FLUTINGS AND TILL FABRICS WITH SPECIAL REFERENCE TO AN AREA IN SOUTH - CENTRAL MICHIGAN

SUMMER PRECIPITATION IN THE WASATCH RANGE AS RELATED TO SELECTED MIDDLE AND LOWER TROPOSPHERIC VARIABLES

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FLUTINGS
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By

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ABSTRACT

The trend of flutings and the orientation of till fabrics have been used to infer directions of past glacier movement. This study consists of (1) a review of the literature concerned with flutings and till fabrics and (2) a description and interpretation of the relationships between fluting trends and associated till fabrics for an area in south-central Michigan. Results indicate that (1) flutings in the southern portion of the study area are erosional in nature, (2) in certain situations glacial ice may override and erode the surface of glacial till without reorienting preexisting fabrics, (3) till fabrics associated with flutings in the study area may have significantly different orientations, and (4) within the study area the margin of the Erie Lobe was more extensive than morainal trends indicate prior to the last advance of the Saginaw Lobe into the area.

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Statement of Problem

Characteristics of certain glacial landforms and sediments may be used to determine directions of past ice movements. Examples include (1) the topographic trends associated with flutings and (2) the sedimentary fabric, or clast orientation, within glacial till--that is, till fabric.

This study is concerned with the relationships between the trends of flutings and the orientation of till fabrics with special reference to an area in south-central Michigan and consists of two major parts. First, a review of the literature concerned with (1) the characteristics and genesis of flutings; (2) the nature, usefulness and limitations of till fabrics; and (3) the relationships between streamlined, elongate landforms and till fabrics is presented. In the second major part, till fabrics associated with a fluted area located near Coldwater, Michigan are described and their relationships to the topographic trends compared with those from other areas as reported in the literature review section of this paper. Possible causes and the significance of apparent anomalies in the relationships observed near Coldwater are also considered.

REVIEW OF THE LITERATURE

Flutings

Terminology

It is generally agreed that flutings are linear landforms produced by glacial ice, but various authors have defined them in different ways. The Glossary of Geology (1972, p. 270) defines them as "large, smooth, deep, gutter-like channels or furrows on the stoss side of a rock hill obstructing the advance of a glacier. . . ."[1] Although this definition interprets them as negative features associated with bedrock, the term "fluting" also encompasses positive and/or negative forms developed on glacial drift (Gravenor & Meneley, 1958; Prest, 1967; Baranowski, 1970; and Flint, 1971). For example, Prest (1967, p. 7) describes flutings as "a narrow and shallow furrowing in drift, with or without adjacent ridging, into markedly elongate forms from about a mile to some tens of miles in length."

Various other authors, including Carney (1910) and Embleton and King (1968), use the term "grooves" or "groovings" rather than "flutings" to describe linear furrows eroded in bedrock. But there is no general agreement in the literature regarding this terminology, as Armstrong and Tipper (1948); Dean (1953); Lemke (1958); and Wardlaw,

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[1] It should be noted that this definition is based on the work of Chamberlain (1888).

Stauffer, and Hoque (1969)[2] refer to grooves or groovings developed on glacial drift or till.

Some authors seem to have expanded on these definitions by dividing flutings into large-scale and small-scale features. Flint (1957, pp. 69-70)[3] appears to make this distinction and, when referring to large-scale features, reports that some grooves are no more than two meters deep while small-scale features may be less than one meter in height and width but as much as 200 meters long. Likewise, in discussing certain large-scale flutings, Shaw and Freschauf (1973, p. 19) state that the features "range in scale from two to three metres high and several kilometres in length." Gravenor and Meneley (1958) also report large-scale flutes, but they give no specific dimensions. Other writers who have described flutings include Dyson (1952), Hoppe and Schytt (1953), Schytt (1963), Karrow (1965), Harris (1967), Cowan (1968), and Baranowski (1970), and though none of them explicitly categorize flutings by differences in dimension, their descriptions are generally complete enough for the reader to deduce the scale involved. Based on the above distinction, small-scale flutings have been recognized in both Europe (Hoppe & Schytt, 1953) and North America (Dyson, 1952), but Shaw and Freschauf (1973) state that large-scale examples appear to be confined to the latter.

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[2] Wardlaw, Stauffer, and Hoque (1969, p. 581) note that, for the features they observed, "Everywhere the topographic ridges are underlain by bedrock 'highs' and the topographic grooves by bedrock depressions."

[3] Reference to this earlier work by Flint is made because his later work (Flint, 1971) makes no mention of scale differences with respect to flutings.

Continuum Nature of Flutings

Alden (1918), Armstrong and Tipper (1948), Smith (1948), Flint (1957, 1971), Gravenor and Meneley (1958), Karrow (1965), Harris (1967), and Prest (1967) have stated that flutings or grooves are one member of a continuum of features which range from flutings through drumlinoid forms to drumlins. Problems in fluting nomenclature have, therefore, emerged with some authors appearing to use different terms to describe similar or identical features (Dean, 1953). Prest (1967, p. 9) obviously recognizes this situation for he distinguishes between fluted ground moraine and drumlinized ground moraine. In the former the ridges and furrows are more closely spaced, and "the ridge tops are more or less at the same level as the surrounding ground moraine or till plain rather than noticeably above it." Gravenor and Meneley (1958) make a similar distinction, but many other authors do not. Thus, though it is not often stressed, the reader should carefully consider the continuum concept when interpreting articles describing flutings.

Spacing

Fluting trends with preferred spacing have been described by a number of authors including Hoppe and Schytt (1953), Gravenor and Meneley (1958), Heidenreich (1964), and Baranowski (1970). Preferred spacing has also been recognized in association with drumlins (Reed, Galvin, & Miller, 1962) and drumlinoid forms (Dean, 1953), thus providing additional evidence of the similarity and continuum nature of these features. It should be noted, however, that tracts of flutings, drumlinoid forms, and drumlins exist that appear to be lacking in preferred spacing.

Relation to Ice Flow

Since 1920 all authors of literature reviewed in this study agree that flutings, as well as drumlins, reflect the flow of glacial ice. Some flutings, however, may be caused by a local readvance which was at variance with the previous regional ice-flow direction (Gravenor & Meneley, 1958). It follows that fluting trends indicate the direction of ice flow locally and can be used to interpret regional flow only where many trends may be viewed collectively.

Definition

On the basis of the literature reviewed, flutings may be defined as streamlined, elongate landforms which may have both positive and negative or just negative topographic components, may be developed in either glacial drift or bedrock, and have long axes that parallel the flow of glacial ice that formed them. They are one member of a continuum of features, may be divided into large-scale and small-scale forms, and have trends which are parallel or subparallel to one another. In addition, flutings in some tracts exhibit a preferred spacing perpendicular to their trend.

