineated topographies. Where linear ridges exist, they are shorter and less well developed than those in lineated areas.

Numerous lineations are shown in Figure 7 of Sendlein and Dougal (1968) crossing the Story City Flats. This study does not recognize such extensive lineation patterns. The Story City Flats area is one of the limited regions of Bemis age ground moraine recognized by Ruhe (1952, 1969).

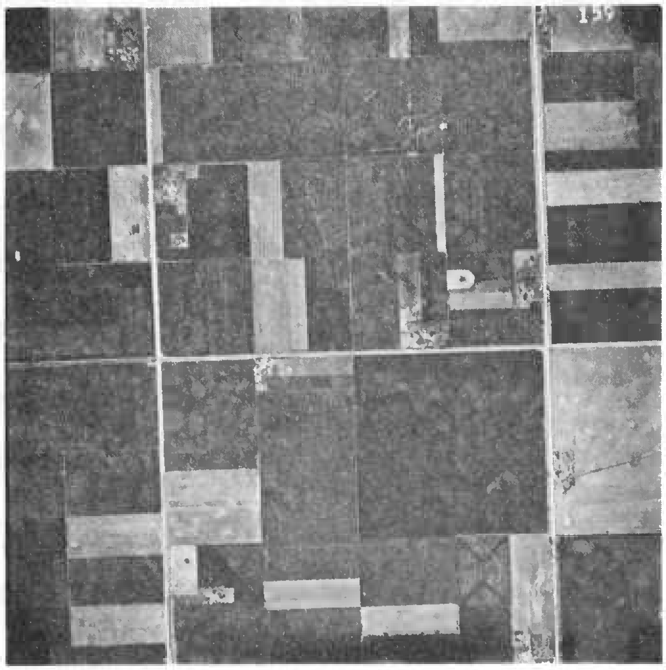
Lineated topography

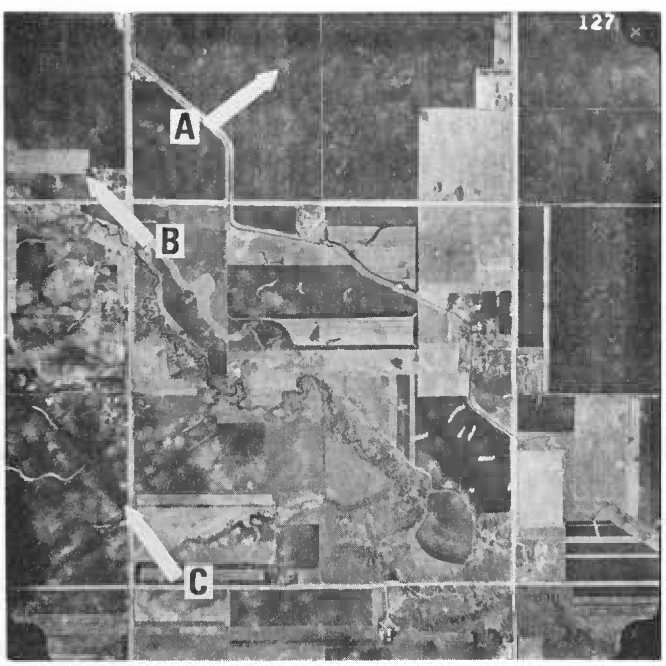
The topographic pattern of intersecting lineaments (lineated topography) resulting from Cary glaciation appears in less than half of the Wisconsin Drift area. This pattern is most pronounced in the marginal portion and toward the southern part of each morphostratigraphic unit.

Within the area defined as having a lineated topography, four distinct topographic features can be isolated. These are 1) parallel

Figure 8. Aerial photograph of the Story City Flats showing the dark tones, lightly mottled texture and polygonal pattern (located 1¼ miles northwest of Story City; top is north; road intersections are one mile apart)

Figure 9. Aerial photograph showing contrast in the tone and texture of the Story City Flats, northeast of Keigley Creek, to the lineated upland southwest of Keigley Creek (A = parallel lineament; B = transverse lineament; C = glacial drainageway paralleling Keigley Creek) (photograph center located at center of section 26, T. 85N., R. 24W.; top is north; road intersections are one mile apart)




127
A
B
C

ridges, 2) transverse ridges, 3) glacial drainageways, and 4) kame-like or esker-like features. Ridges are classified as either parallel or transverse according to their relationship to the margin of each morpho-stratigraphic unit.

The lineated surfaces are characterized by sets of parallel, curvilinear ridges crossed by transverse ridges, depressions and drainageways. Each lobate set of curvilinear, parallel ridges meets at an acute angle to produce a "scalloped-like" pattern along which kame- and esker-like features or modern streams are located (Figure 6A and Figure 35). Each of these topographic features will be discussed separately.

Description of parallel ridges Predominant among the topographic elements within the study area is the northeast-southwest trending series of parallel (?), curvilinear ridges and intervening depressions. Gwynne (1941) named the parallel ridges, minor moraines, because of their approximate parallel relationship to the margin of the Des Moines lobe and described the succession of ridges and depressions as swell-swale topography. Gwynne's (1942, p. 203) description is as follows:

> The pattern of ground moraine is formed of narrow, alternating, discontinuous light and dark streaks swells and swales respectively or patches which give a banded effect. Individual bands cannot be traced continuously for any great distance, but the pattern as a whole may be continuous for many miles [where] the swells range in size from 70 to 600 feet or more in greatest dimension.

The spacing of successive parallel ridges varies between 100 to 600 feet. An average spacing of 350 feet (15/mile) appears to be common for the study area and the Des Moines lobe as a whole. Qualitatively there appears to be no systematic variation in the spacing of parallel ridges either from the margin to the interior of the lobe or locally over preglacial topographic highs and lows.

Relief Relief of lineated surfaces varies between 2 and 40 feet and rarely higher. The threefold descriptive classification of topographic expression used by Gravenor and Kupsch (1959, p. 49) was also used in this study. "High-relief deposits have a local relief greater than 25 feet; intermediate-relief deposits from 10-25 feet; and low-relief deposits less than 10 feet". There appears to be some correlation between relief of linear features and the bedrock topography.

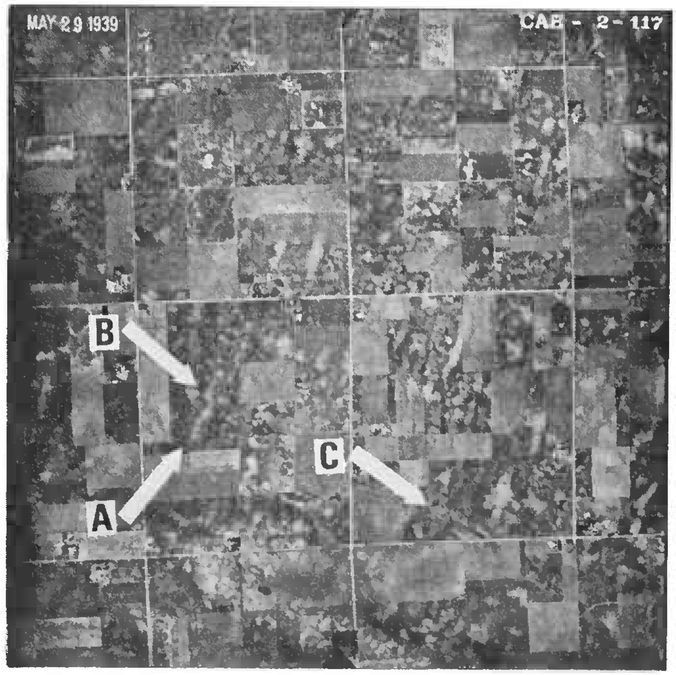
Figure 10 shows an area five miles north of Nevada typical of a low relief lineated surface. Lineated areas of low relief contain numerous undrained depressions, less fully developed parallel ridges which are shorter than in higher areas and a greater number of short, transverse ridges.

Major areas of low relief, lineated surfaces can be found north of Nevada, immediately east of Ames, east and north of Story City and in the southwest corner of the study area. These areas are shown in Figure 12.

Comparison of Figures 3 and 12 suggests that low relief lineated surfaces occur over preglacial topographic lows. This is particularly evident in the low relief area immediately east of Ames. This area is bounded on the west by the Skunk River and on the north, south and east by intermediate to high relief lineated surfaces. From the northwest to southeast (direction of glacial flow) there is an apparent though irregular decrease in the height of parallel ridges into the area of low relief. Subsurface investigations (Twenter and Coble 1965 and Kent 1969, personal communica-

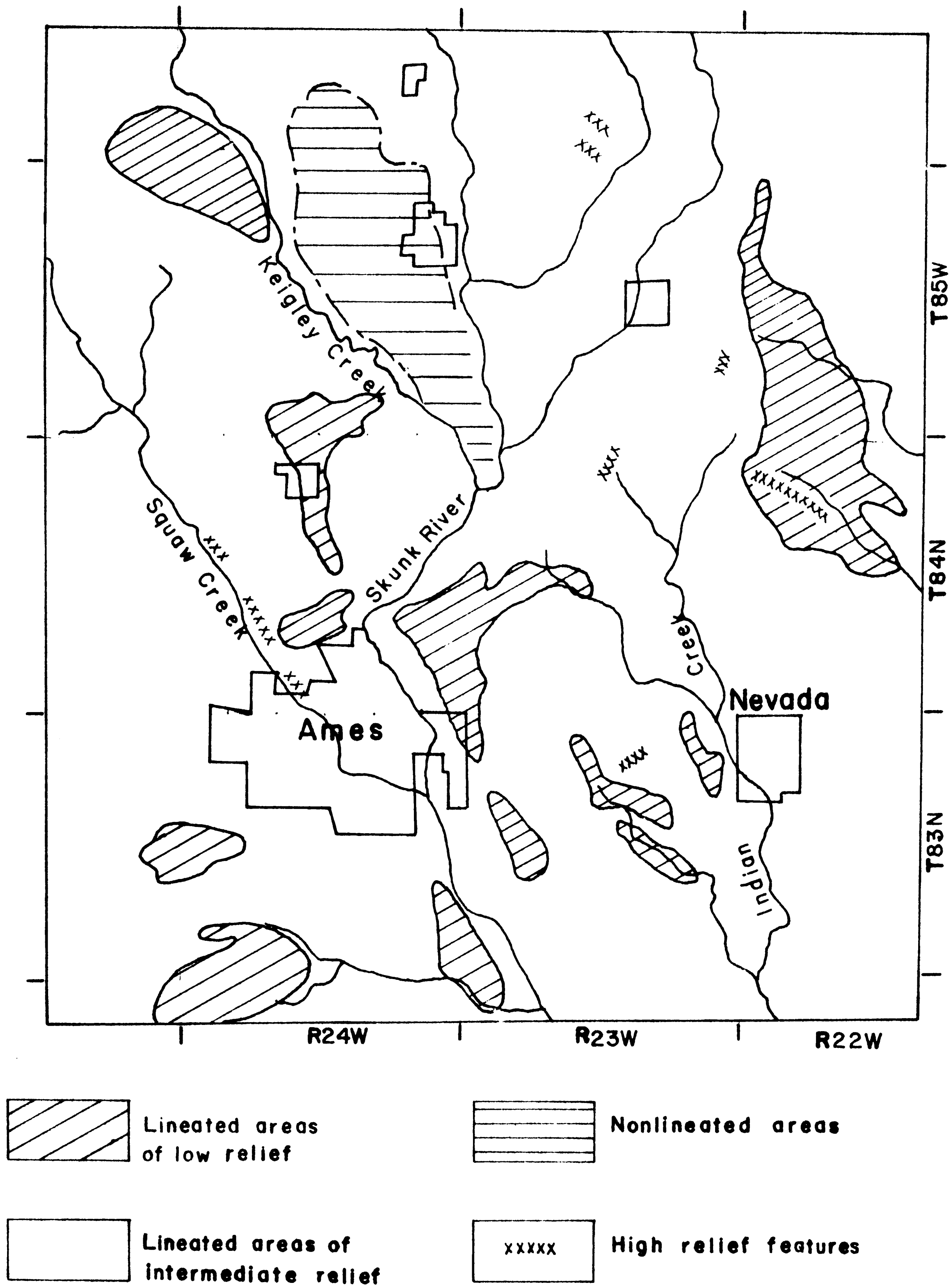
Figure 10. Area of low-relief lineated topography 5 miles north of Nevada (A = parallel lineament; B = transverse lineament; C = glacial drainageway; top is north; road intersections are one mile apart)

Figure 11. Area of intermediate relief topography showing the well developed parallel and transverse elements (A = parallel lineament; B = transverse lineament; top is north; a portion of Nevada showing in northeast corner of photograph)


MAY 29 1939
CAB - 2 - 117
B
C
A


MAY 29 1939
B
A

Figure 12. Map showing areas of low, intermediate, and high relief topography



Keigley Creek
Skunk River
Squaw Creek
Creek
Indian
Ames
Nevada
xxx
xxxxx
T85W
T84N
T83N
R24W
R23W
R22W
Lineated areas of low relief
Nonlineated areas
Lineated areas of intermediate relief
xxxxx
High relief features

tion) indicate that the low-relief area overlies a bedrock channel system draining to the southeast, whereas the adjacent higher relief areas overlie bedrock topographic divides.

Lineated surfaces of intermediate relief (10 to 25 feet) dominate the study area and exhibit the best development of intersecting lineament topography (Figure 11). Characteristic of intermediate relief topography is the fewer number of circular undrained depressions and a more fully developed pattern of repetitive parallel ridges. Intermediate relief topography appears to be best developed over preglacial topographic highs such as the Ames-Roland structural high and other preglacial drainage divides.

High relief topography usually occurs as very small areas of singular, isolated knobs or ridges within an area of intermediate relief. One high relief feature north of Nevada (Figure 13) has been shown by Thomas, Hussey and Roy (1955) to consist of a thin mantle of Cary till covering a topographic high composed of silts and sands. However, most high relief features are composed entirely of Cary till.

<u>Scalloped patterns</u> Parallel ridges locally exhibit a scalloped pattern in which they curve up ice and approach a transverse trend. Scalloped patterns, which were first observed by Gwynne (1941), occur within the study area along Squaw Creek, Skunk River (below Ames), Indian Creek and east of Randall. These patterns are shown in Figure 15. The axes of the scalloped belts are coincident with the preglacial drainage lines along parts of the Skunk River, Squaw Creek and Indian Creek. The Randall

Scalloped belt is anomalous in this respect. Here the parallel ridges are superimposed on a bedrock high or on sands and gravels over this bedrock high, with a maximum drift thickness of only 40 feet.

Figures 14 and 16 show the relationship of the lineated upland topography to the Skunk River in the Ames area. Here, the parallel trends extend to the very edge of the upland and stop only at the crest of the valley wall. Three explanations can be used to account for this occurrence: 1) the Skunk River valley did not exist at the time of formation of lineated upland topography, 2) the Skunk River has widened its valley cutting the valley wall into upland areas and destroying the scalloped pattern or 3) the size of the present valley is similar in size to the preglacial Skunk Valley but its presence has no effect on the formation of the lineated topography in the upland. The third explanation, based on well data, is favored by the author.

<u>Composition</u> Results of the drilling program (Table 1) and outcrop observations indicate that parallel landforms consist predominantly of a sandy, clay-till. Thirty two auger holes were drilled in these features with less than 2% of the total footage consisting of sand or gravel. This observation is also confirmed by Iowa Highway Commission soil survey profiles for Interstate 35 and new Highway 30 east of Ames.

The composition of a parallel trend within the scalloped pattern east of Randall is shown in Figure 18. The significance of the underlying sands and gravels will be discussed later. Figures 19 and 20 show cross sections of outcrops of parallel features. Outcrops within the study

Figure 13. High relief feature outlined north of Nevada surrounded by low relief topography (located $4\frac{1}{2}$ miles north of Nevada top is north; road intersections are one mile apart)

Figure 14. Relationship of lineated upland topography to the Skunk River valley south of Ames (A = parallel lineament; B = transverse lineament; top is north; road intersections are one mile apart; center point of photograph located at center of section 8, T. 82N., R. 23W.)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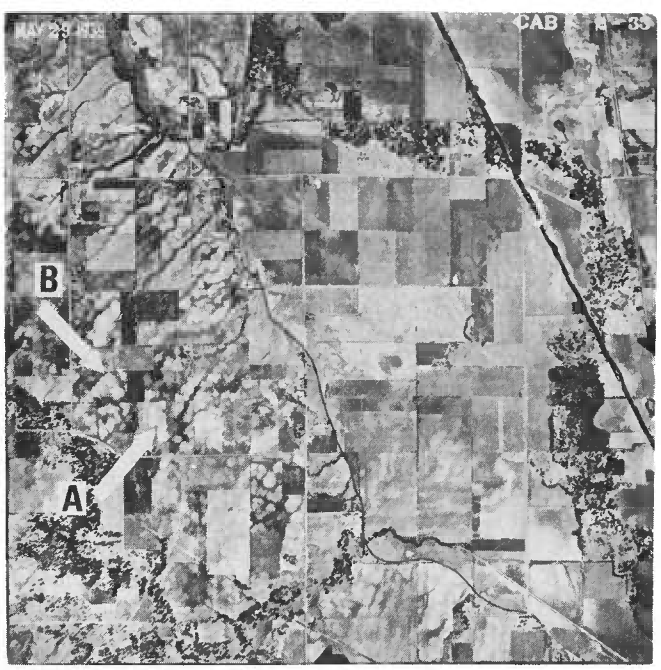

CAB
B
A

Figure 15. Scalloped patterns found within the study area (A = Squaw Creek northwest of Ames; B = Skunk River south of Cambridge; C = Indian Creek northeast of Cambridge; D = Randall scalloped belt east of Randall)

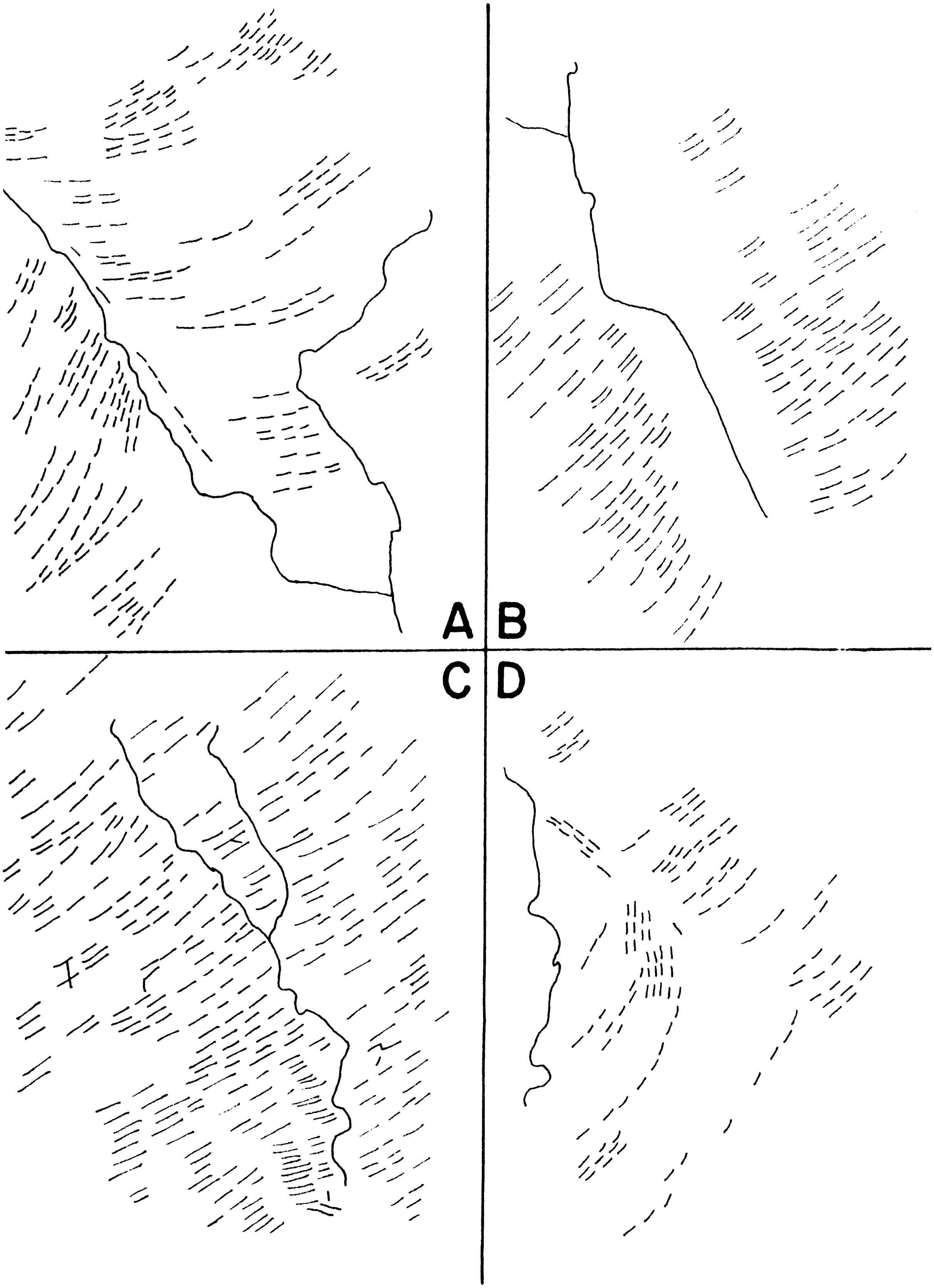
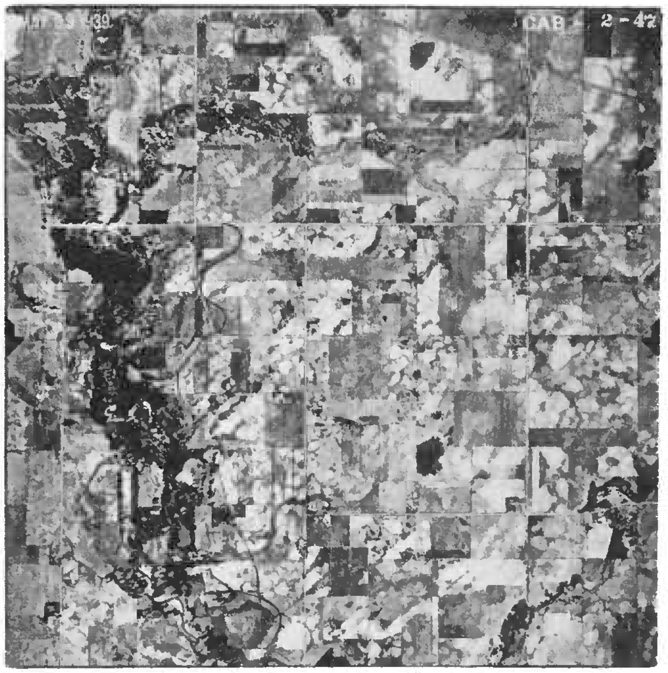