Theories of Formation

Based on their work in northern Alberta and the findings of other authors, Gravenor and Meneley (1958, p. 726) state that any theory regarding the nature of fluting formation must consider the following characteristics:

> (1) Flutings and drumlins are gradational features (2) Flutings are formed of till, stratified drift and bedrock (3) Flutings are regularly spaced, show well developed parallelism and are quite long (up to several miles) (4) There is some evidence to suggest that many flutings were created by a local readvance of a glacier which overrode existing glacial deposits (5) Preliminary fabric data show that there is a lineation parallel to the ridges and foliation which dips away from the ridge tops.

In a review of the literature Hoppe and Schytt (1953) have concluded that there are two basic theories, one involving erosion and the other deposition, which may account for the formation of flutings.

Depositional Theories

Dyson (1952), in describing small-scale flutings in Glacier National Park, observed that most of the ridges terminated (in the upglacier direction) against a boulder and that most of these boulders bore evidence of glacial scour on their top and upglacier sides. These and other considerations led him to conclude that, when ice overrides boulders, its base may become grooved and result in ice tunnels. Pressure of the overlying ice might then force water-saturated unfrozen drift into these tunnels. Subglacial ridges parallel to the direction of ice flow would, therefore, be formed and eventually become a topographic feature upon deglaciation of the area. Dyson discounted erosion of the intervening areas as a cause of the ridges he observed but stated that a polygenetic origin of flutings was possible.

Schytt (1963) supports the reasoning of Dyson and elaborates on the mechanism of formation. He envisions water-saturated drift at the pressure melting point being pressed upward into subglacial cavities formed in the lee of large boulders. According to Schytt, this drift freezes to the upper surface of the cavity and flows with the ice, thus maintaining a void in the lee of the boulder which is in turn filled by more drift. Flow of the water-saturated drift continues until heat loss lowers its temperature, whereupon it will freeze to the underlying drift, cease to flow, and the glacier will override it. Formation of the flute is then at an end.

Frost heaving has also been suggested as a cause of cavities in the base of the ice (Baranowski, 1970). Preferred spacing between ridges is then supposedly accounted for by an analogy to periglacial features and in this regard Baranowski (1970, p. 74) states, "Similarly evenly spaced are sorted polygons or forms of frost heaving action at the surface of the tundra."

Erosional Theories

It is apparent that erosion may be responsible for flutings or groovings in rock. Carney (1910), therefore, subscribes to an erosional origin for the grooves he investigated on Kelleys Island. Smith (1948, p. 512) also accepts an erosional origin for grooves in bedrock and concludes that some factor "within the ice itself" is the ultimate cause.

Some authors believe that erosion can cause flutings in drift as well as bedrock. In a paper describing drumlins and related streamlined features, Aronow (1959) states that their origin is uncertain, but he believes they are erosional rather than depositional. Similarly, Armstrong and Tipper (1959) conclude that a readvance of ice eroded the drumlins and grooves they investigated in British Columbia.

Erosion not directly associated with glacial action has also been proposed as a contributing factor in the formation of some flutings. Based on the study of aerial photographs of northern Canada, Dean (1953) concluded that some of the flutings he observed began as drumlinoid forms and were subsequently modified by solifluction, normal erosion, and lacustrine action.

Other Theories

Some theories of fluting formation involve erosion and deposition in conjunction with one another. Gravenor and Meneley (1958) postulate zones of high and low pressure within the ice (parallel to the direction of flow) which may alternately concentrate and disperse the basal drift. Deposits thus formed could be smoothed and streamlined by the ice to form flutings with the resulting crests being depositional and the furrows erosional. Shaw and Freschauf (1973) accept this concept and propose that a secondary circulation in the ice (helicoidal flow) is the cause of the zones of pressure.

Summary

Theories of fluting formation may be divided into three groups: (1) erosional interpretations that postulate grooving of drift or bedrock through the action of glacial ice, (2) depositional theories that envision the emplacement and streamlining of drift to form the features, and (3) processes involving both erosion and deposition. Given the variations in form, size, and distribution of flutings, it may be that they develop in more than one manner and no single theory is everywhere appropriate.

Till Fabric

Ostry and Dean (1963, p. 165) state that "Till fabric implies the orientation in space of those stones which have a directional property." Measurement and plotting of these orientations may result in a schematic portrayal of the till fabric. Although the first till fabric investigations were concerned only with stones within till which were large enough to be readily measured, many subsequent studies have focused on the till matrix. These two procedures are referred to as macrofabric and microfabric analysis, respectively; and several authors, among them Harrison (1957b), Ostry and Deane (1963), and Evenson (1971), state that results obtained from the two techniques are similar.[4]

Determining Ice-Flow Direction

Holmes (1941), Hoppe (1951), Donner and West (1958), Cowan (1968), Evenson (1971), and Drake (1974), among others, have demonstrated that under certain conditions a significant number of stones in till may become aligned in the direction of glacier flow. Authors who have utilized till fabrics to indicate past ice-flow directions and/or to differentiate between till sheets in a vertical sequence include Harrison (1957b), Gravenor and Meneley (1958), Stevens (1960), Flint (1961), Norris (1962), Wright (1962), MacClintock and Dreimanis (1964), Banham and Ranson (1965), Harris (1967), McDonald (1969), Andrews and Smith (1970), Ramsden and Westgate (1971), and Shaw and

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[4] In addition, Kauranne (1960) and Andrews (1965) report that orientations of surface boulders may coincide with the fabrics of associated tills.

Freschauf (1973). Interpretation of till fabrics has not been standardized, however, and a number of techniques have been developed to determine the directional tendency of clastic particles (i.e., supposed ice-flow direction). In reviewing these techniques, Andrews and Smith (1970, p. 514) state that "commonly the principal modal group is used to designate directional tendency. . . ." This method usually involves the placing of stone azimuths (long-axis orientations) into classes and portraying the total number of stones within each group. The resulting schema is termed a "rose diagram" and its modal group is used to indicate ice flow. Authors who have applied this method include Galloway (1956); Glen, Donner, and West (1957); Gravenor and Meneley (1958); Dreimanis (1959); Norris (1962); Wright (1962); and Penny and Catt (1967). Other measures of directional tendency which have been employed include mean azimuth (Harrison, 1957a, 1957b), median azimuth (Rains, 1969), mean vector summation (Andrews & Schimizu, 1966; Cowan, 1968; and Andrews & Smith, 1970), and eigenvalue (Mark, 1973).

Many analyses of till fabrics utilize the dip of the long axes of stones in addition to their azimuths because this data may indicate the direction of ice movement. Andrews and Shimizu (1966) state that theoretically certain stones within till should have a preferred upglacier dip, and many authors, among them Harrison (1957b), Wright (1962), Andrews and Smithson (1966), Cowan (1968), Harris (1968), and McDonald (1969), either confirm or utilize this relationship in their work. The author is aware of only one study, that of Lotan and Shetron (1968), which identifies a downglacier dip in a till fabric, but no explanation is given for this apparent anomaly.

Some workers report till fabrics with the absence of a preferred dip (West & Donner, 1956) or dips which were too erratic to determine ice-movement direction (Young, 1969). In considering the problem of orthorhombic symmetry (in essence the absence of a preferred dip), Andrews and Schimizu (1966) have concluded that the plane of reference may influence the fabric, and they state that use of a horizontal reference plane may account for most, if not all, of the analyses of till fabrics exhibiting orthorhombic symmetry. There is general agreement that a preferred dip in a till fabric will be inclined upglacier.

On the basis of the works reviewed, it seems appropriate to conclude that, when properly interpreted, the technique of till-fabric analysis can be useful in indicating directions of past ice flow.

Fabric Patterns

Andrews and Smith (1970) describe five methods of visually portraying till-fabric data. Distinct patterns often result with the simplest being a unimodal one in which all stone azimuths are oriented in the same direction. Harris (1969), however, states that there appears to have been only one such fabric reported.

Transverse fabrics,[5] fabrics characterized by a secondary mode more or less at right angles to the primary mode, are more complex but are widely reported. Several causes have been suggested for the formation of a transverse mode, and these include the rolling or thrusting (rather than sliding) of stones about their long axes

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[5] Termed "cross fabrics" by Ostry and Deane (1963) and Evenson (1971).

(Holmes, 1941; Galloway, 1956; Kauranne, 1960; and Penny & Catt, 1967), protracted flow (Glen, Donner, & West, 1957; Andrews & Smith, 1970; and Andrews, 1971), an intermediate axis dip of greater than 75° (Holmes, 1941; and Dreimanis & Reavely, 1953), frequent stone collisions (Glen, Donner, & West, 1957; and Evenson, 1971), the presence of narrow band tills associated with thrust planes (Donner & West, 1956), compressive flow (Boulton, 1970), a greater degree of relief than in adjacent areas (Harris, 1969), and stone shape (Holmes, 1941). Although the transverse mode is most often a secondary mode, there are instances where it predominates. Occurrences of transverse maxima which have either been verified or suspected are reported by Dreimanis and Reavely (1953), Donner and West (1956), Norris (1962), Ostry and Deane (1963), Penny and Catt (1967), McDonald (1969), and Evenson (1971). The data of Shaw and Freschauf (1973) include a fabric with a transverse maxima, but they do not comment on it.

Polymodal fabrics, fabrics with more than two modes, are also a common pattern. Ostry and Deane (1963), using thin-section analyses of microfabrics, state that some modes of polymodal microfabrics may in reality be apparent directions. Because thin sections are two-dimensional in nature, the observed elongation of some particles may represent apparent rather than true directions.[6] Such possible errors do not exist in macrofabric analysis because it is three-dimensional in nature. Other suggested causes of polymodal fabrics include unknown factors (Kauranne, 1960), inclusion in the fabric sample of stones in

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[6] See Billings (1972, pp. 521-24) for a discussion on the problem of apparent directions.

contact with one another (Norris, 1962), and the upward movement by frost action of stones from one till sheet to an overlying one (Harris, 1969).

Deformation Fabrics

"Deformation fabric" is a term used by Harris (1969) to describe fabrics which have undergone alteration after their initial deposition. Suggested mechanisms to cause such alteration include frost action (Harris, 1969), soil-forming factors (Harrison, 1957a), growing and decaying tree roots (Kauranne, 1960), and colluvial action (Rudberg, 1958). Therefore, many authors have adopted procedures to eliminate the possible effects of these factors.

Deformation fabrics may also result from overriding ice producing shear stresses in previously deposited drift that result in a reorientation of the previous fabric. MacClintock and Dreimanis (1969) and Ramsden and Westgage (1971) report situations where the reorientation was parallel to the later ice movement, but Penny and Catt (1967) describe an area in East Yorkshire where the reorientation was perpendicular and was associated with folds in the previously deposited overridden till.

Because they may exhibit different characteristics and be produced by a variety of factors, care must be taken to identify deformation fabrics where they exist.

Variability of Till Fabrics

Studies based on till-fabric analyses often assume that each fabric collected is representative of the surrounding area. This assumption is not necessarily justified, however, because it has been demonstrated that variability in the orientation of till fabrics may exist within short distances.

Significant vertical variations in till fabrics have been described by Galloway (1956), Kauranne (1960), and Young (1969). Although some of these examples appear to exhibit evidence of separate ice advances or differing depositional situations, Andrews and Shimizu (1966, p. 161) report appreciable till-fabric variations within a three-meter vertical distance which they conclude indicates that the fabrics were not from the same population and "suggests that a major change in fabric orientation and dispersion occurred within a limited vertical extent and with no stratigraphic trace." Young (1969) suggests that some form of independent verification, especially in the vertical plane, be utilized when interpreting till fabrics.

Till-fabric variation in the horizontal plane has also been reported. Harrison (1957b) has demonstrated that for till fabrics taken 750 feet apart differences may be considerable but over shorter distances tend to be smaller. Similar results were noted by Kauranne (1960, p. 90), who found variability if the fabrics were samples some tens or hundreds of meters apart, which led him to conclude that "Results obtained in the same area or in the same pit may not always be comparable."

It is apparent that variability in till fabrics may exist in both the horizontal and vertical dimensions and that the likelihood of differences in the horizontal plane may be equated to increasing distances between sample sites. This situation, however, has not prevented many workers (including some who have reported variability) from utilizing till fabrics to denote former ice movements within local and extensive areas.

Relationship of Till Fabric to Elongate, Streamlined Landforms

Many investigators have found that till fabrics of elongate, streamlined landforms are aligned either parallel or subparallel to the long axes of the features. Hoppe (1951) reports that in the area he studied the long axes of pebbles tend to lie parallel to drumlin trends. Wright (1957) and Harris (1967) report similar relationships, but Walker (1973) indicates that the till fabrics he studied tended to be aligned with the peripheral outline of the drumlin rather than its long axis trend.