A
B
C
D

Figure 16. Relationship of lineated upland topography to the Skunk River north of Ames (top is north; east-west road intersections are one mile apart; location two miles southeast of Story City)

Figure 17. Northwest southeast trending glacial drainage channel (outlined) (top is north, road intersections are one mile apart)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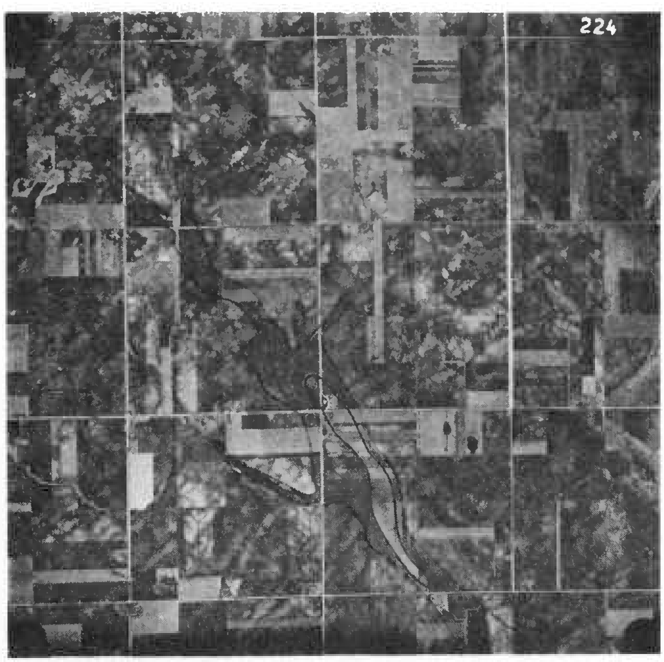
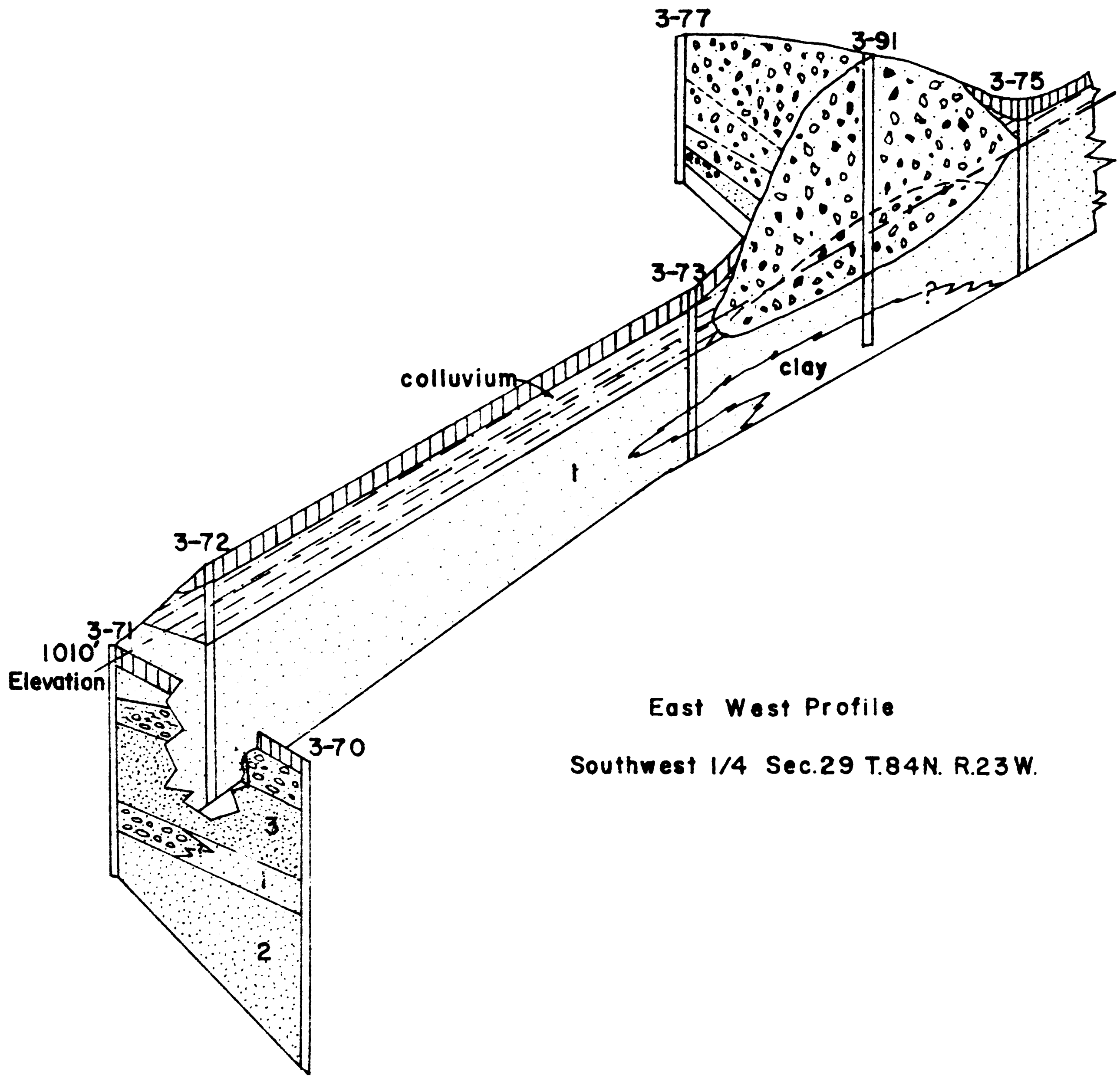

224

Figure 18. Cross-section of parallel trend associated with the Randall Scalloped belt (subsurface stratigraphy determined by auger hole information)
1 = fine sand
2 = medium sand
3 = coarse sand
4 = very coarse sand
(A dashed line separates oxidized from unoxidized till)

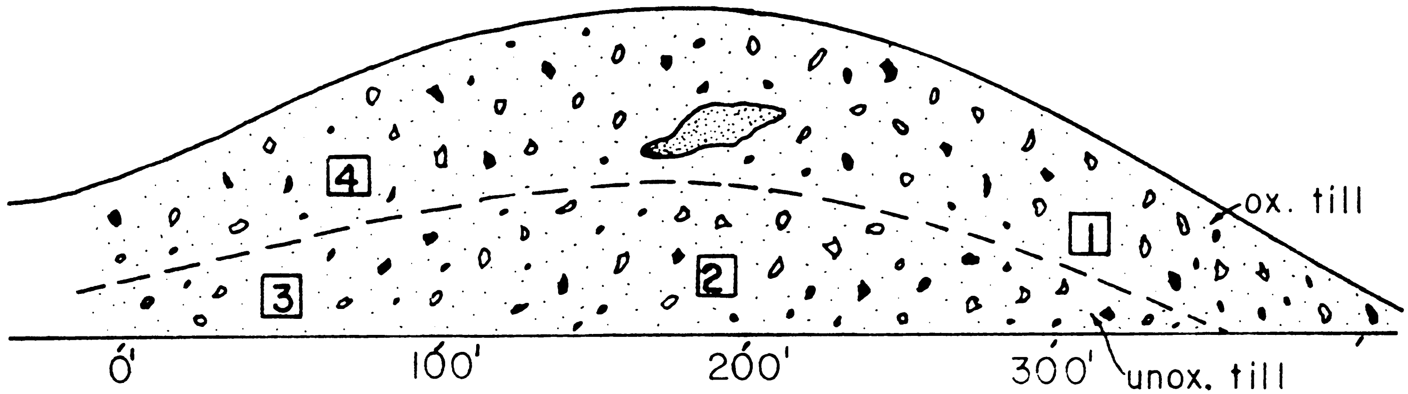


East West Profile

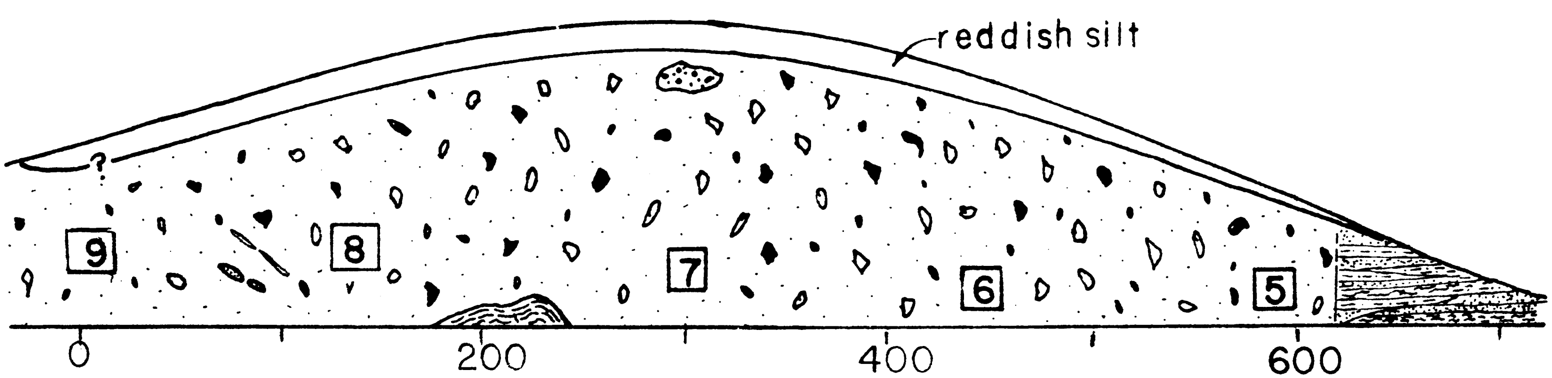
Southwest 1/4 Sec.29 T.84N. R.23W.

Figure 19. Cross-sections of parallel features

A. Randall section with fabric sample sites 1 through 4
B. Cook's quarry section with fabric samples 5 through 9

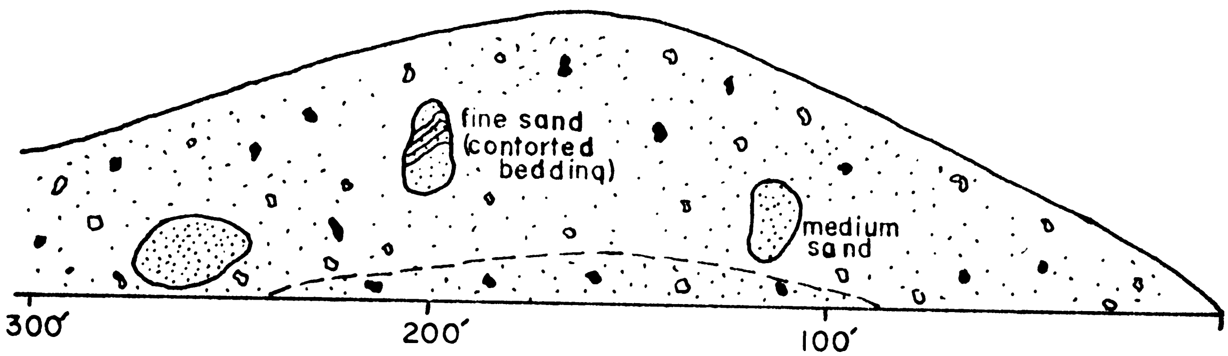


A. Radall fabric site

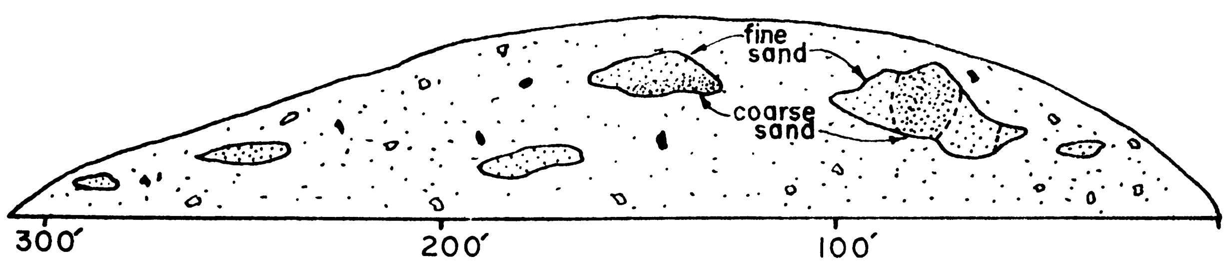


B. Cook's quary fabric site

Figure 20. Cross-sections of parallel ridges along Interstate Highway 3 (dashed line separates oxidized till, above, from unoxidized till, below)



South Center sec.7 T84N R23W



Center sec.19 T86N R23W

Table 1. Results of drilling program

Type of feature	Parallel trends	Transverse trends Type I	Type II[a]	Drainage-ways	Outwash
No. holes drilled	32	4	13	15	5
Thick Wisc. till	759	123	108	211	-
Thick Wisc. sand and gravel	13	7	149	111	104
Others[b]	-	-	24L	51A	21A
Thick Kans. drift	92	11	-	40	-
T.D.	864	141	281	414	125

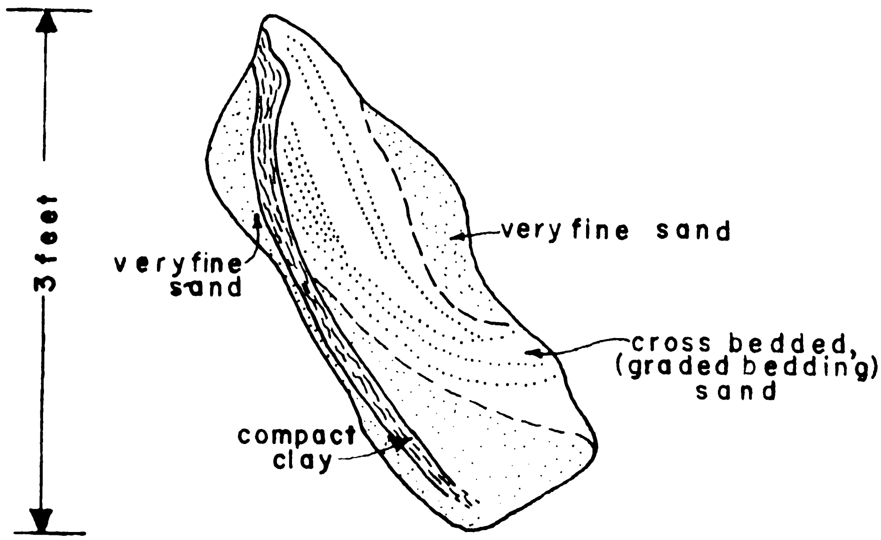
[a]Type II transverse features are scalloped belt axial transverse features.

[b]L = loess; A = alluvium.

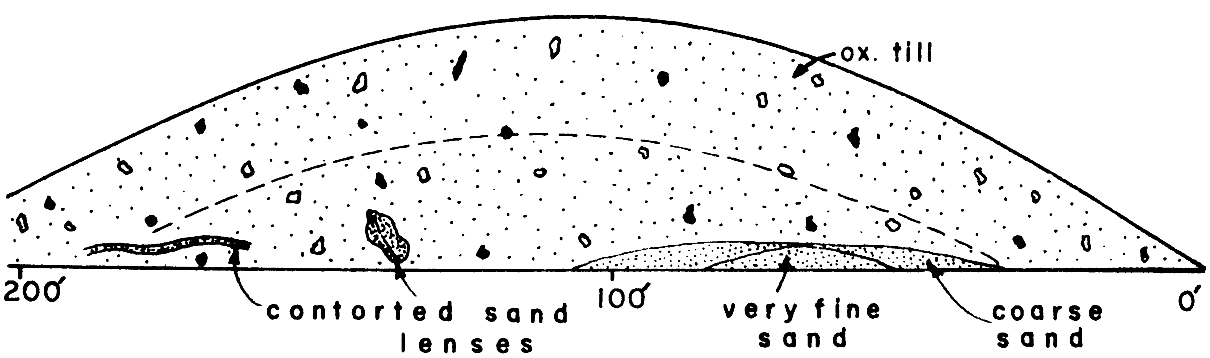
area are limited to roadcuts and quarries. The numbered squares in Figure 19 indicate fabric sites which will be discussed later.

It is important to note that where sand and gravel bodies are found, they appear lenticular to irregular in shape. Oftentimes the sands will have cross bedding or graded bedding. Where crossbedding is evident, the beds will at times dip at extreme angles, 40-60°, and be considerably distorted (Figure 21). Highway Commission borings (Figure 22) show that where large sand bodies are found they generally dip away from the crest of the feature whether parallel or transverse ridges.

Figure 21. Cross-section of parallel (?) trend with detail showing contorted sand lense (sw¼, sw¼, sec. 12, T24W, R84N)

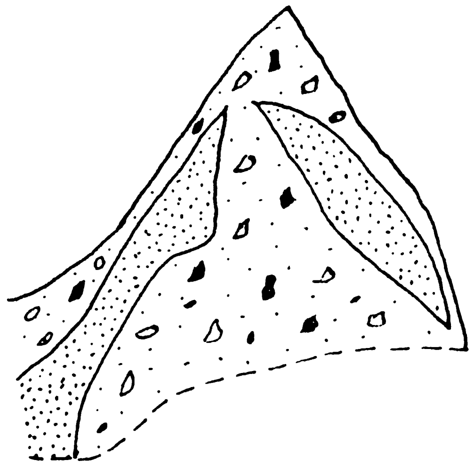


Detail of sand lens

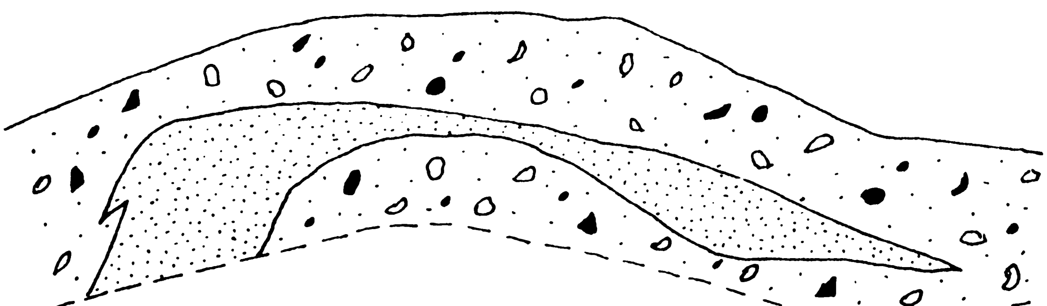


SW 1/4 SW 1/4 sec. 12 T84N R24W

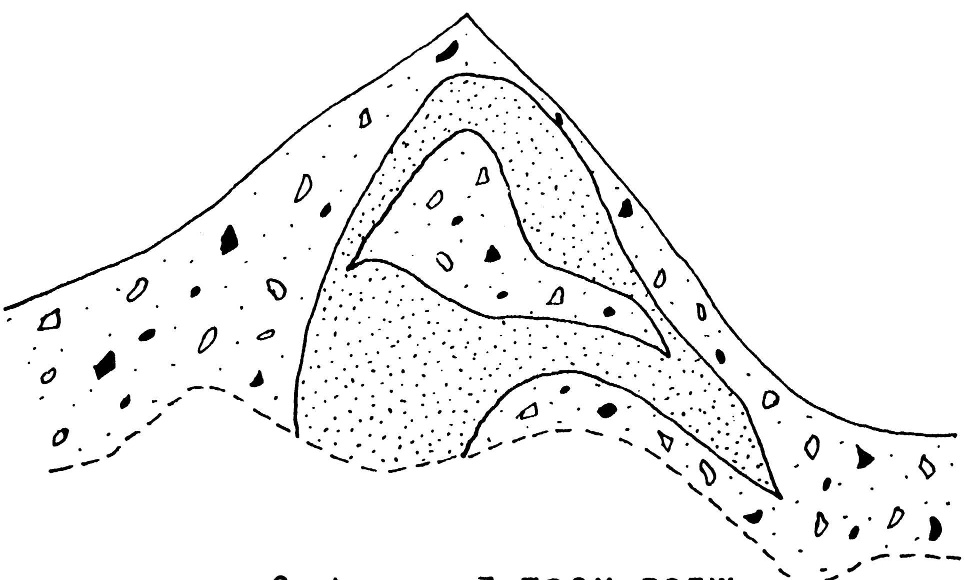
Figure 22. Redrawn Highway Commission cross-sections showing the relationship of sand bodies dipping away from the crest of topographic features (horizontal scale 1" = 200', vertical scale 1" = 5')



South Center sec.19 T85N R23W



Southwest 1/4 sec.11 T83N R23W



Center sec.7 T86N R23W

Description of transverse ridges

The presence of transverse ridges has only recently been associated with the landform patterns of the Des Moines lobe (Sendlein and Dougal 1968). The description of these features is critical to the determination of the origin of lineated glacial topographies.