Gravenor and Meneley (1958), Cowan (1968), and Shaw and Freschauf (1973) have investigated fluting/till-fabric relationships and report that till fabrics from fluting crests are aligned either parallel or subparallel to the features' trend.[7] Hoppe and Schytt (1953) report different results and state that in the area they investigated the level ground moraine had a fabric parallel to ice flow (i.e., fluting trend) but the fluting crests did not. Because these authors do not provide till-fabric data, the degree of nonalignment is unclear, and since they are describing small-scale features, their results may not be comparable with the other examples, all of which are large-scale.

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[7] Gravenor and Meneley (1958) report that this relationship did not exist below a depth of eleven feet, while Shaw and Freschauf (1973) state that the fabrics taken from the flanks of flutings they studied tend to be canted toward the fluting crests.

Summary

The term "till fabric" refers to the orientation of certain macro or micro components of till. These components frequently exhibit a preferred orientation (directional tendency) and have often been used as a basis to determine directions of former ice movement. Various measures of this orientation have been utilized by different workers, and among them are primary mode, mean azimuth, median azimuth, mean vector summation, and eigenvalue. The preferred orientation will oftentimes exhibit a preferred dip which has generally been interpreted as being in the upglacier direction. Till-fabric diagrams are usually characterized by more than one mode, and both transverse and polymodal fabrics are common with some fabrics exhibiting a transverse maximum.

Post-depositional alteration of till fabrics has been reported and is possibly the result of numerous factors, including tree roots, colluvial action, frost action, and overriding ice. Variability of unaltered till fabrics in both the horizontal and vertical directions has also been noted, but this has not prevented many workers (including some who document variability) from utilizing till-fabric data to infer directions of past ice movement. Finally, on the basis of studies reviewed in this paper, it is indicated that the preferred orientation of till fabrics tends to be aligned either parallel or subparallel to the trend of streamlined, elongate glacial landforms.

FLUTING/TILL-FABRIC RELATIONSHIPS IN SOUTH-CENTRAL MICHIGAN

Description and Distribution of Features

Numerous parallel elongate forms developed in glacial drift exist near the city of Coldwater, Michigan. These features, though not apparent at many places to an observer on the ground, are easily observable on large-scale topographic maps and aerial photographs (Figures 1 and 2) and show forms ranging from flutings through drumlinoid forms to drumlins.[8] Similar features in Alberta, Canada were investigated by Gravenor and Meneley (1958, p. 715), who refer to the forms as flutings and define them in the following way: "the term fluting is used in its widest possible sense and except where specified includes low-lying drumlins and giant grooves as well as parallel shallow grooves." On the basis of this similarity, the term "flutings," as described by Gravenor and Meneley, appears appropriate for at least some of the linear landforms in the Coldwater area.

Longitudinal profiles of the fluting crests are broadly convex with minor irregularities. Highest points are not consistently in any one location relative to the features' long axes and, though variable, most of the features range from one-half mile to slightly more than

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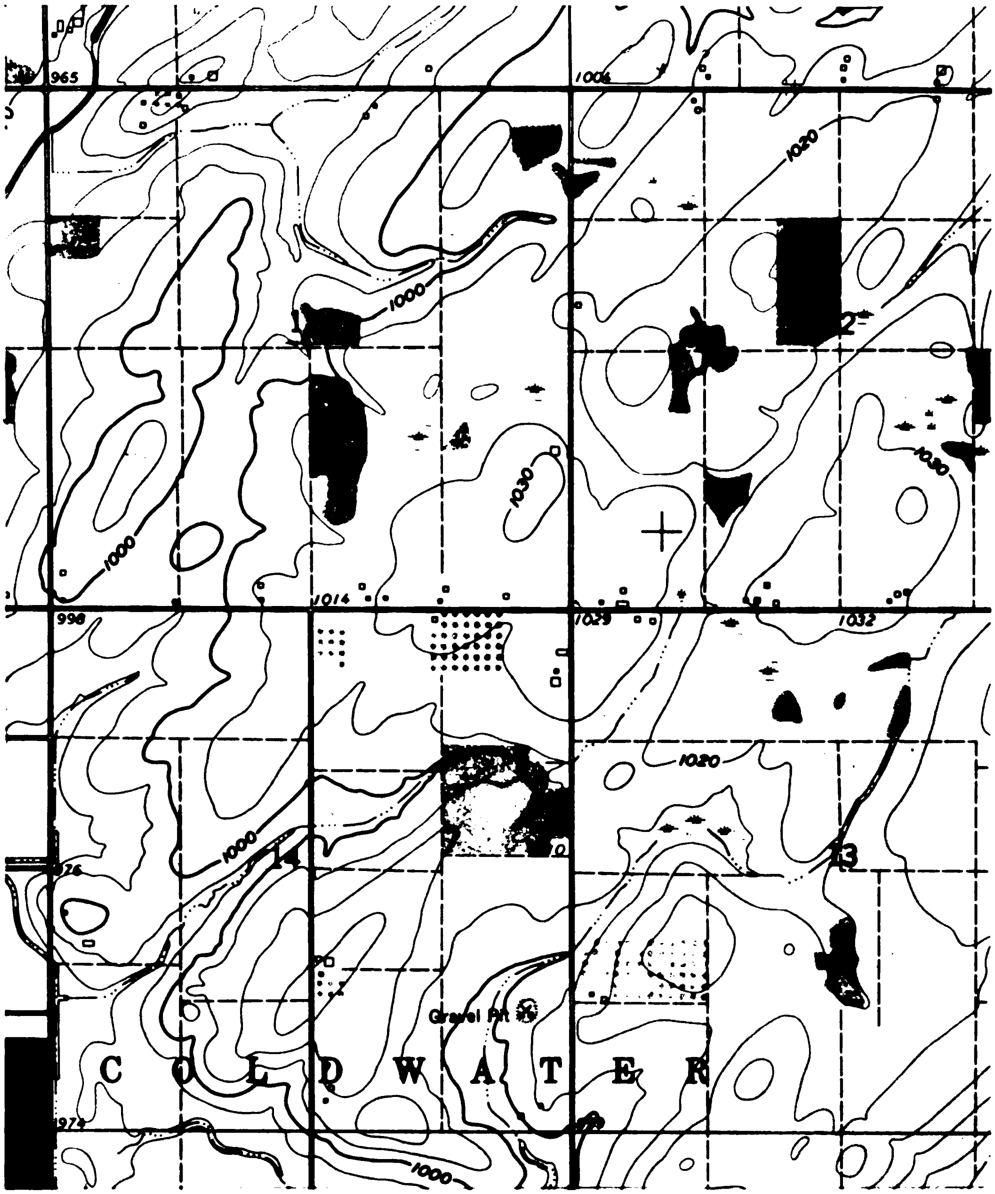
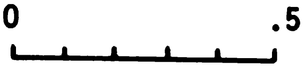
[8] See the literature review for a discussion on the continuum nature of these landforms.

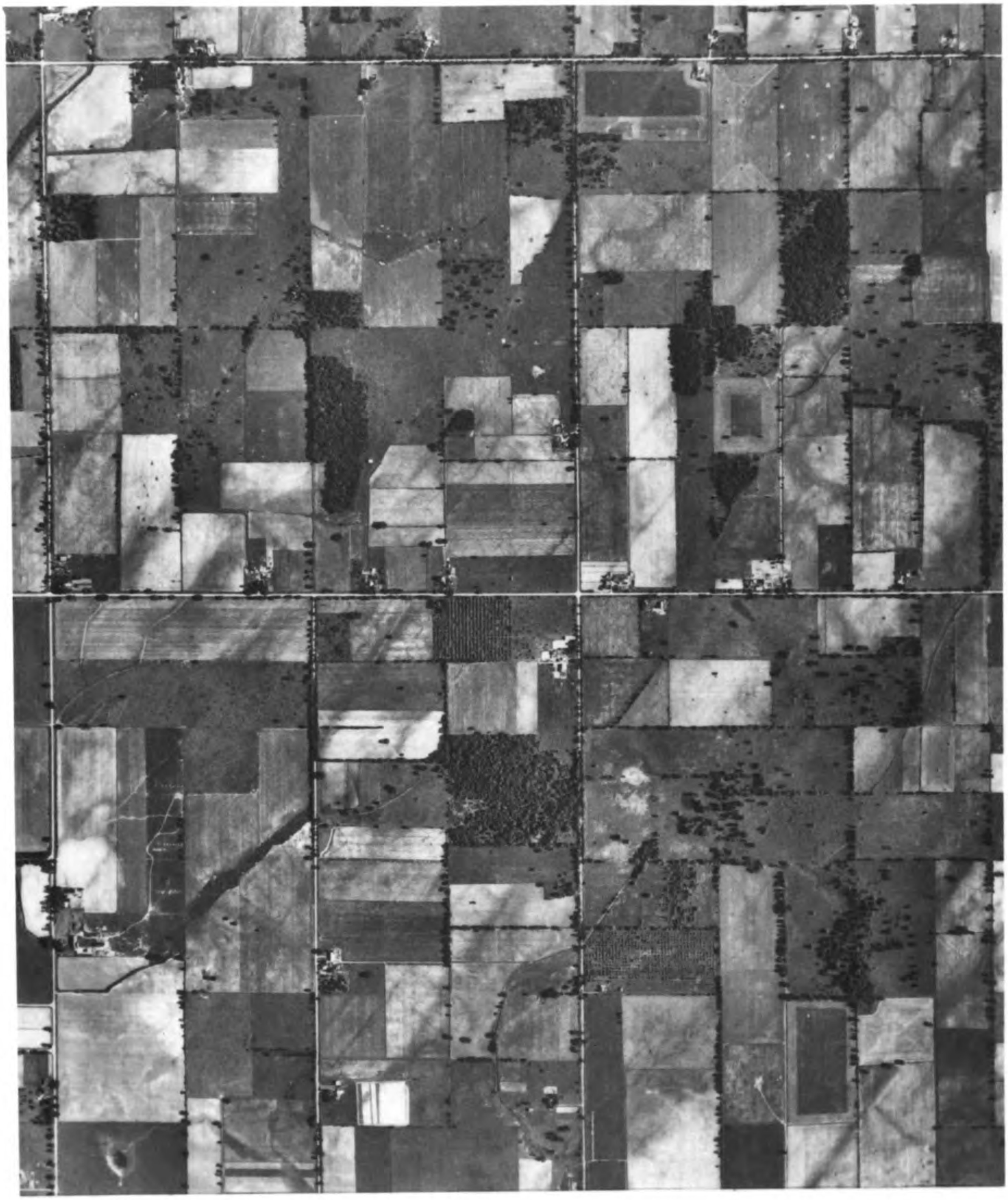


Source: Coldwater East Quadrangle [1:24,000]



Contour Interval 10 feet

Figure 1: Topographic map of Flutings.



Source: U.S. Department of Agriculture [BDE-4G-12, 1950]

Figure 2: Aerial photograph of flutings shown in figure 1.

one mile in length. Transverse profiles of the fluting crests reveal that the features may vary between rather broad forms with gentle slopes on their flanks and more narrow forms exhibiting a tendency toward steeper slopes. Variations of fluting crest form are illustrated by Figure 3. Distances between adjacent crests (normal to the direction of elongation) are variable, but a spacing within the 2,000 to 3,000 foot range is most common. Relief between crests and adjacent low-lying areas ranges from 20 to 50 feet. Direction of elongation of all the forms is north-northeast-south-southwest, and this alignment parallels the direction of flow of the Saginaw Lobe ice as described by Leverett and Taylor (1915).

Topographic maps at a scale of 1:24,000 reveal three areas of fluting development located to the northeast, northwest, and southwest of Coldwater.[9] To the southeast the maps show no fluting formation, but aerial photographs reveal that this area also has lineations although they are less apparent than in the other areas. All four of the fluted tracts are geographically separate and are surrounded by areas underlain for the most part by sand and gravel (Figure 4).

Field Procedures

Till fabrics were determined at four sites near Coldwater, Michigan: two from the fluted area northeast of the city and one each from the southeast and southwest tracts (Figure 4). All were based on certain stones collected from glacial till at sites located on the

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[9] The maps used are the Coldwater East and Coldwater West Quadrangles, and the study area is defined as the area they represent.