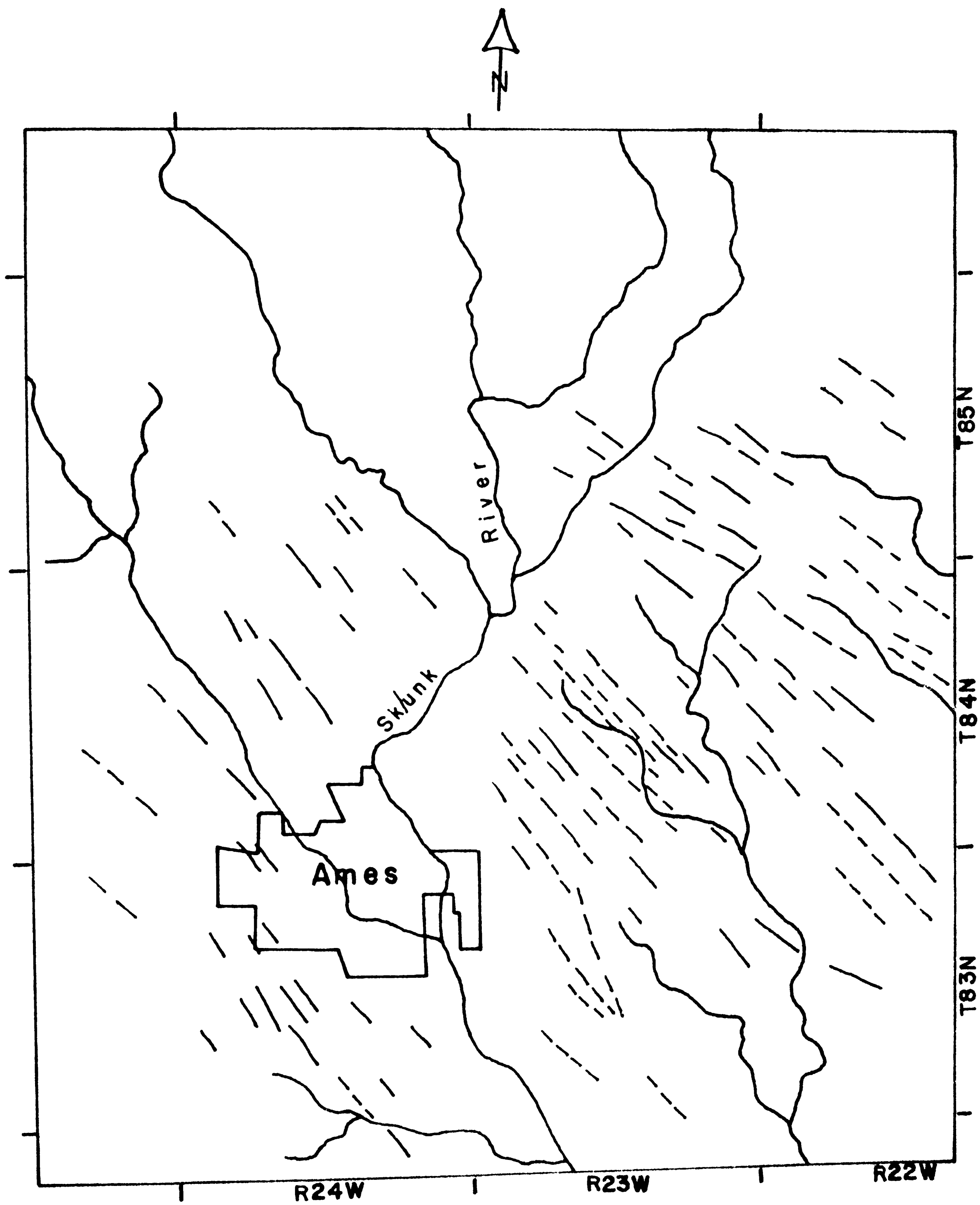
Transverse ridges, composed predominantly of till (Table 1), are identical to parallel ridges in form and composition, but differ in orientation (see B in Figures 9 and 11). Four auger holes were drilled in these features for a total footage of 140 feet. Only 5% of the total thickness of the Wisconsin Drift consisted of sand or gravel. These features are less prominent than parallel trends and were not recognized by Gwynne in his description of the Des Moines lobe.

The transverse features are distributed throughout the upland and are oriented at 45 to 90 degrees to the parallel ridges. Transverse lineations or allignment of groups of transverse ridges can be seen on the county air photo mosaics. These major transverse ridge lineations for the study area are shown in Figure 23. These lineations have a general northwest southeast trend, but appear somewhat radial in design. There appears to be no consistent relationship of the angle subtended by the parallel and transverse lineaments.

Glacial drainage channels

Glacial drainage channels appear on aerial photographs as short, sinuous depressions, a fraction of a mile to several miles in length (Figures 6A and B, 9, 17, 24 and 25). A total of fifteen auger holes were drilled in ten distinct drainage channels (Table 1). Figure 26 shows the cross

Figure 23. Major transverse lineations of the study area


N
River
Skunk
Ames
T85N
T84N
T83N
R24W
R23W
R22W

section of a typical glacial drainage channel (N center sec 15, T85N, R23W). Its composition of graded sands and gravels, averaging about seven feet thick, suggests deposition from flowing water. The upper 3-5 feet of clay or silt represent post-glacial deposition of material eroded from the adjoining uplands.

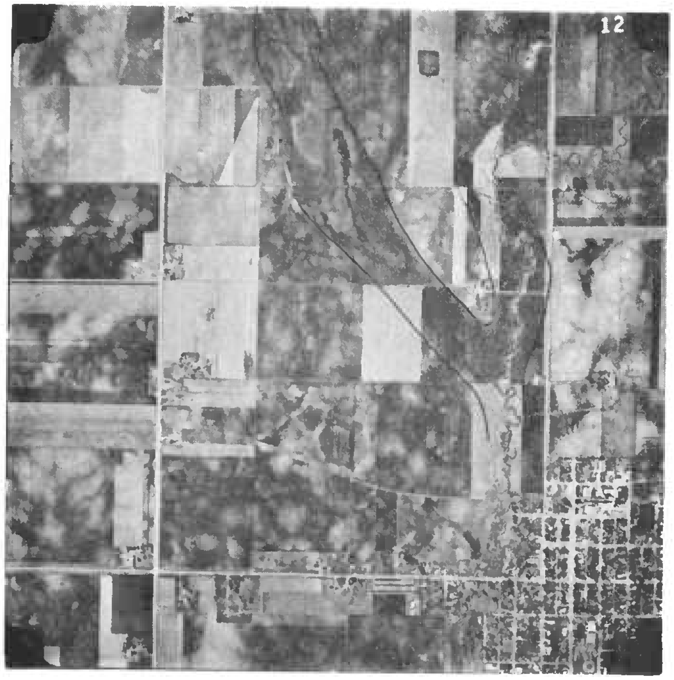
As seen in Figure 26 the Cary till is relatively thin (10-20 feet) and has been deposited on an apparently irregular Kansan topography. The occurrence of a stone line at the surface of the Kansan topography was suggested by the reaction of the power auger used. The difficulty in penetrating the "stone line" and a change from unoxidized to oxidized till were used as the criteria for distinguishing the Kansan till.

Five characteristics of glacial drainageways are apparent: 1) many channels are integrated with the present drainage systems, 2) when integrated with present drainage systems they are distinct and easily recognized only at the source, but downstream become indistinguishable from the modern flood plain (Figure 24), 3) drainage ways are associated with the axis of most scalloped regions, 4) in most cases the glacial drainage channels within the study area have an apparent southeast flow direction, approximately parallel to the transverse trends and the modern drainage. 5) Many drainageways disappear in lineated areas of low relief such as that southeast of Ames (Figure 6B).

Partial nonintegration of glacial drainage channels with the modern drainage is apparent in some parts of the study area. Figure 25 shows the distal portion of the Randall scalloped belt with an axial drainage channel. The apparent glacial drainage channel (outlined) flowed from the northwest

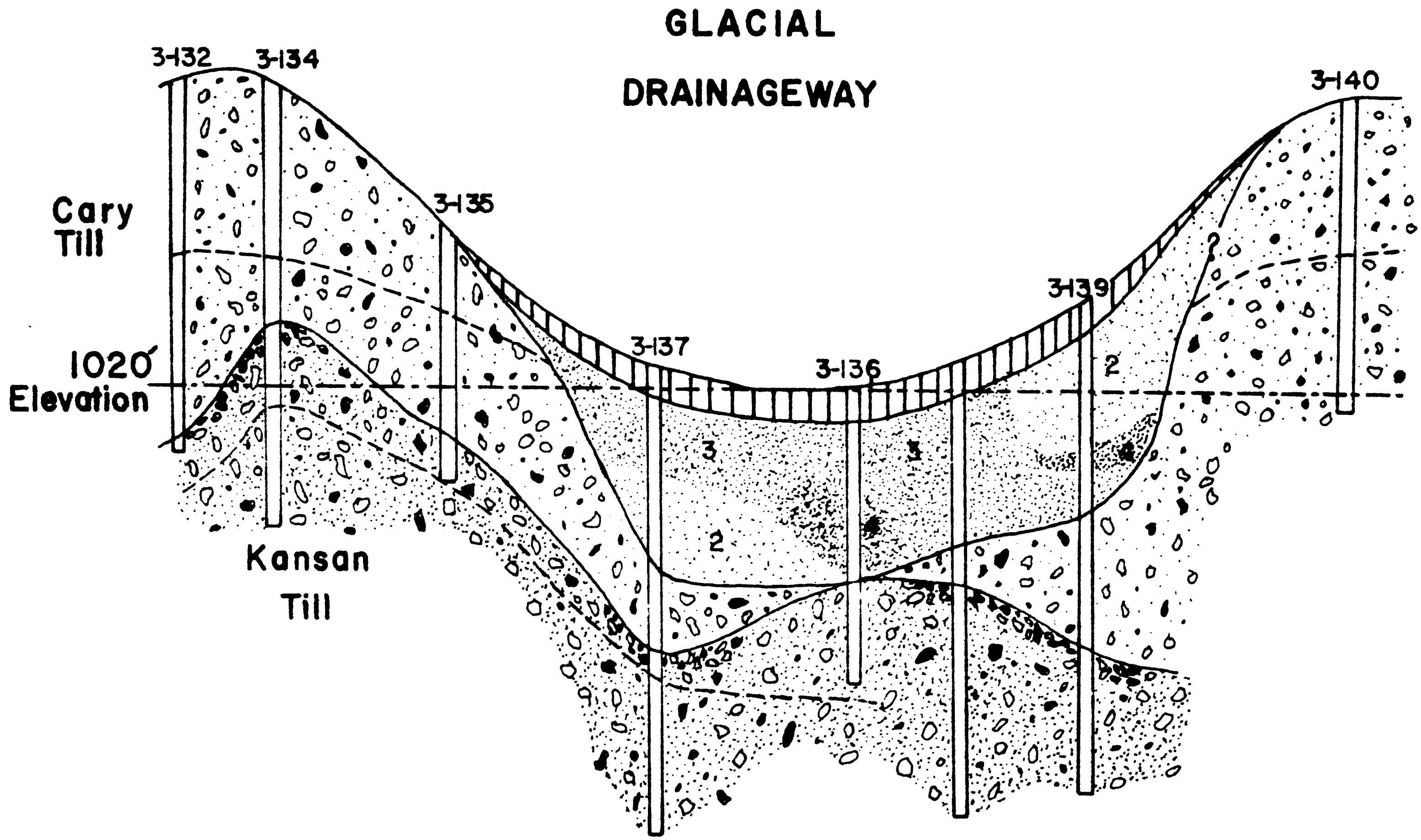
Figure 24. Glacial drainageway (outlined) intersecting Bear Creek north of Roland (east-west road intersections are one mile apart)

Figure 25. Glacial drainageway truncated by Long Dick Creek (photograph center located at northeast corner section 4, T. 85N., R. 23 W.)


12


CAB

Figure 26. Cross-section of a typical drainage channel
1 = fine sand
2 = medium sand
3 = coarse sand
4 = very coarse sand
Dashed line separates oxidized from unoxidized till



North Center Sec.15 T.85N. R23W.

to the southeast continuing past the modern drainage of Long Dick Creek.

Kame-like deposits

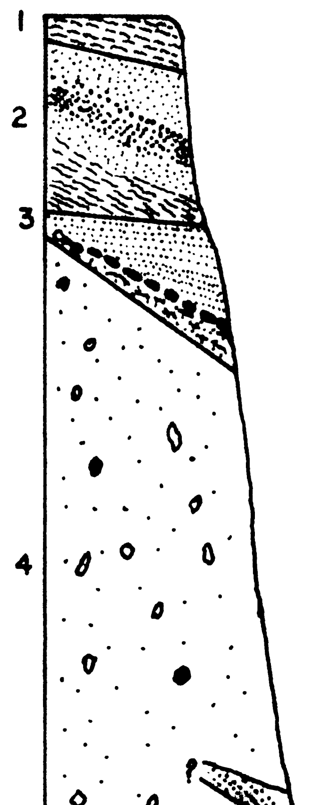
Kames or kame-like deposits occur as conical hills or elongate ridges of high relief. These deposits are found associated with scalloped patterns, where they are clustered along and parallel to the axis of the scallops and flanked by glacial drainageways.

These features are composed almost entirely of sands and fine gravels, which show stratification where exposed in outcrops. In the NE$\frac{1}{4}$, NW$\frac{1}{4}$, NE$\frac{1}{4}$ sec 32, T86N, R23W a 60-80 foot conical hill is flanked by lower hills of about 30 foot relief. At the crest of the high knoll an auger hole revealed 48 ft. of well graded fine gravel. The flanking hills were drilled and found to be composed of fine to very fine sands (3-79 and 3-83).

The high relief transverse ridge along the axis of the Squaw Creek scalloped belt can be traced for several miles. Seven auger holes were drilled along the axis of the ridge. In hole number 3-120, 48 feet of interbedded silts, very sandy till, sands and gravels was revealed. Hole number 3-123 bottomed on what was probably a large boulder at 22 feet, while in the remaining five auger holes depths past 12 or 13 feet could not be achieved probably due again to large boulders. All of the shallow auger holes indicate a sequence similar to the one found in hole 3-120.

Squaw Creek has cut into the western flank of this high relief transverse element revealing the stratigraphic sequence shown in Figure 27. The stratified sands and gravels dip steeply to the west. At least two uncomformable sequences are shown in the outcrop.

Stratigraphic section for the high relief transverse ridge along the axis of the Squaw Creek scalloped belt (center section 29, T. 84 N., R. 24 W.)



1 Fine, calcareous, brown silt (occ. carbonate concretion)

2 Interbedded fine silts, sands & gravels (beds dippin west)

3 Till overlying fine, cross-bedded, quartz sand.

4 Sandy to very sandy till with occasional sand lens.

vertical scale 1"=10'

Outwash deposits

Associated with the Randall scalloped belt is a basal deposit of stratified drift. This upland stratified drift is limited to an area roughly ½ mile wide and 4 miles long, trending southeast and parallel to the axis of the scalloped belt.

The upper surface of the stratified drift appears relatively flat while the topography is interrupted by high relief, transverse ridges (kame-like deposits) and scalloped parallel ridges. The stratigraphic sequence of bedrock, stratified sands and gravels, and till, of the parallel ridges (Figure 17) indicates that the stratified drift is continuous under the till and therefore older than the till. The sequence probably represents proglacial outwash overridden by the advancing glacier. Outwash was also found in the other glacial drainageways.

Intersection patterns

The pattern produced by the intersection of parallel and transverse ridges is highly varied and complex, but generally falls within one of five classes. Combinations of intersections of all the class types produce the complex landform patterns of the Des Moines lobe. The characteristic landform patterns are shown diagramatically in Figure 28 and are classified as 1) offset, 2) "T", 3) box, 4) cross intersections and 5) non-intersection where either a parallel or transverse ridge is discontinuous at an apparent intersection though the trend continues along the apparent intersection point.

Figure 28. Characteristic patterns of intersection for parallel and transverse ridges

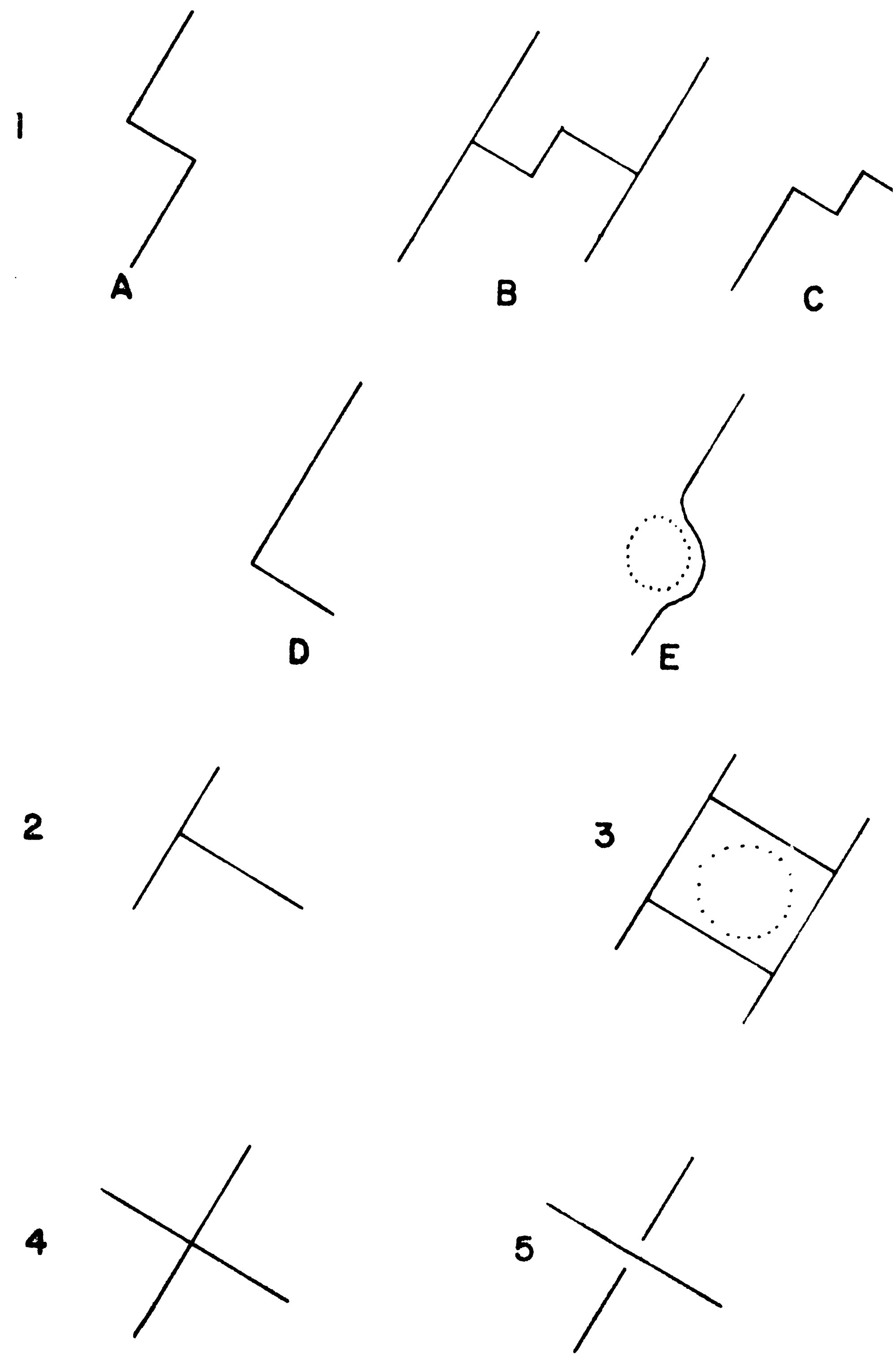
1. Offset intersection patterns; A-parallel offset, B-transverse offset, C-step intersection, D-"L" intersection E-looped intersection

2. "T" intersection pattern

3. Box intersection pattern

4. Cross intersection pattern

5. Nonintersection pattern


1
A
B
C
D
E
2
3
4
5

Offset intersection patterns predominate in the study area and occur in several ways. The most common occurrence in this class is where two offset parallel ridges are connected by a single transverse feature (A in Figure 28). Less common is where a transverse ridge (B in Figure 28) is offset by a short segment of a parallel ridge. Combinations of the first two types produce step intersection patterns (C in Figure 28). "L" intersections occur where a parallel and transverse ridge are not continuous beyond the intersection. Few looped intersections occur but where found usually are associated with a central undrained depression and appear as a gradation of the previous offset patterns.

"T" intersections (2 of Figure 28) are produced where either a parallel or transverse ridge terminates at the intersection while the other ridge continues in either direction from the intersection. Box patterns, which result from the intersection of two sets of parallel and transverse features are relatively scarce. These usually contain an undrained depression within the intersection pattern.

Cross intersections result from the continuation of both parallel and transverse ridges beyond the intersection (4 of Figure 28). Cross intersections are less common than offset or "T" intersections but more common than box patterns.

In many cases either a parallel or transverse ridge will stop before intersection is achieved (5 of Figure 28), then reappear again beyond the point where intersection would have occurred, producing a discontinuous pattern of nonintersection.