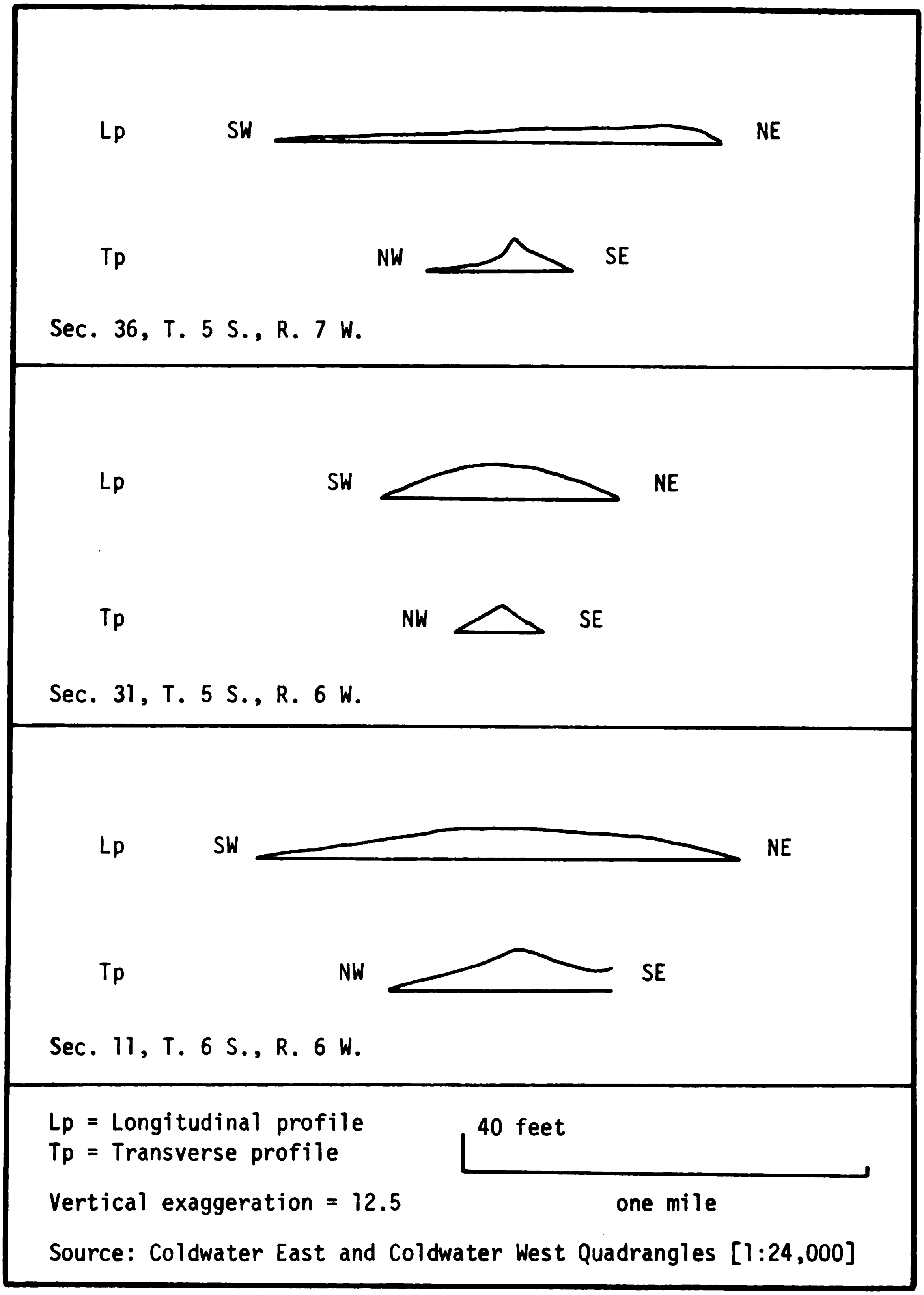

Figure 3: Profiles of three fluting crests. Note: Transverse profiles are through features' highest points.

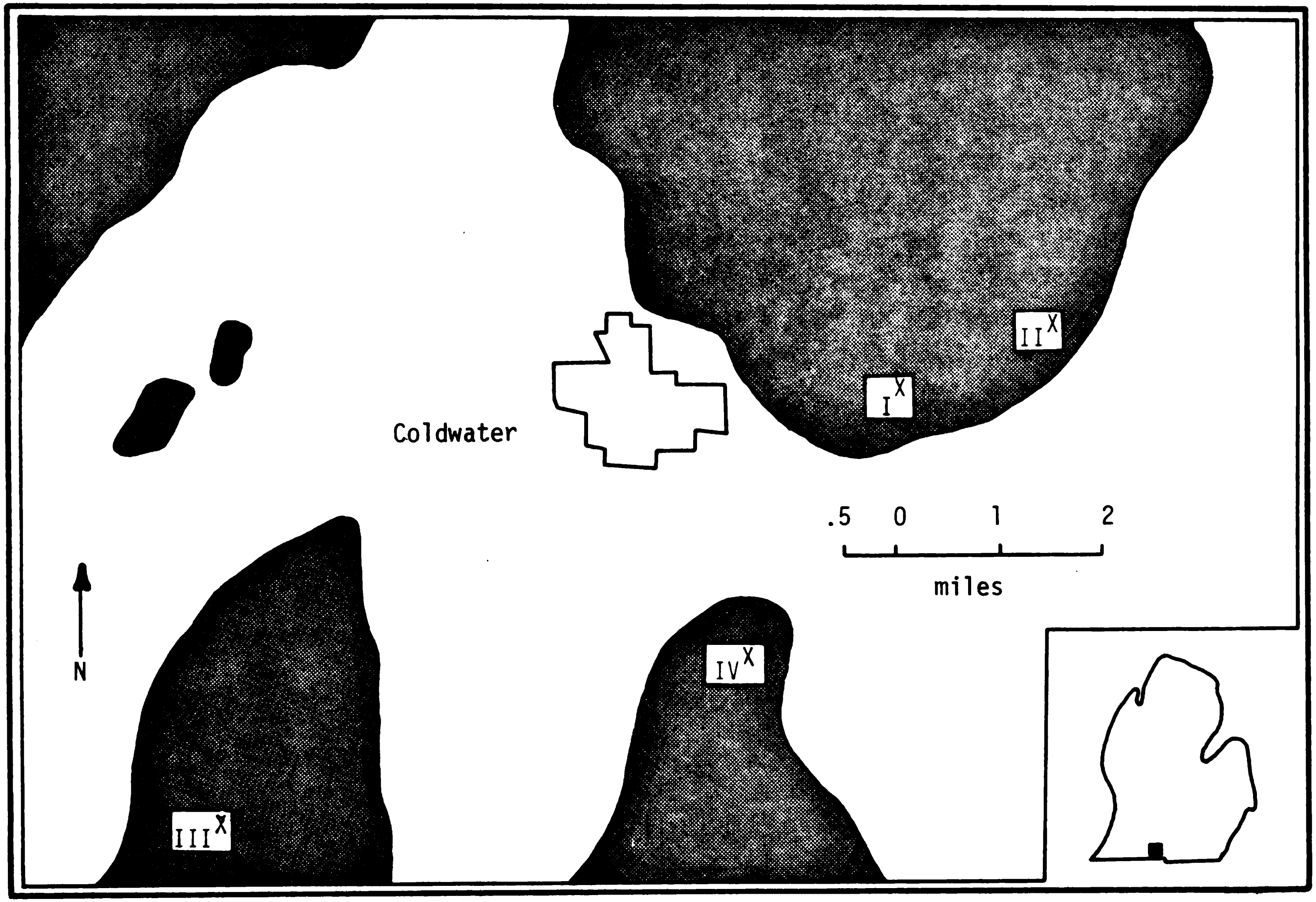

Figure 4: Location of till fabric sites.