Till Petrofabric Investigation

Fabric studies were undertaken to provide additional data on the origin of the landforms. Appendix B describes the method of collecting and presenting the fabric data; the methods outlined by Harrison (1957a) were generally followed. Two sites were selected for detailed fabric studies of parallel ridges. Cross-sections and locations of fabric samples are shown in Figure 19. Site 1 (A in Figure 19) is located 3 3/4 miles west of Garden City on County Road C, Hardin county (sec. 24T.86R.23). The axis of the parallel ridge trends N30^{o}E. Striae on a bedrock surface (sec. 34 T. 86R. 23), previously unreported, in a quarry 2¼ miles southwest of the fabric site trend S35^{o}E.

Sample site 2 is located at Cook's Quarry 1¼ miles northeast of Ames (sec. 24 T. 84 R. 24) (B of Figure 19). The south face of the quarry cuts through a parallel ridge which trends N40^{o}E. Bedrock striae in the immediate area (Gwynne 1950) trend S42^{o}E.

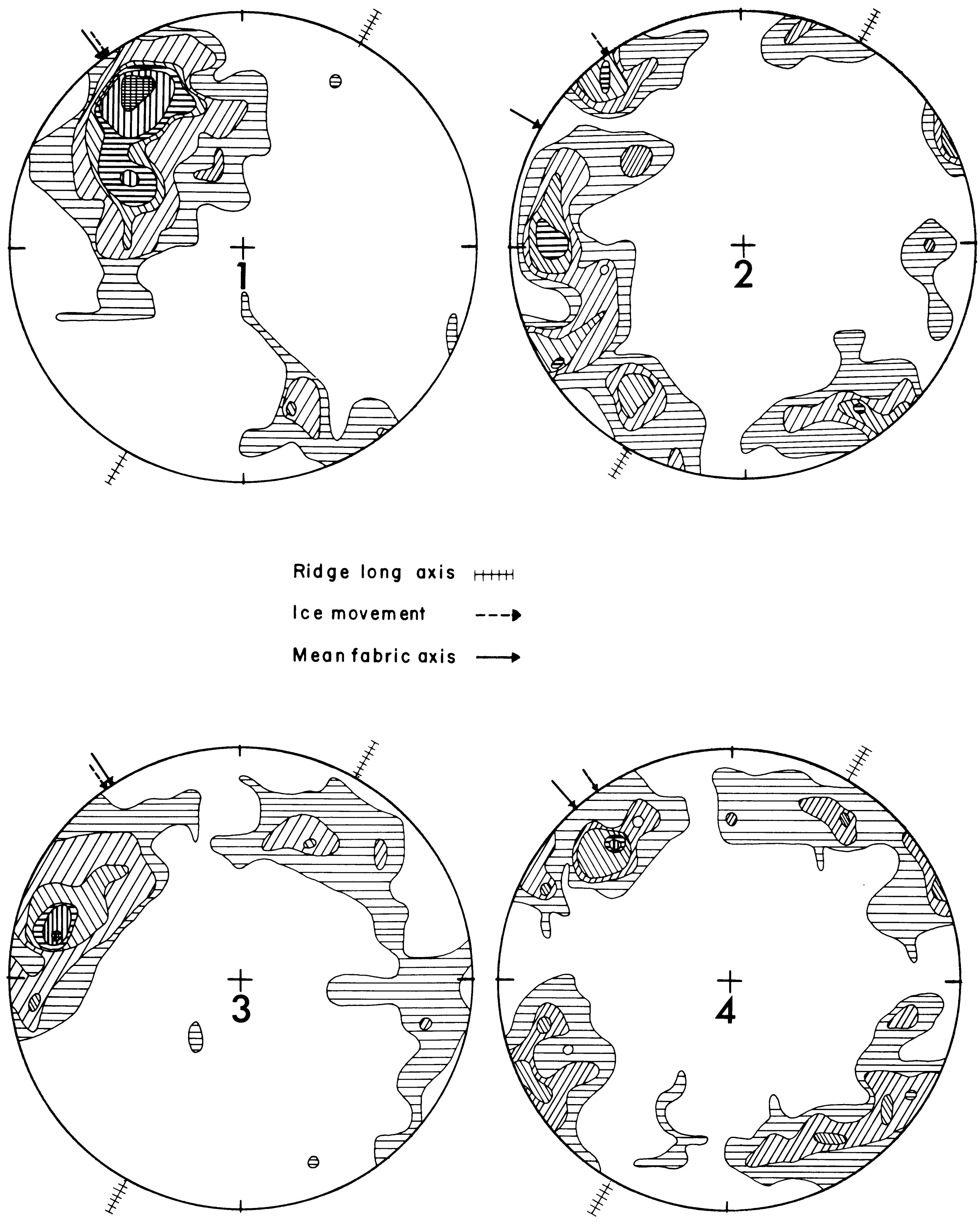
Nine fabric samples were taken from the two parallel ridges (4 from site 1 and 5 from site 2). The location and orientation of each sample is shown in Table 2. For site 1 (Figure 29) samples 1 and 4 represent approximately the same elevation (10 feet below the crest) on the proximal and distal slopes respectively. Samples 2 and 3 were taken along the base (18 feet below the crest) at the center and distal portion of the ridge.

The contoured petrofabric diagrams (Figures 29, 30, 31) represent the concentration of azimuths and plunge for the pebble long axis ('a' axis). The contours were drawn using a 1% counting circle. Also shown with the contoured fabric diagrams is the orientation of the striae trends, ridge long and short axes, and the mean fabric azimuth determined by radius vector analysis (Krumbein 1939).

Fabric sample 1 appears somewhat unique from all other samples. The contoured diagram indicates a very strong concentration of pebble 'a' axes in the fourth quadrant or a preferential imbrication upglacier. There is a weak concentration in the second quadrant which is 180^{o} to the major concentration. Cross-fabrics at 90^{o} do not occur. Sample 3 appears similar to 1 except for a shift in the mean azimuth to the west and a minor cross fabric in the first quadrant 90^{o} to the mean azimuth. Fabric samples 2 and 4 are alike, with major concentrations in the fourth and second quadrants (180^{o} apart) and a cross-fabric roughly at 90^{o}. Both samples 2 and 4 show the development of a girdle pattern which is not evident in samples 1 and 3.

At the Cook's Quarry outcrop all five samples were taken along the base of the cut (see Figure 19 B, sample 5 through 9 from proximal to distal portion respectively). The fabric diagram for sample 6 (Figure 30) appears anomalous, since its fabric axis is 90^{o} to all other fabric axes. (It is possible but not likely that this sample was reoriented improperly in the laboratory resulting in the anomalous fabric orientation). The author believes that it represents the true fabric orientation at the sample site. Sample 8 appears to have a random fabric pattern even though the fabric axis agrees with most other samples. The remaining three fabric samples appear similar, each exhibiting girdle point distribution, concentrations in the fourth and second quadrants and a 90^{o} cross fabric.

Contoured fabric diagrams for the Randall fabric site (site 1, A of Figure 19; contours, 2%, 4%, 6
8%, 10%, 12% per 1% area)


1
2
Ridge long axis
Ice movement
Mean fabric axis
3
4

Contoured diagrams for fabric samples 5 through 8, Cook quarry outcrop (site 2, B of Figure 19; contours, 2%, 4%, 6%, 8%, 10%, 12% per 1% area)

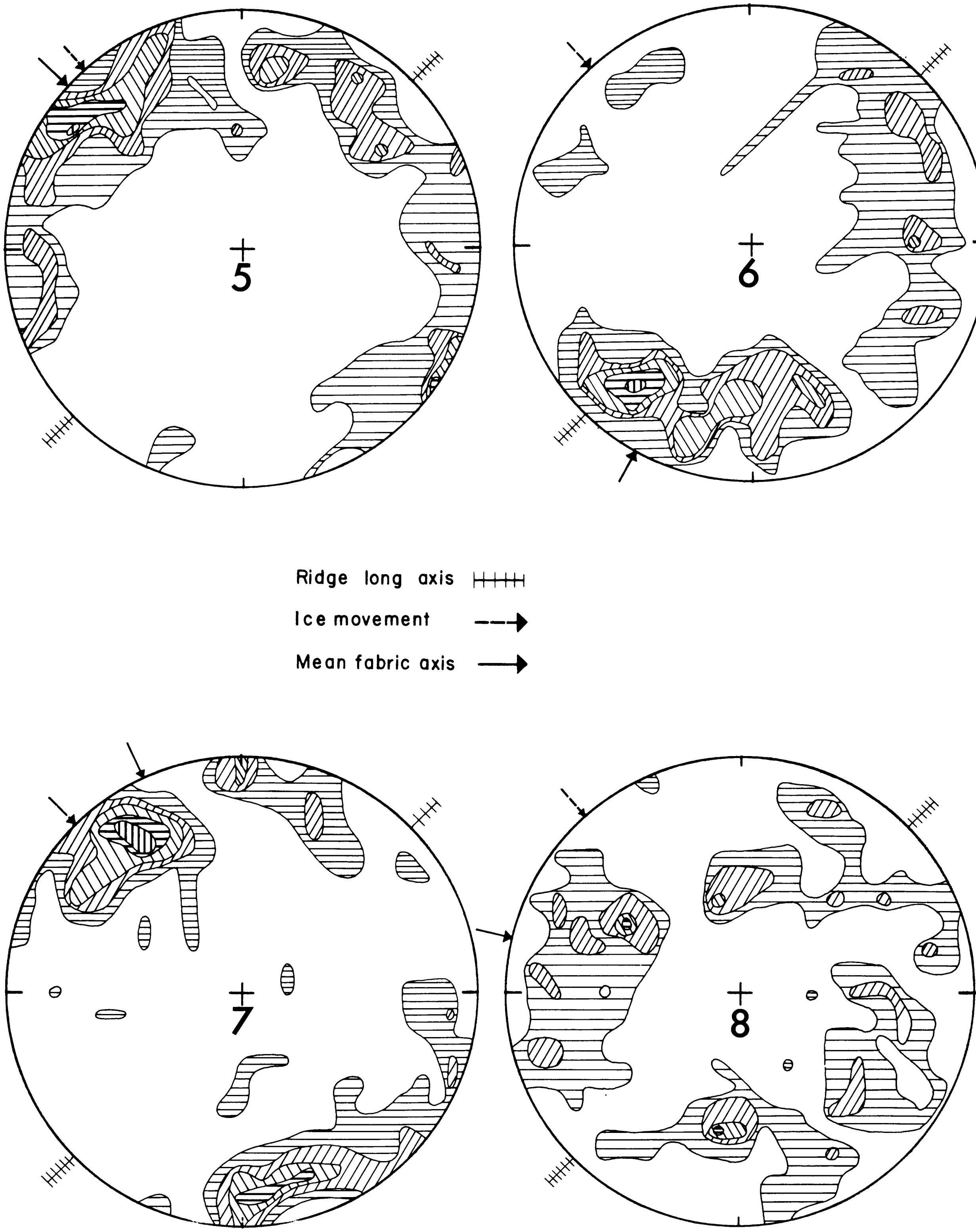

5
6
Ridge long axis
Ice movement
Mean fabric axis
7
8

Figure 31. Contoured fabric diagrams

Sample 9, Cook's Quarry outcrop (contours, 2%, 4%, 6%, 8%, 10% per 1% area)

Diagrams 10 and 11 are composite fabric diagrams for Randall outcrop and Cook's Quarry outcrop, respectivel (contours, 2%, 8%, 14%, 20%, 26% per 1% area)

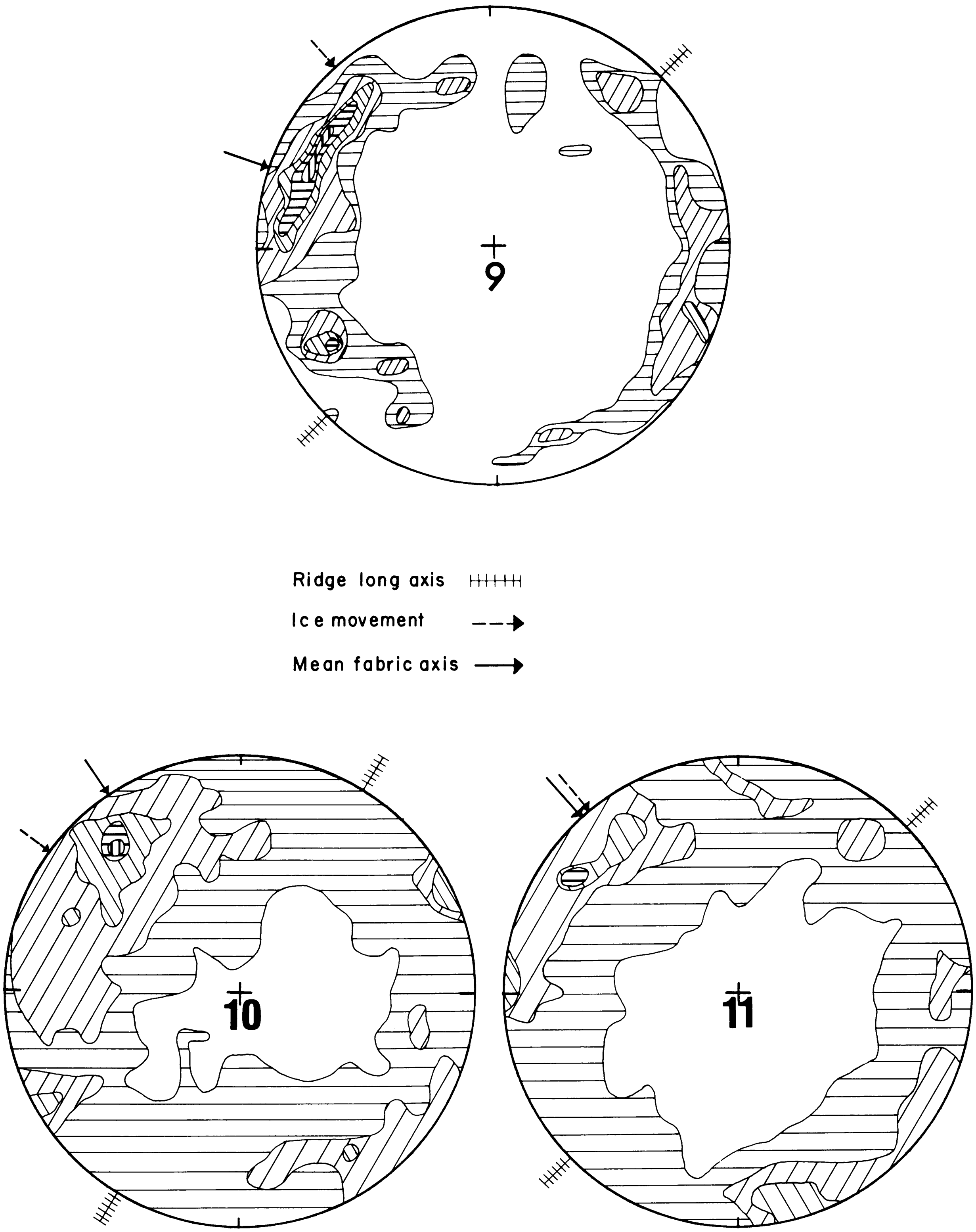

9
Ridge long axis
Ice movement
Mean fabric axis
10
11

Table 2. Compiled fabric data for sites 1 and 2

1	2	3	4	5	6	7[a]
1	323°	325°	30°	-2°	67°	23°
2	300	325	30	-25	90	0
3	326	326	30	1	65	26
4	317	325	30	-8	73	17
average	316			-9	74	16
5	312	318	45	-6	93	3
6	29	318	45	71	16	16
7	335	318	45	17	70	20
8	283	318	45	-35	122	32
9	289	318	45	-29	117	26
average	305			22	100	20

[a]Column 1, sample number; 2, mean fabric azimuth; 3, striae trend; 4, tredd of ridge long axis; 5, deviation of fabric from striae trend; 6, deviation of fabric from ridge long axis; 7, deviation of fabric from ridge short axis. For fabric site 2, sample 6 was excluded for determination of average values.

Examination of the fabric diagrams indicates that vertical variation in fabric concentrations and distributions outweight lateral variations within the outcrop or between outcrops. The characteristics of the fabric diagrams, excluding samples 6 and 8, are listed below.

1. Fabric axes approximate glacial striae trends. Minimum divergence is 1°, maximum divergence is 35°.

2. All of the diagrams have their strongest concentration in the fourth quadrant, 270-360°, indicating a preferential imbrication up glacier of the elongate clasts.
3. Low plunge angle of 'a' axes for majority of pebbles.
4. A secondary concentration in the second quadrant, 90-180°, which is diametrically opposed to the fourth quadrant concentration.
5. Minor cross-fabric at 90° to major fabric axis.
6. Monoclinic girdle pattern for most of the petrofabric diagrams.

DISCUSSION

Introduction

The origin of the landforms of the Des Moines Lobe is directly related to Cary glaciation. Therefore, it is necessary to discuss various aspects of the glacier itself, such as the hypothetical regime, thickness, lines of flow and the possible rate of movement. Next the regional lineation pattern for the Iowa portion of the Des Moines Lobe will be discussed, for only by looking at these regional patterns can their full implications be appreciated. Finally, six hypotheses will be critically evaluated for their validity, and relevance in determining the origin of the glacial land forms of the Des Moines Lobe.

Hypothetical Regime of the Cary Glacier

Classification of glaciers and ice sheets is based on the thermal gradients within the ice, dynamics of flow and the morphology or shape of the ice mass. The Cary glacier, being considered in this report, is a lobate extension of the Wisconsin Continental ice sheet centered in northern Canada. The shape of the lobe was approximately 300 miles long and 130 miles wide, and its flow direction was controlled by a gentle bedrock sag through western Minnesota and central Iowa (Wright and Ruhe 1965).

Thermally, the Cary lobe would be classified as a temperate glacier which, except for a thin surface layer, would be at the pressure melting point throughout its thickness. The important point concerning temperate glaciers is that meltwater can be present throughout (Embleton and King 1968) which effects both the dynamics of flow within the glacier and the deposition of till by the glacier. Melting of the ice will occur with the addition of the latent heat of melting since a change in the temperature of the ice is not involved. The ice and water will then remain in equilibrium with little subsequent refreezing. The heat necessary for melting of the ice is provided at the air-ice interface by climatic factors and at the ice-ground interface by geothermal and frictional heat.

Basal melting of the Cary glacier could provide for the accumulation of ground morainal debris and increase the sliding velocity of the glacier. Since the glacier itself would be everywhere at its pressure melting point and therefore include a small amount of englacial water, the creep rate would be relatively high. The total effect, therefore, could be a glacier with a relatively high velocity.

Glaciers can be classified dynamically as active, inactive or passive, or dead glaciers. Active glaciers are normally fed by a continuous ice stream and are not dependent upon a positive mass balance. Passive glaciers are intermediate between actively flowing glaciers and stagnant ice masses. They occur where lack of slope inhibits ice movement, and have a greatly decreased flow velocity. Stagnation occurs under several conditions: 1) by loss of accumulation or recharge, 2) by isolation from its source due either to topographic control or wholesale thinning, or 3) by separation due to insulation effect of ablation moraine (Flint 1942).

The Cary glacier exhibited all of the three dynamic stages during different periods of its development. Regeneration of a seemingly passive Cary glacier occurred at least four times producing the Altamont, two segments of the Humboldt and the Algona morainal systems.

The onset of stagnation of the Cary ice was probably not marked by terminal retreat, though undoubtedly some retreat occurred. Studies of existing stagnant ice masses and waining glaciers show that stagnation is accompanied by a lowering of the surface elevation with little terminal retreat (Flint 1957, Goldthwait 1951, Hartshorn 1961 and Clayton and Freers 1967). Dissipation throughout the entire glacier lowers the ice surface rapidly until enough debris collects on the surface to protect it from further ablation (Sharp 1949, Ogilvie 1904).

Review of Radiocarbon Chronology

A review of the radiocarbon chronology for the Des Moines Lobe is necessary, since any hypothesis concerning the origin of its glacial landforms must be consistent with this limited chronology.

From the published radiocarbon dates associated with the Des Moines Lobe in Iowa (Table 3), the chronology of glaciation and deglaciation can be inferred. The advancing glacier is dated at approximately 14,000 years b.p. at sites 30-40 miles from the terminus (Ruhe and Scholtes 1955, 1959). The Altamont phase represents a readvance, which has been dated at 13,000 years b.p., of the Cary ice of at least 32 miles. The Britt section in Hancock County contains wood, buried in outwash from the Algona moraine, dated at 12,970 and 13,030 ± 250 years b.p.

From radiocarbon dates of basal sediments in peat bogs, published by Walker (1966), it is possible to determine the time of deglaciation. Lack of contorted bedding and lateral continuity of all the units, indicate that the bog could not have been of superglacial origin. The location and basal dates of the bogs are shown in Figure 32 and Table 3. The lower silt

(LS) interval represents sediments derived from the initial erosion of the Cary drift (Walker, p. 852). Dates within or at the top of the lower silt strata, therefore, represent a minimum date for deglaciation of the region around the individual bogs.

The published radiocarbon dates for the Des Moines Lobe appear contradictory, if a simple model of glacial advance and retreat is used. Ruhe and Scholtes (1955) have dated the Altamont readvance at from 12,120 ± 250 and 13,030 ± 250 years b.p. and stated that "in addition to the advance of 32 miles distance from the margin to radiocarbon sites dating 14,000 years b.p. a recession of 107 miles from the Cary maximum advance to the Algona retreat [Britt site] was required in a period of 1,000 years."

These dates of approximately 13,000 b.p. imply that the Altamont and Algona readvance occurred at the same time, yet geographic position of the Algona moraine in relation to the Altamont moraine, indicates that it must be younger. The basal dates for the Jewell and McCulloch bogs (11,635 and 14,500 years b.p. respectively), both situated within the Altamont moraine (as defined by Ruhe), indicate that either the dates are incorrect or that deglaciation was not synchronous.

The close age relationship between the Lizard Creek and Britt sections indicates that the much reduced glacier was still active along its lower extremity. The progression of dates appears to indicate that lateral thinning progressed at a greater rate than terminal thinning and deglaciation. It is evident, though, that not enough radiocarbon dates are now available to reconstruct the glacial history of the Des Moines Lobe to any

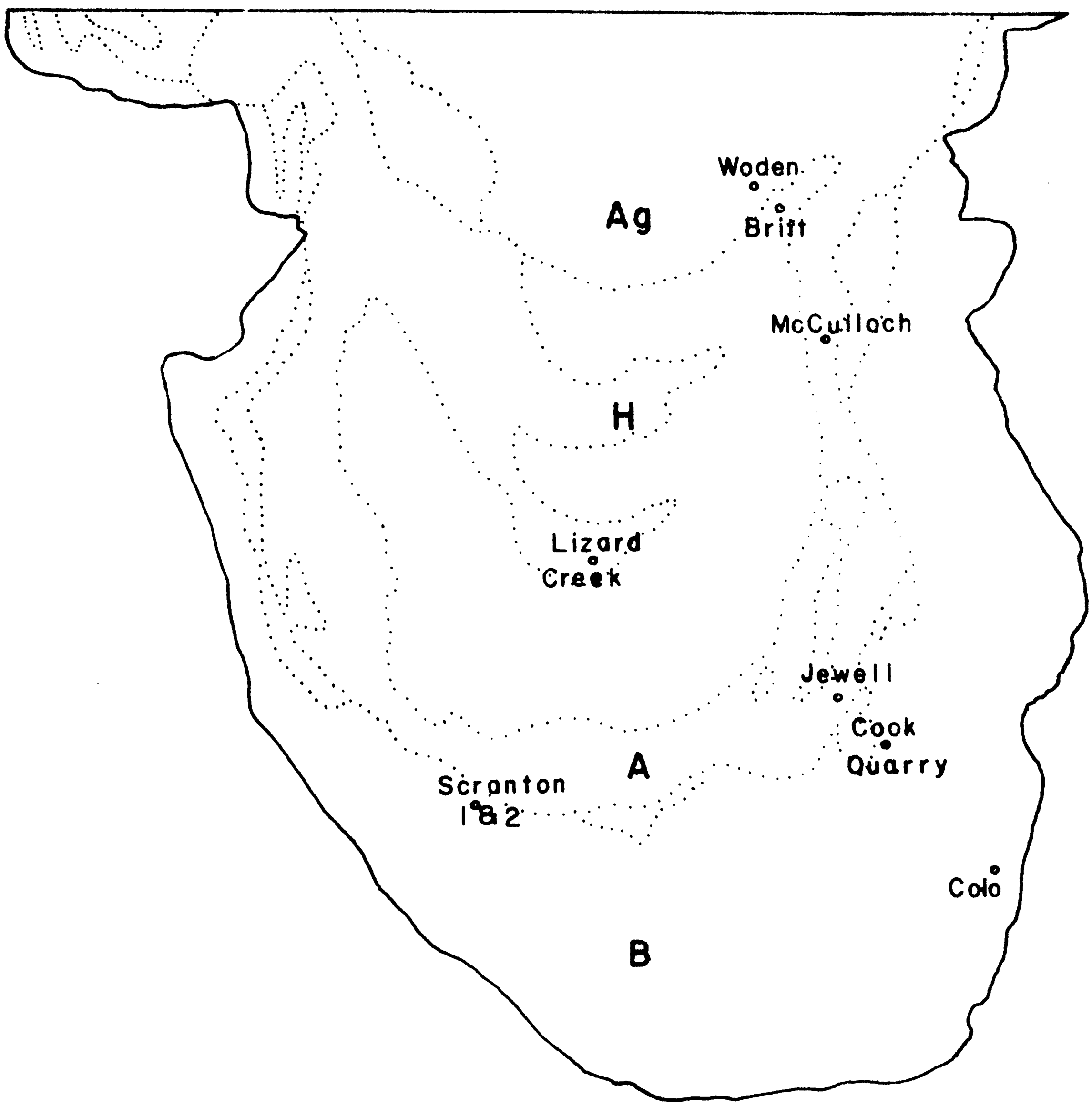
Table 3. Partial list of the radiocarbon dates associated with the Des Moines Lobe[a]

Site designation	Location	Date	Significance	Reference
Woden Bog	Hancock Co.	11,570±330 LS	Deglaciation	Walker 1966
Jewell Bog	Hamilton Co.	11,635±400 B[b]	"	"
Mankato	Mankato, Minn.	12,650	"	Wright and Ruhe 1965, p.39
Lizard Creek	Webster	12,120±530 13,300±900	Altamont advance	Ruhe and Scholtes 1955
Britt	Hancock Co.	12,970±250 13,030±250	Algona outwash	"
Colo Bog	Story Co.	13,775±300 LS*[c]	Deglaciation	Walker 1966
Scranton no. 2	Greene Co.	13,910±400	Cary Advance	Ruhe and Schultes 1959
Cook Quarry	Story Co.	14,042±1,000	"	"
Scranton no. 1	Greene Co.	13,820±400 14,470±400	" "	"
McCulloch Bog	Hancock Co.	14,500±340 LS*	Deglaciation	Walker 1966

[a]See Figure 32 for location of radiocarbon site.

[b]B = indicates date at base of lower silt layer.

[c]LS = Lower Silt layer, * indicates date at top of lower silt layer.



∘ Radiocarbon Sites

degree of certainty.

Probable Thickness of Cary Ice

Thickness values for the Cary glacier in Iowa have not been determined. Two methods of thickness approximation must then be used. These methods are 1) extrapolation of work done in other areas for Wisconsin glaciers of similar shape and size, and 2) mathematical treatment of an idealized glacial profile.

One approximation of the thickness of the Cary ice can be gained by extrapolation of the work done in Indiana. Harrison (1958) has attempted to reconstruct the paleoglacial thickness of the Champaign glacier (Early Wisconsin) using preconsolidation values of overridden silts. The lobate Champaign glacier has the same approximate width as the Cary glacier, but its length was much shorter.

Using preconsolidation values, Harrison estimates that at a point 27 miles from the terminus, the ice was 2,500 feet thick. This thickness value is slightly larger than that of 2,000 feet considered by Ruhe[1] for the Cary glacier.

Values for the thickness of the Wisconsin ice in North and South Dakota are not given, but Gwynne (1951) and Clayton and Freers (1967) consider it to be relatively thin. This is suggested by the radius of morainal arcs and the apparent influence of bedrock topography on flow direction.

Mathematical treatment of glacier profiles is discussed by Nye (1952). Using a simplified flow law for ice and assuming an ice sheet of large

[1]Ruhe, Robert V., Ames, Iowa. Thickness value of Cary Glacier. Private communication. 1968.

extent and of uniform thickness, h, which rests on a plane bed with slope, α, the shear stress on the bed is given by:

$$T = \rho gh \sin \alpha \qquad (1)$$

where T = the shear stress at the glacier bed, ρ = density of ice, and g = the acceleration due to gravity. Although calculated shear stresses range from .5 to 1.5 bars, Nye assumes "for a first calculation that T is constant (1 bar) over the floor of a moving ice sheet? (Nye, p. 529).

Equation 1 may be writton as:

$$h = h_o \operatorname{cosec} \alpha \qquad (2)$$

or for small α

$$h = h_o/\alpha \qquad (3)$$

where $h_o = T/\rho g$. Therefore if T = 1 bar, h_o = 11m.

Nye then applies this equation to calculate the ice surface, knowing the configuration of the glacier and the direction of flow. Equation 3 is then written as

$$H = \frac{h_o}{h} \quad S \qquad (4)$$

where H is the increase in absolute height of the ice surface and S is the distance from the margin along line of flow.

If the bed of the glacier is essentially horizontal, equation 4 can be further refined and becomes the equation of the parabola

$$h = \sqrt{2h_oS} \qquad (5)$$

Equation 5 can be used to calculate the thickness of the Cary ice if we assume that the surface over which the Cary ice advanced has essentially no slope. Using Kay's (1928 p. 27) generalized bedrock map of Iowa and assuming a constant drift thickness above the bedrock surface, there is a 175 foot drop in elevation in 150 miles. This surface, therefore, is essentially horizontal.

To determine thickness values of the Cary lobe using Nye's equation, two cross sections must be considered, one parallel to and another perpendicular to the flow of the Cary ice. This is necessary since the lobate form does not meet the original assumptions of an infinitely wide ice sheet.

The long profile of the Cary glacier is given in Figure 33A. Assuming a glacier of infinite lateral extent, the thickness would be approximately 1,030 m, (3,400 feet) thick, 30 miles from the terminus (vicinity of Ames). Figure 33B represents the cross profile of the Cary glacier, assuming that lateral expansion is dominant. It shows that in the vicinity of Ames, 34 km from the margin, the thickness would be 840 m or 2,700 feet. This value, representing the shortest distance of ice flow, is the maximum thickness value for the Cary glacier. Because Nye's equation does not hold for very near the center of the ice cap, a smoothed out center profile must be expected as shown by the dashed line in Figure 33B.

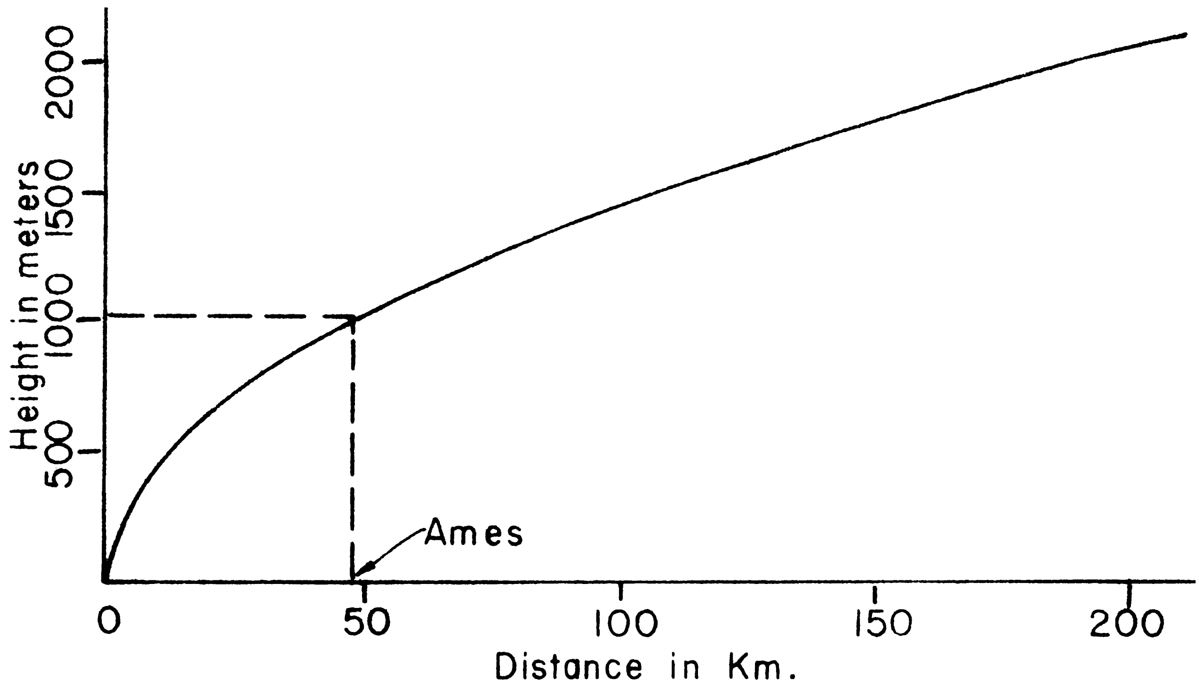
Hypothetical Glacial Flow Lines

The hypothetical glacial flow lines for the Cary glacier are shown in Figure 34. In plan view the flow lines should appear somewhat radial in design, with flow toward the greatest extension of the lobe. These flow lines are suggested by the outline of the lobe and are confirmed in two

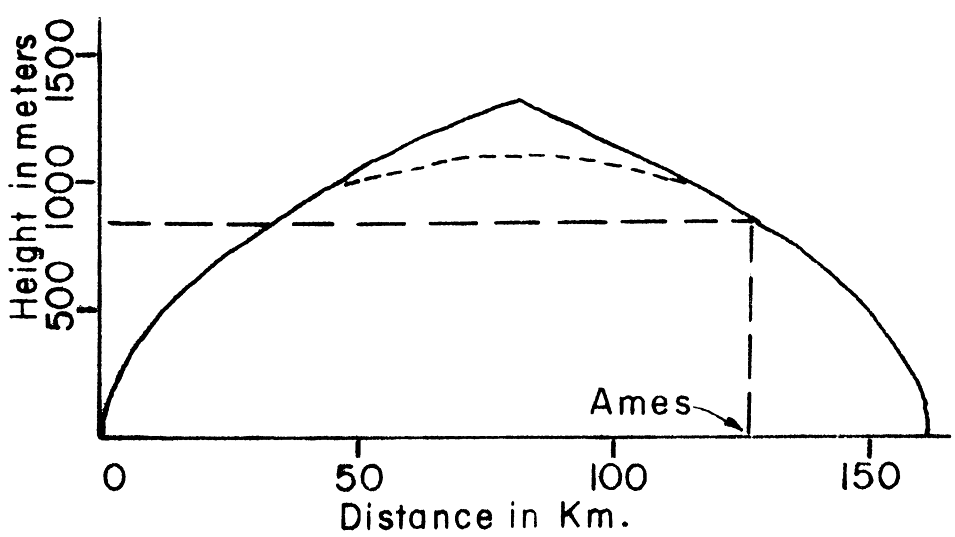
Hypothetical profiles for the Cary Glacier (based u
equations in Nye 1952)

A. Longitudinal profile of the Cary Glacier

B. Cross profile through Ames of the Cary Glacier


Height in meters
500
1000
1500
2000
Ames
0
50
100
150
200
Distance in Km.

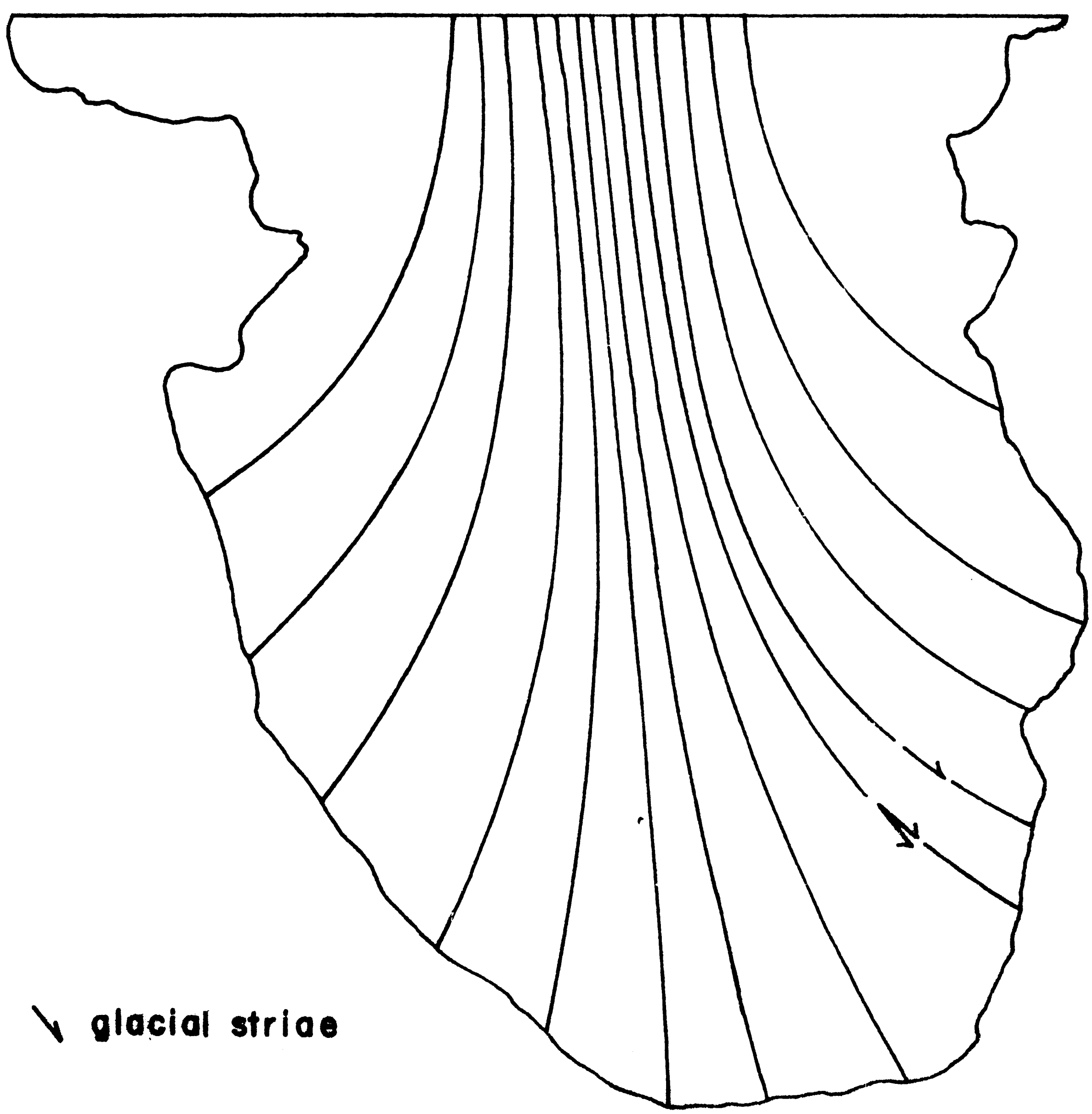
A


Height in meters
500
1000
1500
Ames
0
50
100
150
Distance in Km.

B

Hypothetical glacial flow lines
the time of maximum extension

Hypothetical Cary Flow Lines



places by bedrock striations (Gwynne 1950, Author). It must be stressed, though, that the flow lines are representative only at the time of maximum extension. New flow lines would have to be drawn for the glacier at each successive stage.

Rate of Cary Advance

The rate of advance of the Cary ice margin is not known, but reasonable values can be assumed. Flint (1955) has studied the rate of marginal advance for Wisconsin glaciers in Illinois using C^{14} dating and direction and distance of ice flow.

For an early Wisconsin glacier (not named) which reached its terminus 21,000 years b.p., the rate of advance was calculated to be 160 feet/year. The Mankato glacier was calculated to have a rate of advance of from 1,680 to 3,080 feet/year (Flint 1955). These rates of advance of Wisconsin glaciers are of the same magnitude, though slightly greater than modern glaciers.

The author believes that a rate of approximately 1,000 feet/year would be reasonable for the Cary glacier since the glacier is flowing down the regional slope. Most likely the flow rate was quite variable and as the ice reached its greatest extension the flow was much reduced. This is reasonable due to climatic warming and regional thinning of the ice sheet in Late Wisconsin time.

Regional Patterns

Figure 35 represents the distribution and orientation of the glacial landforms throughout the Des Moines lobe in Iowa. The map was constructed from individual county mosaics where linear ridges (swells) appear as light areas interspaced with the darker depressions. Some areas show no apparent linear elements, either because the pattern does not exist or is not apparent on the photo-mosaics. Other areas show a poorly developed, randomly oriented pattern. In all cases the lineated pattern is best developed toward the margin and southern portion of each morphostratigraphic unit.

The predominant linear elements are alligned roughly parallel to the drift margin (see Polk, Guthrie, Buena Vista, Cerro Gordo and Franklin Counties) or truncate the margin at very slight acute angles (see Hardin, Marshall, Jasper, Dallas, Carroll, Dickinson and Osceola Counties). A secondary set of linear ridges exists either perpendicular or at an acute angle to the dominant "parallel" trends. In isolated areas the transverse pattern is dominant (see Webster and Calhoun Counties).

Two factors are controlling the orientation of parallel and transverse ridges. The colinear to subcolinear relationship of parallel ridges to the margin of the Des Moines Lobe or associated recessional moraines, suggests that their orientation is partially controlled by the shape of the individual lobes. It can not be distinctly shown, though, whether the formation of ridges within a lobe are adjusted to the distal margin, representing the stagnant-active ice margin during deglaciation, or are controlled by some other mode of origin.

Regional lineation patte
of Iowa (1" = 4 miles)

It is evident that parallel ridges can be formed at or near the margin because these linear elements are associated with all of the end morainal systems. Truncation of the margin by parallel lineaments generally occurs at a low angle ($< 15^{o}$) but can be as great as 75^{o} (see northwest Marshall County). This truncating relationship suggests that these elements are not strictly controlled by the position of the lobe margin either during glaciation or deglaciation, but rather are ice flow controlled, assuming that the drift margin has been accurately mapped.

Transverse elements as defined in this paper have not previously been associated with the Des Moines lobe landform patterns which have been mapped separately by Gwynne (1942a)and Ruhe (1952, 1969). The relationships of transverse elements to parallel elements and the flow mechanics of the Cary ice is critical to the determination of the origin of intersecting lineament patterns.

Transverse elements appear to parallel hypothetical flow lines of the glacier, (compare Figure 34 with Figure 35) suggesting an ice flow control for their origin. The apparent ice flow control, pattern of intersection and similarities of composition of parallel and transverse ridges suggest that their formation resulted from variations in a singular mode of origin.