Fluted areas ■ Till fabric sites I X

crests or gently sloping flanks of flutings. Pits were excavated at two of the four locations while the other sites utilized previously existing exposures. Each fabric was collected from below the zones of leaching and present frost action. Depth of leaching was determined through the use of a 7 percent solution of hydrochloric acid while, following Harrison (1957b), a depth of three feet was considered sufficiently deep to negate the effects of frost action.

At an appropriate depth a horizontal surface of approximately two square feet was exposed, thus allowing stones to be located by gently probing the surface with a knife and removing part of the surrounding matrix. Only stones with an A:B axis ratio of 3:2 or greater and an A axis of at least one cm were utilized, and stones touching one another were rejected. Once several appropriate stones had been exposed, the azimuths of their long axes were measured to the nearest five degrees with a Brunton compass. Measurements were facilitated by use of an aluminum knitting needle which was aligned with each stone's long axis. Some stones needed to be removed from the matrix in order to determine their long axes, and in these cases the needle was inserted into the resulting cavity to obtain the measurement. Since this allowed the direction of dip of each stone's long axis to be determined with the Brunton's clinometer, the procedure was followed for all dip measurements. When all of the appropriate stones in the upper part of the exposed surface were measured, the process was repeated at successive lower levels. At no site was a sampling of more than one foot of vertical distance necessary.[10]

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[10] From four to six hours were required for excavation and measurement at each site.

Data on horizontal orientation were grouped into fifteen-degree intervals and plotted on rose-type diagrams for purposes of interpretation. Three of these diagrams show both direction of dip and horizontal orientation of the component stones' long axes while the fourth portrays horizontal orientation only. Stones in the latter diagram, and horizontal stones in the other diagrams, were plotted at half-value in opposite directions while dipping stones were plotted at full value in their respective interval. Each interval is represented by its azimuthal midpoint with adjacent midpoints being connected. The length of each interval is proportional to the number of stones contained therein.[11]

Sites and Fabrics

Site I

This fabric is associated with a sandy glacial till located within the northeast part of the study area within the SW SW Sec. 18, T. 6 S., R. 5 W. The site was a recently excavated drainage tile trench located on the gently sloping flank of a fluting. Depth of leaching was 36 inches, and fabric was collected about 40 inches below the surface. Inspection of the fabric diagram (Figure 5) reveals that the primary mode ($A-A_1$) is aligned subparallel to the trend of the fluting. There is also a prominent secondary mode to the fabric ($B-B_1$) which, although not directly at right angles to the primary mode, appears to be a transverse mode. No data on the dip of the component stones' long axes were collected for this site.

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[11] This method is similar to that of Wright (1962).

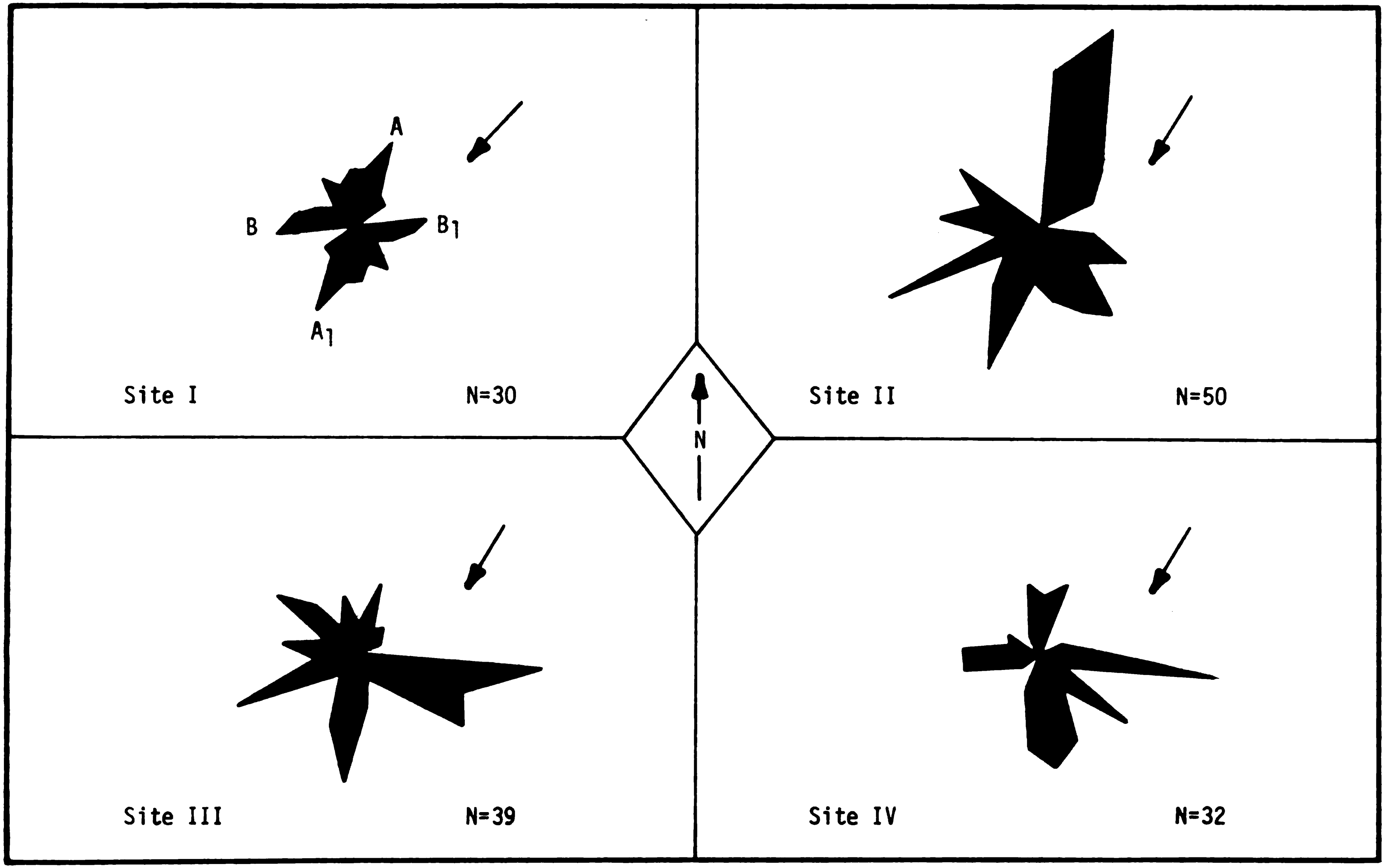

Figure 5: Till fabrics. Note: Arrows represent the topographic trend of associated flutings.