Scalloped patterns have been previously described for the study area. There are nine such scalloped belts located along the southern and eastern portion of the Des Moines lobe. The reentrants along the axes of these scalloped belts have been, in places, completely reoccupied by modern streams (see Squaw Creek, Indian Creek, and Skunk River in Story County; Figure 35). The scalloped belts along the North Raccoon River (north central Dallas County) and the Iowa River (southwest Hardin County) are occupied only in part by modern streams. In central Winnebago County the scalloped belt appears relatively undrained.

The Randall scalloped pattern (Figure 15D) was studied in detail and suggests a developmental sequence which is probably representative for most, if not all, of the scalloped belts. The sequence involves 1) deposition of the proglacial outwash (indicated by the basal stratified drift) from a superglacial stream situated along a longitudinal crevasse, 2) advance of the glacier, bringing this longitudinal crevasse and associated superglacial stream into the position represented by the transverse axis of the scalloped pattern, 3) stagnation of the glacier and deposition of the parallel ridges while crevasse fill kames developed. The absence of till between ridges indicates that the till within the parallel ridges was either transported to its present location from elsewhere or was collected in a surficial depression in the ice.

The association of bedrock channels with the origin of scalloped patterns is suggested by 1) the occurrence of the Skunk River, Squaw Creek and Indian Creek scalloped patterns over bedrock channels. The Raccoon River and Upper Des Moines River scalloped belts are also associated with bedrock drainage channels. It is recognized by the author that the pre-Cary topography need not be similar to the preglacial bedrock configuration. However, the thick sequences of sands and gravels of various ages within these channel systems indicate that, in part, preglacial drainage lines were reestablished after each successive glacial advance. 2) All of the scalloped belts are located along the southern and eastern portion of the Des Moines Lobe. It appears, therefore, that scalloped belts form where glacial flow parallels the regional, pre-Cary drainage trends. Along the western margin of the lobe the ice advanced across the drainage trends, whereas to the south and east the ice flowed in the direction of the pre-Cary drainage lines, developing the scalloped patterns.

The scalloped pattern east of Randall is not consistent with the five associations previously described. Here the pattern is developed on a bedrock high with no apparent relationship to any pre-Cary channel systems. For the remaining three scalloped belts, detailed subsurface information is lacking.

Correlation of Surficial Topography with Bedrock Topography

There appears to be a moderate correlation between the "degree of development" of the surficial topography and the underlying bedrock topography. If Figure 12 is compared with Figure 3, the bedrock map of the study area, it is evident that the areas of low relief, including the Story City Flats, occur over bedrock channels (lows), while the intermediate relief areas are generally situated over bedrock topographic highs.

Of interest is the area east of Ames. The Ames-Roland structural and topographic high parallels the northeast-southwest reach of the Skunk River. East of the Skunk River and southeast of Ames is located a drift filled bedrock channel trending northwest-southeast. There is a progressive decrease in the height of the parallel ridges, in the direction of glacial flow, from intermediate-relief features over the Ames-Roland structured high to low-relief features situated over this bedrock channel. This trend suggests that the factor controlling parallel ridge formation is flow of the ice and that the intensity of the ridge forming process varies with the bedrock configuration. The low relief area southwest of Ames is also situated over a bedrock channel trending southeast.

Bedrock configuration is probably not the only controlling factor which determines the intensity of formation of linear elements, as suggested by the presence of the Story City Flats. This area overlies the upper reach of the bedrock Skunk Channel and should predictably exhibit a low-relief lineated topography. The atypical nonlineated topography which is just an extremely low relief topography, may result from a factor not previously considered, that of the piezometric surface of the subglacial aquifer. Presently the piezometric level throughout the central and lower portion of the Story City Flats is at or above the surface, resulting in numerous flowing wells (Schoell 1967, Sendlein and Dougal 1968). The piezometric head is derived from the basal sand and gravel "Ames Aquifer" which has bedrock recharge, the constriction of the aquifer at Sopers Mill (sec. 7 T84N,R23W) and overlying, impermeable Wisconsin till and silts. It is likely that a high piezometric level existed during Cary times. The presence of the Skunk bedrock channel and the high piezometric surface effectively reduced the factors controlling the development of linear elements. This was effected by partial buoyancy of the ice and reduction in basal frictional drag.

The classification of the surficial topography of the Story City Flats as one end member in a developmental continuum is suggested by 1) a decrease in the number and height of linear elements from the northwest to southeast (direction of glacial flow) into the area and 2) the presence of poorly defined linear elements within the area of the Story City Flats.

The variation in intensity of the factors controlling the formation of linear elements is also seen in Figure 13. The high relief feature has a core of pre-Cary sediments with only a thin veneer of Cary till. The area surrounding this isolated high relief feature has a low-relief surficial expression. Developed on the high relief feature itself are numerous, short, close-spaced, parallel and transverse elements. This isolated pre-Cary topographic high evidently affected the dynamics of the ice enough to increase the intensity of formation of the linear elements. The presence of a pre-Cary drift and loess cored topographic feature suggests that the Cary ice was depositing rather than eroding in this region and suggests a very fluid ice mass. The combination of the minor variations in the configuration of pre-Cary topography which effected the ice, along with the lack of erosion of pre-Cary topographic features, suggest that the Cary glacier was quite thin (1,000 to 2,000 feet thick) at the time.

Origin of Till Fabric

The characteristic fabric of the two ridges sampled is indicative of a lodgment till or ground morainal deposit (Holmes 1941, Krumbein 1939, Harrison 1957b, Yeend 1969). Harrison suggests that the fabric-pattern maxima "define vanished slip planes" produced by internal deformation of the moving glacier and that the till was transported over "up-stream-inclined thrust surfaces".

All of the till fabric samples, except 6 and 8, show a strong tendency for upglacier imbrication for pebble 'a' axes, a diametrically opposed concentration, a cross-fabric at 90° and a concentration of the mean azimuth about known ice flow directions. These characteristics are identical to those found by the before mentioned authors for ice flow controlled, lodgment tills.

The mean orientation of sample 6 is at 90° to all other fabric orientations. Lindsay (1968) has described fabrics of tillites from the Queen Alexandra Range, Antarctica which exhibit this same characteristic cross-fabric. It is possible, therefore, that this fabric sample is not discordant with the origin of the other sample fabrics. The cause for the randomness of sample 8 is not yet known. Even though it appears random, the mean azimuth corresponds with the other fabric samples, except sample 6. Further evaluation of the fabric samples is discussed under the appropriate hypothesis.

Review of Hypotheses of Origin

Glacial topographies dominated by linear elements, similar to that found for the Des Moines Lobe, have been observed in North Dakota and Minnesota (Gwynne 1951), Western Canada (Gravenor and Kupsch 1959), Alberta (Stalker 1960), Baffin Islands (Andrews 1963) and east of the Hudson Bay, Quebec (Prest 1968). Glacial topographies dominated by linear elements of the type found throughout the Des Moines Lobe have been variously named by these authors, swell-swale topography, minor moraine topography, cross-valley moraines and De Geer moraines.

Various hypotheses have been advanced to explain the formation of glacial topographic lineaments. These hypotheses can be generally classified as 1) minor moraine origin, 2) inclusion of subglacial material by basal freezing, 3) thrust plane origin, 4) crevasse fill origin, 5) basal crevasse fill origin, and 6) basal boundary wave phenomenon. These hypotheses will now be critically evaluated in light of this study.

Hypothesis 1: Minor moraine origin: First proposed by Gwynne (1941), this hypothesis states that swell-swale patterns are in essence minor end moraines of a receding glacier, possibly representing an annual fluctuation of the margin of the ice sheet. Ruhe (1969) has accepted the minor moraine hypothesis and has mapped large areas of the Des Moines Lobe as end moraine using swell-swale topography as his criteria.

Gwynne's hypothesis advocates the classical concept of advance and retreat of a continental glacier. As discussed under "Hypothetical Regime of the Cary Glacier", recent studies of ice-masses and glaciers indicate that deglaciation is a result of ice stagnation and downwasting rather than backwasting. Where a stagnating glacier becomes covered with 1-2 feet of superglacial debris, the processes of ice wasting become substantially slower (Sharp 1949). Where found in central North America, a 350 foot mean spacing of parallel ridges is characteristic , (Stalker 1960, Andrews 1963). This spacing could not be produced by annual backwasting of a continental glacier throughout the diverse climatic regions of northern North America. The minor moraine mechanism also does not explain the lack of proglacial outwash on the uplands and the origin of transverse ridges.

Till fabric studies indicate, generally, an inability to distinguish, on the basis of fabric, between end moraines and ground moraine (Harrison 1957b, Yeend 1969). End moraines which exhibit an ice flow controlled fabric represent material deposited subglacially at the ice margin by shearing of the ice over the previously constructed end morainal debris. Galloway (1955) has shown, though, that where shove of constructed moraines has occurred, the fabric elements will be reoriented, with the mean azimuth of pebble 'a' axis parallel to the crest.

Hypothesis 2: Inclusion of subglacial material by basal freezing: At some point within a glacier it is hypothesized that the 0^{o} isotherm is depressed into the basal till layer with subsequent freezing of the material to the base of the glacier. This material is then carried along the base of the glacier until it is deposited subglacially as the ice stagnates, or is brought to the surface in the marginal region along flow lines.

This mechanism was first postulated by Weertman (1962) to account for the occurrence of debris bands found within the marginal ice of the Greenland ice cap near Thule, Greenland. If this mechanism were operative in the Cary glacier it could possibly account for 1) the ice controlled, till fabric, which would be produced while the debris was frozen in the ice and 2) the isolation of the parallel-till ridge in the Randall scalloped belt (Figure 15). Unfortunately the mechanism postulated is operative only in cold based, polar glaciers, if even then, and would not be present in temperate glaciers which are at their pressure melting point throughout. Also this mechanism fails to account for the origin of transverse ridges and the composition of both parallel and transverse ridges, specifically the distorted sand and gravel lenses found within these ridges.

Hypothesis 3: Thrust plane origin: To account for the orientation and lodgment till fabric of washboard moraines spaced 350 feet in Manitoba, Canada, Elson (1957) proposed a thrust plane origin. Till ridges are deposited subglacially by the "lodgment of till at a line (zone) where the brittle upper ice extended down to the sole of the glacier" resulting in thrusting of active ice over marginally stagnant ice. Elson speculated that the interval between ridges represented annual (?) retreat of the thrust zone.

In considering the simplified flow law of ice it can be assumed that deformation of the ice is negligible below a critical yield stress, k, and that shear stresses do not rise appreciably above this value. Therefore, if the strain rate is greater than that which can be compensated by plastic flow, shearing will occur. The process of shearing is most pronounced toward the thinning margins of glaciers and ice sheets where compressive flow is maximum.

The existence of marginal shear zones has been observed in the Barnes Ice Cap, Baffin Island (Baird and Ward 1952, Goldthwait 1951). in the Greenland ice sheet and outlet glaciers (Battle 1949, Rausch 1956, Hartshorn 1961, and Swinzow 1962) in the Antarctic (Souchez 1966, Boulton 1968, Hooke 1968 and Souchez 1968) and some Alaskan and Canadian piedmont glaciers (Meier 1960 and Clayton and Freers 1967). Theoretical treatment of shear zone formation is given by Flint (1947), Finsterwalder (1950), Kingery (1963), Nye (1967) and Embleton and King (1968).

The phenomena of shearing in glaciers provides a mechanism of basal erosion and transport of debris within and to the surface of the ice. Shear zones, in plan view, are arranged parallel to the glacial margin and have an upglacier dip at the surface of approximately 30-40 degrees (lesser dips can be encountered as the ice surface is lowered). The closely spaced shear planes discharge debris on the glacier surface which retards ablation of the stagnating margin.

Nye (1967) has derived the mathematical solution of the slip-line field for a glacier snout. He assumed that the ice was a plastic rigid material where 1) the elastic component of strain is disregarded, 2) the material is rigid when stressed below the yield point, k, and 3) Young's modulus approaches infinity (no volume change under strain).

If the glacier is undergoing compressive flow the slip-line field is similar to that produced in a plastic material deformed between rough, parallel plates. The slip-line field was started with a field of radii and arcs of circles and extended toward the margin of the glacier. It was expected that, so long as the field is started in a way consistent with the plasticity equation, the details of how it is started will not matter. The slip-lines will quickly settle down to an approximately cycloidal field. The numerical computation can then be continued to find the field in the tip region of the glacier, where the cycloidal field is no longer even approximately valid.

Computation of the approximate slip-line field involves a series of successive approximations involving use of a computer. Of interest is the fact that there was a critical point near the margin beyond which the slip-line field could not be extended. This marginal region does not deform plastically but acts as a rigid block, while the bounding slip-line PQ acts as a thrust plane (Figures 36, A and B).

It is now possible to visualize a model which can account for both the periodicity and fabric of swell-swale features. Figure 36 represents a glacial profile where PQR indicates the rigid portion of the glacier, with shearing along PQ. The location of Q, the surface expression of the slip-line PQ, is determined by the critical thickness, T. The thickness, T, the minimum thickness at which ice will deform plastically, is approximately 150 feet.

For a single shear plane or set of closely spaced shear planes to remain active for any significant length of time, the shear zone must remain stationary. This will occur only when the volume of glacial flow is equal to the rate of ablation, assuming both flow volume and ablation are constant with time. If this condition is not met then the glacier is either advancing or "retreating" (retreat in this sense refers to recession of the active-stagnant zone and not necessarily to the actual glacier margin).

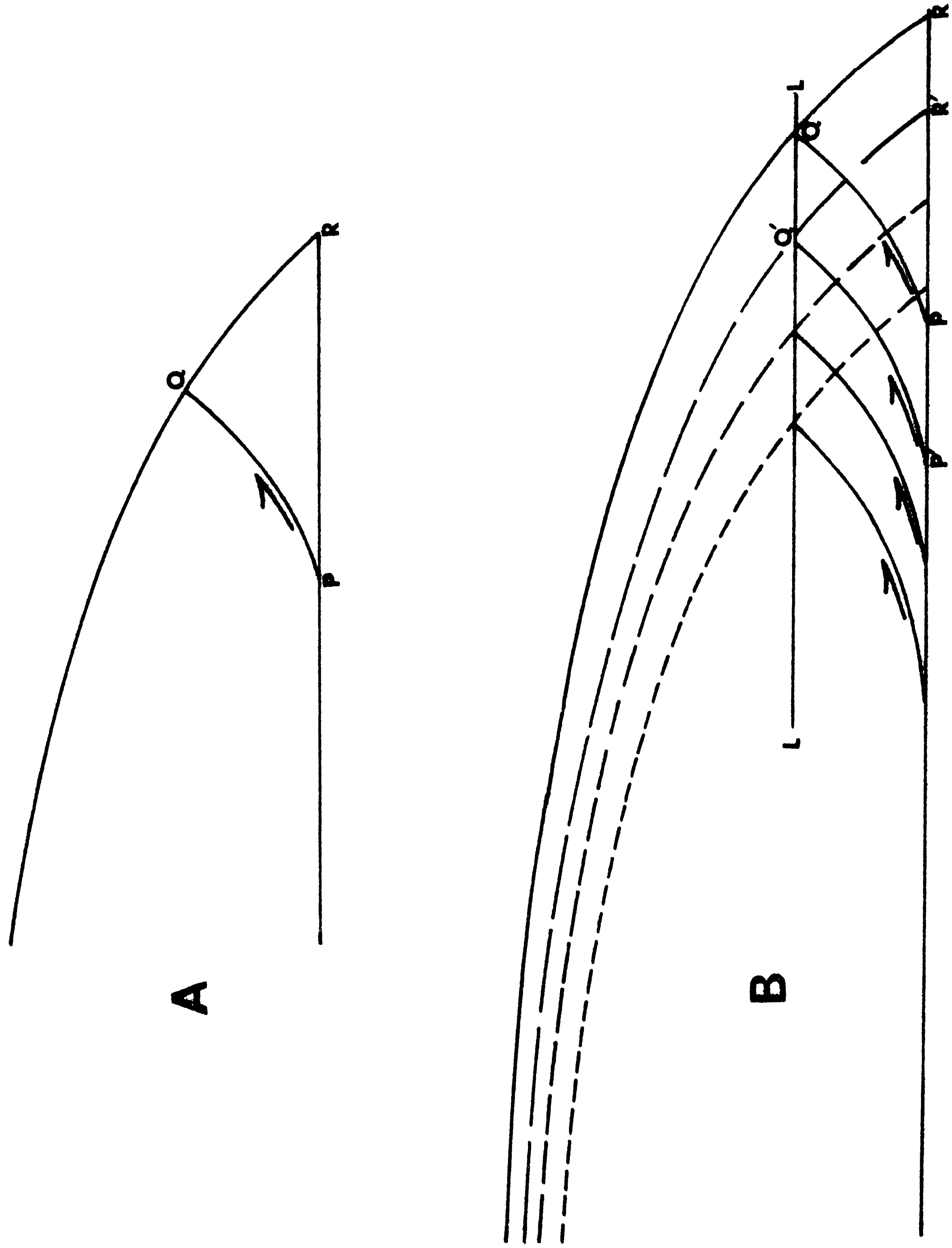
The line L-L' (Figure 36b) represents the critical thickness. The shear plane will reach the surface at the point where L-L' intersects the surface. Therefore, if we assume that the volume of ice removed by ablation is constant and greater than the volume of ice transported by the glacier, the surface profile will be lowered at a constant rate. Since the surface profile is lowered at a constant rate, the point Q and subsequently the shear plane PQ will also retreat at a constant rate.

A constantly retreating shear zone, though, will not produce the periodicity seen in the glacial landforms since all shear zones will remain active for the same length of time. Therefore it is necessary to consider variations in either the rate of flow or ablation of the glacier. Seasonal

Figure 36. Hypothetical slip-line field for the margin of the Cary Glacier

A. Marginal region where PQR represents the rigid portion below the critical thickness

B. Glacier model with a constantly retreating margin; L-L' represents the critical thickness of 150 feet for the active-stagnant ice boundary


A
P
Q
R
B
L
L
Q
Q'
R
R'
P
P'

variations in the flow rate of existing temporate glaciers are observed but are not significant enough to be considered. The effect of seasonal variations on ablation is considered the dominant factor in producing periodic fluctuations in the glacial margin. Nye (1960) states that "glaciers are extremely sensitive indicators of climate, for a very slight climatic variation is sufficient to cause a considerable advance or retreat of the ice". Therefore the rate at which new shear zones are formed, or inversely, the length of time any single shear zone is active, depends on the ablation factor.

The model presented to account for the formation of swell-swale features is one which is controlled by the rate of ablation. Since ablation is variable (seasonal) the rate of marginal retreat and ultimately the rate at which new shear zones are formed and the length of time any set of shear planes are used is also variable. Therefore summer melting and retreat of the ice margin (active-stagnant zone) can be accomplished with few shear zones being formed, and those that are formed remain active only for a short period of time.

During fall and early winter the ablation rate decreases. With decreasing ablation, the rate of shear zone formation increases. The shear zones formed will remain active longer and carry more debris in the glacier than during the summer months. The rate of shear zone formation will steadily decrease during early spring as ablation and downwasting increase. The ultimate product of the shear mechanism is to produce a debris zone within the base of the glacier. The variability in thickness of the debris zone produces swell-swale topography.

Unfortunately for the shear hypothesis, it is not, at the present, possible to explain the presence of distorted, stratified sand and gravel bodies within the till matrix of parallel, linear features. Also the shear hypothesis does not adequately describe the origin of transverse features. Also inconsistent with the seasonal control of retreating shear zones, is the occurrence of equally spaced parallel features over diverse climatic regions. If the variation of summer and winter temperatures is controlling the spacing of parallel features then this spacing should decrease toward the north since the summer melting period is becoming shorter.

Hypothesis 4: Crevasse fill origin: The crevasse fill hypothesis states that an actively flowing glacier will develop a system of crevasses oriented roughly parallel and perpendicular to the margin, which at the time of stagnation and dissipation of the ice mass will provide sites for the accumulation of debris. It is necessary, to prove the hypothesis, to show that a glacier, generally undergoing compressive flow, can exhibit extending flow at or near the surface. The hypothesis also must predict the orientation, spacing, composition and fabric of the glacial landforms.

The general configuration of crevasses in relation to glacier flow has been studied by several authors (Tarr and Martin 1914, Flint 1947 and Sharp 1960). These studies show that for an expanding piedmont glacier or ice sheet near the margin, two orthogonal sets of fracture patterns exist, one parallel to the margin and a second roughly at 90 degrees to the margin. Valley glaciers show a profusion of fracture patterns with various orientations to flow direction. The most common type of crevasse pattern observed is splaying crevasses which are "longitudinal near the flow centerline and splay out to strike the margin at an angle slightly greater than 45°" (Meier 1958).

The mechanics of crevasse formation has been studied by Nye (1952) and Meier (1955, 1958, 1960). Crevasses are mechanical fractures within the brittle surface layer of ice resulting from tensional forces set up by glacier motion (Flint 1957). Nye (1952) has derived mathematically the theoretical positions and directions of crevasses in valley glaciers for three possible cases where σ_x is compressive, $\sigma_x = 0$ and σ_x is tensil (σ_x = stress component acting along the glacier axis in the direction of flow). Nye shows that when σ_x is compressive throughout the bulk of the glacier the surface can be in tension.

The work of Meier represents the most comprehensive study to date, of the mechanics of crevasse formation. His study shows that the longitudinal strain rate at the ice surface can be given by the expression

$$= 1/h\left(\frac{d\emptyset}{dX} + \frac{\emptyset}{R'} \cot \alpha \right)$$

where h = glacier thickness, $\emptyset$ = total discharge through a unit width, R' = radius of surface curvature, and α = bed slope. Meier (1958) found that the accumulation gradient term $d\emptyset/dX$ is of much less importance than the surface curvature term. It was also found that the depth/spacing ratio was relatively constant when crevasses first form "because this ratio is determined by geometrical considerations and the mechanical properties of the ice or firn" (Meier, p. 507). The crevasse opening rate $\dot{W}$, the substratum extension rate $\dot{E}$, and the spacings, of crevasses are related as follows:

$$\dot{W} = \dot{E}s$$

Using the experimental results of Meier's study and using a spacing of 350 feet, the distance between parallel ridges in the study area, it is possible to show that this spacing is within the strain and opening rates given by Meier. Since the radius of surface curvature determines, to some degree, the spacing of adjacent crevasses, it is possible that the regularity of spacing for parallel ridges through northern North America is related to similarities in glacier profiles at the time of crevasse formation. Similarities in glacial profiles suggest similarities in rates of flow and ablation but this is not likely over such a large geographic and climatic region.

Transverse crevasses result from lateral expansion of a glacial lobe. Unfortunately there is no way to predict their occurrence or spacing, though they do generally form along flow lines.

Unfortunately, hypothesis 5 is not compatible with either the composition or fabric of parallel and transverse ridges. Crevasse fill features exhibit a chaotic texture, with steeply dipping beds and clast imbrication transverse to the crevasse axis and dipping away from the axis (Suttner 1967). This has not been found for linear ridges in the study area, except for the axial transverse ridge associated with the Squaw Creek scalloped belt.

Hypothesis 5: Subglacial crevasse origin: Parallel and transverse ridges are a result of previously deposited unfrozen, supersaturated, ground moraine being forced or squeezed into either subglacial crevasses which have perforated the base of a stagnant ice mass. The mechanism of crevasse formation has been previously mentioned.

The mechanism of subglacial squeezing would account for the spacing and orientation of linear ridges, and intervening depressions. The depressions result from the loss of material (till) by plastic flowage into basal crevasses (Stalker 1960). The sand and gravel bodies possibly represent subglacial streams established along the crevasse. As the ground moraine is squeezed into the basal crevasse, these sand bodies will become distorted and plunge away from the crest of the ridge (see Figure 22).

This mechanism must be ruled out on the basis of fabric studies. Andrews (1963) has shown that the cross-valley moraines of the Baffin Island are a product of subglacial squeezing. These features exhibit a fabric which is perpendicular to the ridge axis and plunging away from the crest on either side. This fabric has not been found for this study.

<u>Hypothesis 6: Basal boundary wave phenomenon</u>: This hypothesis proposes that the origin of swell-swale topography is related to the interaction of the till-ice boundary. If ice and till are both treated as viscous or semi-viscous materials, flow of the glacier will set up waves at the till-ice boundary. These waves result in the formation of swell-swale topography.

Theoretical treatments of glacier sliding has been given by Weertman and Lliboutry (in Scheidegger 1961). Glacier sliding is a result of two related factors, pressure melting and stress concentrations. If a glacier is to effectively slide over its bed with relatively high velocities it must become detached, in part, from its base. An idealized glacier bed, therefore, consists of parallel sine waves which are formed to reduce frictional drag.

The mechanism for the formation of the parallel sine waves has been suggested by Smalley (1966) and Smalley and Unwin (1968). Although they used the mechanism to describe the formation of drumlins it is likely that the same mechanism, in a slightly different situation, will produce the parallel sine waves described by Weertman and Lliboutry. The conditions necessary for the formation of these waves is, 1) that the glacier-terrain was such that a relatively thin mobile layer of material separated the moving glacier from this terrain. Smalley (1966) suggests that this thickness, "which acted like a film of lubricant, was about 1 to 5 percent of the thickness of the glacier", and 2) that this lubricating layer was composed of a concentrated dispersion of boulders in a dense clay-water system. Unfrozen, saturated till can be considered such a material.

The sandy clay-till at the base of the ice will exhibit a property known as dilatancy. A dilatant material expands when deformed, due to a change from a tight packing arrangement to a loose arrangement, and when fully expanded will flow easily. Therefore, in the flow layer, which has a loose packing, flow will occur until the flow stress drops below some critical value. Below this critical value deposition will occur.

Variations in stress at the till-ice boundary can be caused by stress concentrations or a crevasse pattern within a very thin, sluggish ice mass. These stress variations concentrate deposition of till to form swell-swale patterns. As has been stated, sliding of a glacier over its bed produces pressure melting and stress concentrations which will vary as a sine function.

Where the stresses reach a minimum, deposition of the dilatant till will occur as a series of sine waves. This further reduces the stress at the base of the glacier since the glacier will become detached from its base, and will also increase the sliding velocity of the glacier.

A second mechanism which must be considered is that in a very thin ice sheet the location and orientation of either surficial or subglacial crevasses will determine the location of the minimum stress. Thus where these crevasses occur deposition of the till is found.

The last mechanism probably best describes the formation of parallel and transverse features. Separation of the glacier from its base would produce openings for meltwater flow and the segregation of the sands from the clay in the till. These sand bodies may be incorporated within the flow layer of the till and deposited with it or deformed when till is deposited on top of it. This mechanism would also best describe the characteristic fabric patterns which show an ice flow control.

One problem not discussed is that if the crevasse pattern within the flowing ice is controlling the formation of subglacial till ridges, these ridges can not remain stationary but must move with the ice. If a till ridge is formed and the maximum stress is below the point where the dilatant properites occur, the ridge will remain stationary. It is possible that there are a series of waves at the till-ice boundary which are mobile and move with the glacier until the maximum stress drops below some critical value. The differential stress at the base of the glacier will determine the amount of dilatant material deposited or flowing at any one time. This differential stress will be influenced by the configuration of the bedrock topography and/or the piezometric head below the glacier.

Development of Modern Drainage

Four factors controlled the development of modern drainage trends. These are 1) the configuration of the pre-Cary topography, 2) the location of superglacial drainage lines, 3) the presence of glacial drainageways and 4) the orientation of linear depressions.

Several of the master streams within the study area have a preglacial history. The Skunk River and Squaw Creek appear to have been reestablished after each successive glacial advance. Two bedrock channels, though, have been completely filled with glacial drift and do not control the modern drainage, except for possibly minor tributaries. These channels are located southwest of Ames (the Jordan Channel) and southeast of Ames.

The importance of superglacial drainage trends has been previously discussed. Generally they are formed along preglacial drainage lines and provide the means for reestablishment of these trends. Glacial drainageways play an important role in the development of upland drainage lines. They provide a preexisting channel by which the modern drainage trends have been reestablished.

The orientation of parallel and transverse depressions, associated with the linear ridges, determines the minor drainage trends for the upland. Integration of these linear depressions produces a trellis drainage pattern.

CONCLUSIONS

The Des Moines lobe offers a unique opportunity, not only to study the glacial landforms, but to possibly also study the mechanical and physical properties of the glacier that formed them. Any theory proposed for the origin of lineated topography must account for 1) the orientation for both sets of orthogonal ridges, 2) the local variation in the character of the landforms and the regional distribution for lineated topographic areas, 3) the composition of the linear ridges, specifically the relationship of distorted sand bodies to the mode of ridge formation, 4) the till petrofabrics and 5) the apparent equivalence of spacing for parallel ridges over large regions of north central North America.

Six hypotheses which have been proposed to describe the origin of lineated topographies were critically evaluated. No single hypothesis can account for all of the characteristics of the landforms indicating that either several mechanisms are operating either at the same time or in sequence, or that none of the hypotheses correctly describe the origin of lineated topographies and that some mechanism, yet undescribed, is operating. Hypothesis 6 is purely speculative since this phenomenon has never been observed in modern glaciers. Further research may indicate its feasibility in accounting for the origin of lineated topography.

Some of the interpretations resulting from this study are valid regardless of the origin of the lineated glacial landforms. These interpretations provide a "frame of reference" for further studies of lineated topographies. The interpretations are as follow.

1. The Cary ice was relatively thin, probably 1,000-2,000 feet. This is suggested by the regional bedrock control of glacial flow direction, coincidence of preglacial drainage trends, flow direction and distribution of scalloped belts and the apparent effect of minor topographic variations on the intensity of formation of lineated topographies.

2. The origin of linear ridges shows ice flow control which is indicated by the till petrofabrics and the orientation of linear ridges.

3. Progressive stagnation and thinning occurred rather than marginal retreat. This is suggested by the limited amounts of outwash on the upland and the lack of distinct end morainal systems.

4. The similarities of spacing and regional distribution suggests that the origin of lineated topographies is related to the mechanics of the ice rather than ablation or ice wastage as the controlling mechanism of formation.

5. The piezometric surface at the base of the glacier effectively reduced the intensity of formation of lineated topography.

SUGGESTIONS FOR FURTHER STUDY

This report presents a description of lineated topographies and speculates as to its origin. Further research is needed before the exact mode of origin can be determined. This further research should include the following:

1. The thickness of the Cary ice needs to be determined at various locations throughout the Des Moines lobe since the thickness of the glacial ice is critical to several of the hypotheses. Use of preconsolidation values of Cary till and pre-Cary sediments would provide the data needed to construct ice iso-thickness maps for the Des Moines lobe.

2. A more detailed till petrofabric investigation must be completed before the origin of the linear ridges can be determined. This investigation should include fabric studies of numerous parallel and transverse features throughout the Des Moines lobe. Also the fabric within linear depressions should be determined.

3. Relationships between the surficial and pre-Cary topography have been shown in this report. The assumption used in this report was that the Kansan(?) topography reflected the configuration of the bedrock. The relationships of the surficial topography to the Kansan topography must be studied in detail.

4. The radiocarbon chronology of the Des Moines lobe is insufficient to determine the rates of marginal advance and the deglaciation chronology. More samples must be obtained and dated before these factors can be determined.

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APPENDIX A: LIST OF AUGER HOLE RECORDS

The additional subsurface data was obtained from Schoell (1967) and Sendlein and Dougal (1968, part 2).

ISU well number	Depth (feet)	Location	Glacial feature
3-57		SE¼SE¼ Sec 32 T86N R23W	Parallel ridge
	0-3	oxidized till	
	3-6	gravel lens	
	6-9	oxidized till	
	9-13	gray unoxidized till	
	13-22	brown to buff sandy till	
	22-27	light gray till - sandy clay	
	25-27	boulders	
	27	refusal bedrock(?)	
2-58		NE¼SE¼SE¼ Sec 29 T86N R23W	Slope north of 3-57
	0-15	oxidized sandy till	
	15-30	unoxidized sandy till	
	30	TD	
3-59		NE¼SE¼SE¼ Sec 29 T86N R23W	North side of small hill north of 3-58
	0-12	oxidized sandy till	
	12-30	unoxidized sandy till	
	30	TD	
3-60		NE¼NE¼SE¼ Sec 16 T84N R23W	drainageway(?)
	0-6	fill	
	6-8	sandy clay	
	8-36'	sandy till to sandy clay w/intermittent gravel layers	
	36	TD	
3-61		NE¼NE¼SE¼ Sec 20 T84N R23W	drainageway(?)
	0-6	sand	
	6-14	unoxidized sandy till	
	14	gravel lens	
	16	gravel lens	
	16-30	sandy till	
	30	TD	
3-62		SE¼SE¼ Sec 29 T86N R23W	
	0-8	sandy till	
	8-21	fine sand	
	21-23	sandy till(?)	
	23	refusal	

ISU well number	Depth (feet)	Location	Glacial feature
3-70		SE½SE¼ Sec 30 T86N R23W	drainageway associated with scalloped belt
	0-3	coarse gravel	
	3-6	fine to medium gravel w/boulders	
	6-14	coarse sand	
	14-18	fine sand	
	18-34	medium-coarse sand w/boulder at bottom	
	34	refusal TD	
3-71		SE¼NE¼SE¼ Sec 30 T86N R23W	drainageway associated with scalloped belt
	0-2	coarse gravel	
	2-6	fine-medium sand	
	6-8	clayey gravel	
	8-18	coarse sand	
	18-20	coarse gravel	
	20-26	fine-medium sand	
	26	refusal TD	
3-72		SW¼NW¼SW¼ Sec 29 T86N R23W	low area 300 yd north of farm
	0-2	black silty clay loam	
	2-9	gray unoxidized clay w/small pebbles	
	9-27	fine sand and water w/cobbes at bottom	
	27	refusal TD bedrock(?)	
3-73		Center SW¼Sec 29 T86N R23W	auger hole at base of parallel trend
	0-2	black clay	
	2-7	gray clay	
	7-15	sand w/clay lenses	
	15-19	till or clay layer w/boulders at bottom	
	19	refusal TD	
3-74		East ½SW¼ Sec 29 T86N R23W	top of parallel trend
	0-14	oxidized till (sandy silt loam) w/ boulders	
	14-23	sandy clay loam - till red	
	23	refusal clay(?)	
3-75		East ¼SW¼ Sec 29 T86N R23W	low area east of parallel trend
	0-15	black clay loam	
	5-19	clayey sand	
	19	refusal clay(?)	
3-76		NE¼SW¼ Sec 29 T86N R23W	Nose of parallel trend
	0-5	black clay loam	
	5-17	unoxidized till, gray sandy clay loam, w/pebbles	
	17	auger crooked	

ISU well number	Depth (feet)	Location	Glacial feature
3-77		NE¼SW¼ Sec 29 T86N R23W	SE of 3-76, nose of parallel trend
	0-4	black sandy silty clay loam	
	4-10	gray till - sandy silty clay loam w/small pebbles	
	10-15	slightly more sand in till-w/cobbles	
	15-17	gravely till	
	17-19	stiff blue clay w/boulders	
	19	refusal - very sandy-gravely compact clay	
3-78		Sec 32	Kame-like feature
	0-6½	sandy gravely till	
	6½-48	gravel	
3-79		NE¼NE¼ Sec 32 T86N R23W	top of low rise west of 3-78
	0-3	sandy silty clay loam	
	3-9	clayey sand-some silt	
	9-23	fine sand w/boulder at 15'	
	23-36	sandy silty blue till w/boulders	
	36	blue gray till recovered	
3-80		NW¼NW¼ Sec 17 T84N R24W	
	0-8	oxidized till (water table at 5')	
	8-30	unoxidized till	
	30	TD	
3-81		N½ Sec 4 T84N R24W	
	0-16	very sandy oxidized till	
	16-22	oxidized gray till	
	22-25	gravel	
	25	refusal bedrock(?)	
3-82		NW¼NE¼ Sec 32 T86N R23W	southeast of 3-78
	0-5	gravely-sandy silt loam, some clay and boulder at bottom	
	5-9	fine red, oxidized sand w/boulders	
	9-11	till	
	11	TD	
3-83		NW¼NE¼ Sec 32 T86N R23W	8' north of 3-82
	0-2	fine sand	
	2-5	coarse sand	
	5-12	sandy, clayey till	
	12	TD -clayey sand	

ISU well number	Depth (feet)	Location	Glacial feature
3-84		SE¼NE¼ Sec 29 T86N R23W	Crest of SE Transverse trend-ditch
	0-5	oxidized till - silty clay loam	
	5-19	oxidized till	
	19	TD	
3-85		SE¼SE¼ Sec 29 T86N R23W	top of parallel trend
	0-10	sandy-clay loam -oxidized till	
	10-22	unoxidized till w/pebbles boulders or cobbles at base	
	22	refusal TD	
3-86		NW¼SW¼ Sec 33 T86N R23W	crest of kame(?)
	0-1½	sandy clayey till	
	1½-4	very fine sand w/some clay and pebbles	
	4-7	coarse sand	
	7-16	fine sand	
	16-20	fine gravel	
	20-23	very fine sand and clay or silt	
	23-26	fine to medium sand w/pebbles and silt	
	26-30	till	
	30	TD - till-sandy clayey loam	
3-87		NW¼NE¼NW¼ Sec 4 T85N R23W	top of parallel feature
	0-2	black topsoil	
	2-10	oxidized till - sandy clay loam	
	10-18	cobbles(?)	
	18-30	unoxidized till	
	30-32	compact bluegray till-silty clayloam	
	32	TD	
3-88		SW¼NE¼NW¼ Sec 3 T85N R23W	1/8 mile east of Long Dick Crk
	0-6	black silty clay-very wet muck	
	6-18	unoxidized till-sandy	
	18	TD	
3-89		NW¼SW¼SE¼ Sec 33 T86N R23W	Top of parallel trend
	0-20	oxidized till-pebbley-silty loam	
	20-33	unoxidized till	
3-90		NW¼ SE¼ Sec 33 T86N R23W	kame(?) deposit
	0-9	fine sand	
	9-12	till-oxidized gravely, sandy	
	12-14	fine clayey sand lens-silt loam	
	14-16	till	
	16	refusal - bedrock(?)	

ISU well number	Depth (feet)	Location	Glacial feature
3-91		SW¼NE¼SW¼ Sec 29 T86N R23W	top of parallel tre
	0-18	oxidized till	east of 3-74
	18-25	unoxidized till	
	25-29	fine reddish brown silty sand	
	29-33	very fine gray silty sand-till(?)	
	33	TD - hard pulling	
3-92		SE¼SE¼NE¼ Sec 30 T86N R23W	linear trend
	0-3	silt loam	
	3-9	oxidized till-silty clay loam	
	9	TD-boulder	
3-93		SW¼ Sec 5 T85N R23W	Top slight rise
	0-15	oxidized till-sandy silty clay loam w/ pebbles	
	15-40	unoxidized till	
	40	TD	
3-94		SW¼SE¼SE¼ Sec 27 T85N R23W	drainageway
	0-3	till for farm lane	
	3-13	sandy silty clay loam-unoxidized till	
	13-17	coarse poorly sorted-sand-w/boulders	
	17	TD sandy-gravely stiff yellow clay	
3-95		SE¼SE¼NE¼ Sec 34 T85N R23W	drainageway
	0-½	fine sand -aluvium	
	½-1	sand silt loam-till	
	1-6	sandy silty clayey loam	
	6-13	unoxidized till	
	13-15	yellow silty clay (loess?)	
	15	refusal	
3-96		SE¼SE¼NE¼ Sec 27(?)34 T85N R23W	near drainage wall
	0-1½	oxidized till	north of 3-95
	1½-2½	reddish yellow-clayey sand lens	
	2½-7	oxidized sandy till	
	7-16	unoxidized till (boulder at 8 feet)	
	16-16½	light gray till	
	16½	refusal	
3-97		Sec 15 T84N R23W	drainageway
	0-6	black-silty clay	
	6-8	unoxidized till-silty clay loam	
	8-26	sandy till, sandy-silty clay loam	
	26-29	yellow sandy-to-very-sandy till	
	29	refusal	

ISU well number	Depth (feet)	Location	Glacial feature
3-98		NE¼NW¼NW¼ Sec 15 T84N R23W	top of parallel trend
	0-3	topsoil	
	3-25	yellow sandy to very sandy till w/layers of gravely till (boulder at 17')	
	25-34	unoxidized till	
	34-47	oxidized till (yellow sandy silt loam and stiff bluegray clay)	
	47	TD	
3-99		Sec 15 T84N R23W	side slope east of 3-98
	0-5	topsoil	
	5-12	sandy to very sandy yellow till	
	12-16	unoxidized till-very sandy	
	16-18	fine sandy silt(?)	
	18-23	coarse sand	
	23-30	fine gravel or very coarse sand poorly sorted (boulder at 28')	
?	30	stiff clay (none recovered)	
	41	coarse sand	
3-100		NW¼NE¼NW¼ Sec 16 T84N R23W	top high parallel trend
	0-15	oxidized till-sandy silt loam (sand lens at 10')	
	15-30	very sandy till, oxidized	
	30	TD	
3-101		NW¼NE¼NE¼ Sec 16 T84N R23W	axis of drainageway
	0-1	topsoil - black clay loam	
	1-3	unoxidized till	
	3-11	coarse sand - poorly sorted	
	11-20	unoxidized very sandy till	
	20	TD color change - yellow sandy till (oxidized till ?)	
3-102		SE¼NE¼SE¼ Sec 16 T84N R23W	drainage channel
	0-1	black clay loam	
	1-3	oxidized till-sandy silt loam	
	3-14½	coarse poorly sorted sand	
	14½-33	very coarse gray sand	
	33-43	fine sand - yellow oxidized sandy till	
	43-45	sandy silt loam or fine sand	
	45-48	black dense clay	
	48	TD	

ISU well number	Depth (feet)	Location	Glacial feature
3-103		NE¼NE¼NE¼ Sec 15 T84N R23W	flank of parallel
	0-7	colluvium - black - clay loam	trend(?)
	7-14	grayish black sandy clay loam unoxidized till	ditch (section corner
	14-28	gray till	
	28-33	yellow gray till - sandy clay loam	
	33-36	unoxidized till	
	36	TD gray till, sandy clay loam	
3-104		NW¼NW¼N¼ Sec 15 T84N R23W	east of 3-103 (97')
	0-3	black clay loam	colluvium(?)
	3-5	gray unoxidized till, sandy silty clay loam	
	5-10	yellow sandy oxidized till	
	10-19	unoxidized till (Wisconsin?)	
	19-20	gray unoxidized till	
	20-30	sandy yellow till (Kansan?)	
	30-36	unoxidized gray till	
	36	TD	
3-105		NE¼NW¼NW¼ Sec 15 T84N R23W	197' east of 3-103
	0-2	black clay loam	
	2-4	brown silt loam	
	4-7	very sandy oxidized brownish yellow till	
	7-18	sandy yellow till (boulder at 12')	
	18-30	unoxidized till yellowish-gray	
	30-32	yellow oxidized till	
	32-35	compact blue-gray unoxidized till	
	35	TD	
3-106		Sec 15 T84N R23W	302' east of 3-103
	0-3	silty clay loam	
	3-14	oxidized-yellow sandy silt loam (till)	
	14-30	unoxidized till	
	30	TD yellow oxidized till	
3-107		NW¼NW¼NW¼ Sec 15 T84N R23W	402' east of 3-103
	0-3	topsoil - black sandy silt-loam	
	3-15	oxidized till - sandy silt-loam w/ clay and pebbles (boulder at 9')	
	15-33	unoxidized till (boulder at 32')	
	33-38	brown till	
	38	TD blue clayey till	

ISU well number	Depth (feet)	Location	Glacial feature
3-108		Sec 15 T84N R23W	525' east of 3-103
	0-3	black clayey silt loam	
	3-21	oxidized till, brown till, sandy silty clay loam grades into coarse sandy to gravely till	
	21-33	unoxidized till (w/boulder at 28')	
	33	TD	
3-109	Sec 15 T84N R23W		595 east of 3-103
	0-2	black topsoil - clayey silt loam	
	2-4	brown silt loam (till)	
	4-9	tan or buff - sandy silt loam	
	9-18	very sandy till or silty sand	
	18-27	unoxidized till (boulders at base)	
	27	TD - refusal - boulder	
3-110		Sec 15(?) T84N R23W	735' east of 3-103
	0-2	black silt loam	
	2-4	brown sandy silt loam till	
	4-10	very sandy to gravely till w/boulders	
	10-14	silty coarse sand grades to very sandy till	
	14-27	unoxidized till	
	27	refusal	
3-111		NW¼NE¼NW¼ Sec 15 T84N R23W	1300' east of 3-103
	0-2	topsoil	
	2-12	buff pebbly sandy silt loam - oxidized till	
	12-20	gray unoxidized till w/boulders at base	
	20-30	buff to yellow-brown sandy till	
	30	TD stiff - oxidized till	
3-112		SE Sec 1 T84N R25W	below upland, 15-20' above stream
	0-1	topsoil	
	1-4	buff-sandy till	
	4-12	fine buff silty sand w/pebbles	
	12-18	fine sand	
	18-30	gray fine to medium sand-poorly sorted	
	30-56	sandy gray till - sandy clay -less sand w/depth	
	56	TD	
3-113		NE¼NE¼NE¼ Sec 12 T84N R25W	Floodplain of Squaw C
	0-8	black-sandy clayey silt-colluvium	
	8-19	gray silty fine-medium sand poorly sorted	
	9-24	gray unoxidized sandy silty clay	
	24	TD	

ISU well number	Depth (feet)	Location	Glacial feature
3-114		NE¼NW¼NW¼ Sec 6 T84N R24W	top of transverse trend
	0-7	very fine buff sand, silt increases w/depth, pebbles	
	7-12	very sandy buff till	
	12-35	gray unoxidized till	
3-115		NE¼NE¼NW¼ Sec 6 T84N R24W	crest of transverse trend
	0-6	very sandy buff till	
	6-8	gravely till w/cobbles	
	8-20	very sandy till	
	20-36	unoxidized sandy pebbley till	
	36	TD	
3-116		SE¼SE¼SE¼ Sec 29 T85W R24W	axis of drainageway
	0-1½	topsoil	
	1½-3½	light gray silty clay	
	3½-10	oxidized till - sandy silt loam	
	10-35	unoxidized till	
	35	TD	
3-117		SE¼NE¼NW¼ Sec 5 T85N R24W	glacial drainageway
	0-2	pebbly colluvium - sandy silt loam	
	2-4	red pebbly clay	
	4-8	coarse sand, poorly sorted	
	8-11	oxidized till - very sandy and gravely silt loam	
	11-27	unoxidized till	
	27	refusal	
3-118		NW¼NW¼SW¼ Sec 30 T83N R24W	crest small transverse feature
	0-19	buff oxidized till-very sandy loam	
	19-41	unoxidized till	
	41-51	oxidized till	
	51	refusal	
3-119		NE¼SE¼SE¼ Sec 36 T83N R24W	axis of drainageway
	0-6	black sandy-clayey silt loam colluvium more sand, less clay w/depth	
	6-10	blue fine sand - coarser w/depth, more silt w/depth	
	10-16	brown very sandy till (water)	
	16-29	gray-very sandy unoxidized till or silty sand, decrease in sand w/depth	
	29	TD	

ISU well number	Depth (feet)	Location	Glacial feature
3-120		$SE\frac{1}{4}SE\frac{1}{4}NW\frac{1}{4}$ Sec 33 T84N R24W	axis high transverse trend parallel to Squaw Creek
	0-2	very fine silt loam	
	2-18	oxidized till - sandy silt loam	
	18-20	very sandy pebbly oxidized till	
	20-33	sandy silt loam till - increased sand w/depth	
	33-41	medium sandy, moderately sorted, gravel lens, fine gravel, well rounded to subrounded, pred. rollers sand grades to coarse poorly sorted	
	41-45	Till-unoxidized very sandy pebbly silt loam	
	45	TD - too stiff	
3-121		Sec 23 T84N R24W	axis of transverse tren top of hill 75' north of 3-120
	0-4	brown silt	
	4-12	till-light brown	
3-122		Sec 23(?) T84N R24W	5' N of 3-121
	0-4	brown silt	
	4-7	light brown pebbly-sandy till	
	7-10	very fine brown sand	
	10-12	till	
	12	refusal - rock(?)	
3-123		Sec 33(?) T84N R24W	12' NW hole 3-122
	0-15	oxidized till (lens very fine silty sand at 7-8')	
	15-20	medium pebbly sand	
	20-22	clayey sand or very sandy till	
	22	refusal	
3-124		Sec 33 T84N R24W	crest terrace-like transverse trend
	0-4	very fine brown sandy silt	
	4-7	brown pebbly sandy till	
	7-10	fine well-sorted yellow sand, pebbles increase w/depth	
	10-12	white sand - poorly sorted w/pebbles, grades into gray silt	
	12	TD refusal - rock(?)	
3-125		Sec 33 T84N R24W	5' west 3-124
	0-4	dark brown silt	
	4-6	sandy pebbly till	
	6-7	very sandy till lens	
	7-9	yellow very fine silty sand	
	9-11	medium grained, compact silty sand	
	11-12	till - very sandy, pebbly	
	12	TD - refusal - rock(?)	

ISU well number	Depth (feet)	Location	Glacial feature
3-126		Sec 33 T84N R24W	18' WSW 3-125
	0-3	brown silt	
	3-5	yellow clayey silt	
	5-10	brown clayey silt w/pebbles - fill	
	10-13	medium fine sand	
	13	TD too stiff - refusal	
3-127		center W¼ sec 24 T84N R25W	crest parallel trend
	0-1	topsoil and wash	
	1-6	oxidized till - sandy silty clay loam	
	6-9	unoxidized till	
	9	TD refusal - rock(?)	
3-128		Sec 24 T84N R25W	8' west 3-127
	0-7	oxidized till	
	7	refusal - rock (?)	
3-129		Sec 24 T84N R25W	9' west 3-128
	0-12	oxidized till - very sandy silt loam w/boulder at 3-5', decreased sand w/depth	
	12-20	unoxidized till	
	20	TD refusal	
3-130		Center west ¼ Sec 24 T84N R25W	crest small parallel trend
	0-1½	black colluvium - silty clay loam	
	1½-15	oxidized till - sandy silt loam	
	15-50	unoxidized till	
	50	TD	
3-131		Sec 31 T84N R24W	crest parallel trend
	0-10	oxidized till - sandy silt loam	
	10-20	unoxidized till	
	20	TD refusal	
3-132		Sec 10 T85N R23W	west 100' of crest of parallel trend
	0-1½	black topsoil	
	1½-12	oxidized till - sandy silt loam	
	12-13	very sandy till	
	13-24	unoxidized very sandy till	
	24	refusal - very sandy oxidized till	
3-133		Sec 10 T85N R23W	distal flank parallel trend 150' from 3-132
	0-6	oxidized till - sandy silt loam	
	6-20	unoxidized till	
	20	refusal	

ISU well number	Depth (feet)	Location	Glacial feature
3-134		Sec 10(?) T85N R23W	16' west 3-133
	0-10	oxidized till	
	10-16½	unoxidized till (boulder at 15')(blue?)	
	16½-20	light brown or tan till	
	20-21	sandy clayey silt loam	
	21-24	very clayey blue till w/boulders	
	24-29	oxidized sandy till	
	29	refusal - rock(?)	
3-135		Sec 10 T65N R23W	west of glacial drainageway axis
	0-1½	black silty clay loam -colluvium	
	1½-3	yellow brown oxidized gravely sandy till	
	3-5	tan very sandy till	
	5-13	unoxidized blue till	
	13-16	tan till, much less clay than blue till above	
	16	blue till	
3-136		Sec 10 T8.5N R23W	axis drainageway east of 3-137
	0-2½	clay loam colluvium	
	2½-12	very coarse sorted sand	
	12-19	oxidized till	
	19	TD	
3-137		Center bottom NW¼ Sec 23 T85N R23W	between 3-135 and 136 west of ditch
	0-2	black silty clay colluvium grades into gray	
	2-7	coarse poorly sorted sand	
	7-13	medium well sorted sand, grades to fine sand at depth	
	13-18	Till - stiffer drilling	
	18-20½	oxidized till, very sandy	
	20½-30	unoxidized till	
3-138		Sec 23 T85N R23W	east of 3-136
	0-3	black silty clay colluvium	
	3-6	very silty poorly sorted coarse sand grades into medium moderately sorted sand	
	6-11½	(?)	
	11½-30	unoxidized till - stiff drilling	
	30	TD	

ISU well number	Depth (feet)	Location	Glacial feature
3-139		Sec 23 T85N R23W	East of 3-138 west 25' of field tile
	0-2	colluvium	
	2-5	gray and brown silt	
	5-11	silty medium grained sand	
	11-14	fine sand-grades into coarser sand at depth	
	14-23	unoxidized till - stiffer drilling	
	23-32	rock	
	32	TD refusal	
3-140		Sec 23 T85N R23W	crest of linear trend east of 3-139
	0-10	oxidized till - sandy silty loam	
	10-18	unoxidized till	
	18-20	rock	
	20	refusal	

APPENDIX B: TILL FABRIC ANALYSIS

Introduction

Fabric refers to the orientation in space of the elements of which a body is composed. Determination of till micro-fabric involves either X-ray measurements (Meade 1961) or oriented microscopic thin sections (Sitler and Carleton 1955). Neither of these methods were used because of the time and equipment involved.

Methods of collecting, presenting and evaluating till macrofabric data have been given by Holmes (1941), Krumbein (1938, 1939), Harrison (1957a, 1957b) and Galloway (1955). Holmes, Krumbein and Galloway determined the orientation of individual pebbles either in the field by using a brunton pocket transit or by marking vertical and horizontal axis on the pebbles and later reorientating it on a two stage contace goniometer. It was found by these authors that from 50 to 100 pebble orientations were needed from any one outcrop to determine statistically if an oriented fabric exists.

The method used in this study is essentially that described by Harrison (1957a) with slight modification on the method of collecting oriented till blocks and construction of the two stage contact goniometer. The procedure involved in till fabric analysis includes: 1) collecting from the field an oriented block of till, 2) reorientation of the till block in a two stage contact goniometer, 3) measurement of long axis and intermediate axis where possible of particles larger than 3-4 mm and 4) presentation of the data by standard statistical and petrographic techniques.

Field Procedure

The sample sites shown in Figure 19 were located in two artificial cuts through parallel trends. These sites were chosen because the expression of the parallel features were well defined and could be located on air photographs and the land forms were large enough to produce multiple sample sites. All samples were taken below the zone of frost heave (approximately 3 feet) and along the face of the cut.

Once a site was selected, a fresh surface was prepared by removing the upper one to two feet of till. Then two parallel trenches, approximately three feet apart, were dug vertically into the road cut, perpendicular to the face, and to a depth of two to three feet. Two more trenches, again approximately 3 feet apart, were then cut parallel to the face of the cut which produced a block of till approximately three feet by three feet by three feet. The upper surface of the till block was then leveled, using a carpenter's level, and several north arrows inscribed then painted on this surface. Figure 37A shows a till block which has been trimmed and leveled with the sighting arm of the brunton pointing north. Finally the block was trimmed down to an approximate two feet by two feet by two feet size, wrapped with plastic tape, to avoid fracturing during transport, covered with a cardboard box, cut to size, and cut off at the base. The liberated till block was then inverted and transported to the laboratory.

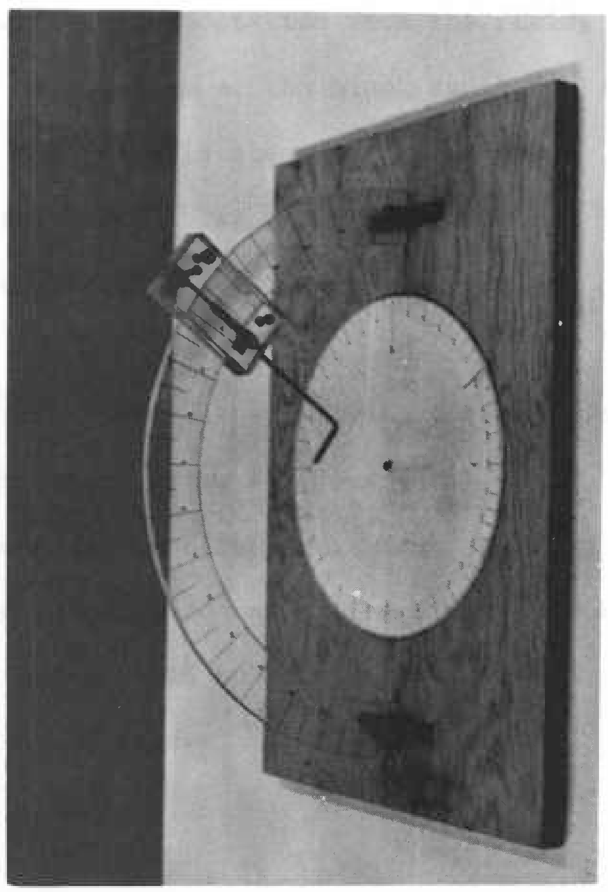
Figure 37. Method of collecting and analyzing oriented till fabric samples

A. Till block which has been trimmed and leveled with the sighting arm of the brunton compass pointing north

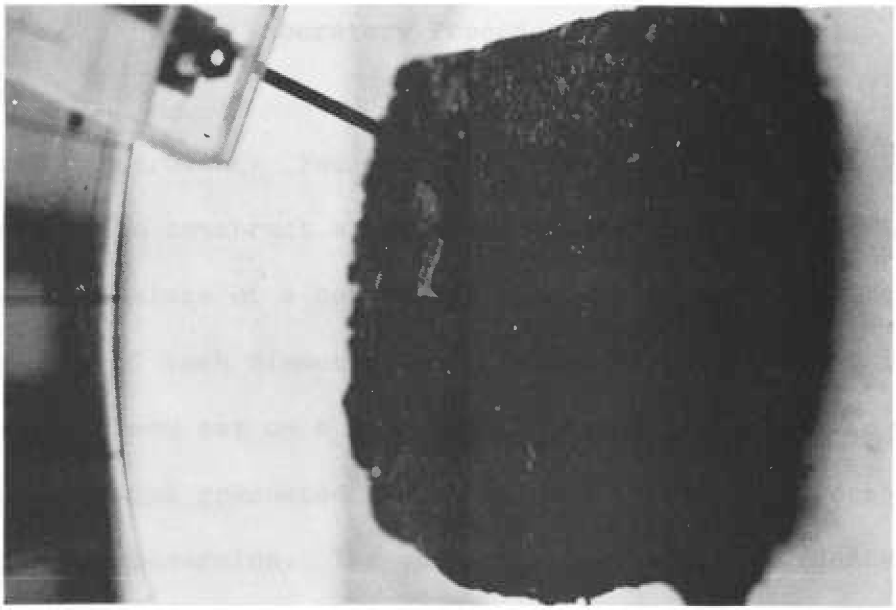
B. Two stage contact goniometer used to determine orientation of pebble axes

C. Measurement of an oriented pebble

A



B



C

Laboratory Procedure

Measuring instrument: For studying fabric of oriented till blocks it was necessary to construct a two stage contact goniometer (Figure 37B). The goniometer consists of a horizontal stage of 10 inch diameter and a vertical ring of 17 inch diameter, constructed of ¼ inch and ½ inch plexiglas respectively and set on a wood base. The horizontal stage was graduated counterclockwise graduated scale was used to obtain direct azimuthal readings without conversion. The vertical ring is also graduated in five degree intervals from 0-90 degrees from the top down both sides.

Sample reorientation

The till block, which was inverted for transportation from the field, is set upside down on a level surface. The bottom of the block is then leveled and the block turned rightside up. At this stage the cardboard box and plastic tape are removed from the block. The block was then cut vertically into four separate blocks, each with a north arrow painted on it.

With the horizontal stage set at zero (north) the individual till block was set on the goniometer stage with its north arrow alligned parallel to the vertical arc and pointing in the zero degree direction. Next, a strip of masking tape was placed on the stage parallel to one of the sides of the till block. This was done so that the block could be reoriented in case it was inadvertently moved during fabric analysis.

Particle measurements

Once the till block is properly reoriented on the goniometer stage the upper one inch surface of the till block is carefully removed since it could have been disturbed during preparation. Also pebbles found along the sides of the block are not considered for fabric studies. Harrison (1957a) states that "moist-not wet or dry-clay is easiest to work. Samples not being studied are stored under a cover of damp cloths" and a plastic sheet to prevent drying.

Dental tools were used to pick away the till block. When a particle which was acceptable for orientation measurements was found, it was uncovered by picking and blowing away of the debris. It was found useful in most cases to use a straight pin to define the axis of the uncovered pebbles for ease of measurement. Next the stage was rotated until the pebble axis being measured was parallel to the vertical arc and plunging toward the zero degree azimuth. Figure 37C shows a pebble which has been uncovered and properly oriented with the plunge to the right (north).

Once the pebble has been oriented the azimuth bearing can be read from the horizontal stage and the plunge angle read by aligning the foot of the measuring arm parallel to the pebble axis. All measurements were taken to the nearest five degree interval.

Graphic Presentation of Fabric Data

Table IV shows the schedule used in collecting orientation data of pebbles within the till blocks. For each sample a minimum of 150 pebble orientations were collected to assure statistical validity. The orientation of b-axis was not used in this study.

Fabric presentation involves the use of an equiareal net (Schmidt net) so that plotted points are in their proper relation to each other for contouring. Plotting the data involves two coordinates: the azimuth of plunge direction and the angle of plunge. Azimuth is measured clockwise around the circumference, and the angle of dip increases from the circumference toward the center.

Construction of contoured diagrams involves use of a 1% counting circle and a 1 cm coordinate grid. The data points, which were plotted on tracing paper, are placed over the 1 cm coordinate grid. The center of the counting circle is then placed over each grid intersection and the number of points within the 1% circle recorded on the tracing paper. Where the counting circle overlaps the Schmidt net, the points in the opposite circle are added to the total in the counting circle. By this method a series of values are determined each value depending on the concentration. These values are then contoured at appropriate intervals to obtain a visual analysis of fabric concentrations and orientations.

Sample form of table for pebble orientation data:

Location of outcrop T.__________ R.__________ Sec.__________

Glacial landform type_______________

Rock no.	'a' axis Azimuth	Dip	'b' axis Dip	Form (shape)	Size (cm)	Roundness	Lithology	Remarks

Statistical Presentation of Fabric Data

Contoured petrofabric diagrams provide a subjective, visual concept of fabric concentrations and orientations. For this study, though, it was necessary to use a more objective method of mean azimuth determination.

The method of mean azimuth determination of fabric data involves radius vector analysis and is described fully by Krumbein (1939). Briefly the method involves summation of the number of pole plots within each 20^{o} class interval (arbitrarily selected). Class intervals which are 180^{o} opposed were also summed, producing a combined frequency of reoccurring azimuths. The combined frequency data was written in column r, Table V, $n(\Theta)$, and multiplied by both sin 2Θ and cos 2Θ making sure that the proper sign was used. The two columns were totaled and the tan $2\Theta_m$ determined by the relationship:

$$\text{Tan } 2\Theta_m = \frac{\Sigma[n(\Theta) \sin 2\Theta]}{\Sigma[n(\Theta) \cos 2\Theta]}$$

The value of $2\Theta_m$ and Θ_m can be obtained from standard trigonometric tables. The sign of Θ_m indicates whether the value of Θ is to be plotted in the clockwise or counter clockwise direction (from 0^{o}) on the fabric diagrams.

Table 4. Method of radius vector analysis

Class mid point	Frequency	Class mid-point	Frequency	Combined frequency
20°		180°		
40°		200		
60		220		
80		240		
100		260		
120		280		
140		300		
160		320		
		340		

1	2	3	4	5	6	7	8
Azimuth classes	Mid-point θ	2θ	n(θ)	sin2θ	n(θ) sin2θ	cos 2θ	n(θ) cos 2θ
350-10 170-190	0°	0°		0.000		+1.000	
10-30 190-210	20	40		+.643		+0.766	
30-50 210-230	40	80		+.985		+0.174	
50-70 230-250	60	120		+.866		-0.500	
70-90 250-270	80	160		+.342		-0.940	
90-110 270-290	100	200		-.342		-0.940	
110-130 290-310	120	240		-.866		-0.500	
130-150 310-330	140	280		-.985		+0.174	
150-170 330-350	160	320		-.643		+0.766	
Total							

$$\tan 2\theta_m = \frac{\Sigma[n(\theta)\sin 2\theta]}{\Sigma[n(\theta)\cos 2\theta]} = \_\_\_\_\_\_\_\_\_\_.$$

$$2\theta_m = \_\_\_\_\_\_\_\_\_\_$$

$$\theta_m = \_\_\_\_\_\_\_\_\_\_$$