Site II

The fabric at site II is also from the northeast part of the study area and was determined from an exposure of sandy and fissile till adjacent to a road along the level crest of a fluting[12] within the SE SE Sec. 8, T. 6 S., R. 5 W. A pit was excavated to a depth of 3.5 feet, and the fabric data obtained below the depth of leaching (34 inches). The rose diagram (Figure 5) reveals a well-defined primary mode aligned subparallel to the fluting trend with the preferred dip suggesting ice flow from the northeast. A well-developed transverse mode is also evident.

Site III

This fabric, associated with a dense, tough clay till that was fissile in places, was determined within a pit excavated into the level crest of a flute located in the southwest part of the study area within the NW NW Sec. 12, T. 7 S., R. 7 W. Depth of leaching was 36 inches and the fabric was determined about 48 inches below the surface. Inspection of the rose diagram (Figure 5) reveals a well-defined primary mode with a preferred dip suggesting ice flow from slightly south of east. This is not aligned with the fluting trend. A transverse mode is also well developed, but, curiously, it exhibits a preferred dip to the south.

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[12] This feature might also be interpreted as a drumlinoid form or even a drumlin by some.

Site IV

The fabric at site IV was associated with till exposed in a pit on the gently sloping flank of a flute located in the southeast part of the study area within the SW SW Sec. 26, T. 6 S., R. 6 W. The till, sandy to a depth of 30 inches, was underlain by a zone of sand and pebbles to a depth of 50 inches. A mottled clay till with sand stringers existed below the sand and pebbles. Depth of leaching was 50 inches, and the fabric was determined from stones at least 55 inches below the surface. Although the drift at this exposure was somewhat variable, the site was the most suitable location examined in the southeast part of the study area. Inspection of the rose diagram (Figure 5) reveals that, as is the case with site III, the primary mode is not aligned with the trend of the fluting and indicates an ice flow from slightly south of east. Likewise, the transverse mode exhibits a preferred dip to the south.

CONCLUSION

It was established in the review of pertinent literature that the preferred orientation of till fabrics associated with flutings and other streamlined, elongate landforms tends to be aligned either parallel or subparallel to the features' trend. Field study within a fluted area in south-central Michigan indicates that such a relationship exists at the two sites north of Coldwater but is lacking at the two locations south of the city. The preferred orientation of certain clasts within till at the two southern sites is nearly transverse to the trend of the flutes and suggests that the till fabric is most likely related to ice flowing from slightly south of east. Although the fabrics at these two southern sites might conceivably have transverse maxima, this possibility is considered unlikely because (1) the primary mode of each fabric has a preferred dip to the east and there is no known mechanism to produce a preferred dip in a transverse orientation and (2) there is no reason to suspect that any of the reported causes of transverse maxima (i.e., protracted flow, stone shape, stone collisions, folds in the till, etc.) were present in the southern portion of the study area but absent several miles to the north. Since one of these southern fabrics (site III) was taken from the level crest of a flute, it appears that reorientation by colluvial action is not a factor. Thus, on the basis of this evidence and contrary to most published accounts, flutings with similar trends and interpreted to have been formed by the same glacial lobe do not necessarily have till-fabric orientations which are parallel or even similar to their axial orientation.

It is generally recognized that during Wisconsinan time central lower Michigan was influenced by the advance of at least two major lobes of ice, the Saginaw and Erie Lobes. The axis of the Saginaw Lobe extended in a southwesterly direction through what is now Saginaw Bay, while the axis of the Erie Lobe trended west from the Lake Erie lowland toward central Illinois. It is also recognized that the margins of these two lobes were in close proximity or in contact with one another in south-central Michigan during Woodfordian time, and it appears that the Coldwater area was within or at least marginal to the zone of influence of both lobes. Based on the trends of the flutings investigated, it is apparent that they were all formed by ice associated with the Saginaw Lobe. However, on the basis of the till fabrics, it appears that the sediments associated with the sites north of the city reflect Saginaw Lobe movement while the sediments at sites to the south are aligned in a manner that suggests association with Erie Lobe ice.[13] It is conceivable that the till fabrics at the sites north of Coldwater represent Erie drift that was reoriented by Saginaw Lobe ice at the time of fluting formation, but this possibility is unlikely because there appears to be no such reorientation at the sites to the south.

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[12] Leverett and Taylor (1915) report a southwesterly trending moraine of the Erie Lobe in the eastern portion of the study area near Quincy, Michigan.

Thus, on the basis of the accumulated data and their relationships, it is most logical to conclude that at some time prior to the last glacial advance Erie Lobe ice extended into the southern, but probably not the northern, part of the study area, producing the till fabrics revealed at sites III and IV. Subsequently, the Saginaw Lobe overrode all of the area, resulting in extensive tracts of fluted topography. If this interpretation is correct, it implies (1) that the flutings south of Coldwater are erosional in origin as deposition most likely would have obscured the anomalous fabrics while the flutings to the north may be either depositional or erosional in nature because an erosional origin for them would necessitate a reorientation of the till fabric or a previous ice advance parallel to the one which formed the flutings, (2) that in certain situations ice moving in a direction quite different from a previous episode of glaciation may override and erode the surface of glacial till to form flutes without reorienting preexisting fabrics, (3) that till fabrics and flutings within the same area may have significantly different orientations, and (4) that within the Coldwater area the margin of the Erie Lobe was more extensive than morainal trends indicate prior to the last advance of the Saginaw Lobe into the area.

LIST OF REFERENCES

Alden, W. C. 1918. The Quaternary Geology of Southeastern Wisconsin. U.S. Geol. Survey, Prof. Paper 106, p. 356.

Andrews, J. T. 1965. Surface Boulder Orientation Studies Around the Northwestern Margin of the Barnes Ice Cap. Jour. Sed. Petrology, v. 35, pp. 753-58.

Andrews, J. T. 1971. Methods in the Analysis of Till Fabrics. In R. P. Goldthwait, J. L. Forsyth, D. L. Gross, and Fred Pessl, Jr. (eds.), Till, a Symposium. Ohio State Univ. Press, pp. 321-27.

Andrews, J. T., and K. Shimizu. 1966. Three-Dimensional Vector Technique for Analyzing Till Fabrics: Discussion and Fortran Program. Geog. Bull., v. 8, pp. 151-65.

Andrews, J. T., and D. I. Smith. 1970. Statistical Analysis of Till Fabric: Methodology, Local and Regional Variability. Geol. Soc. London Quart. Jour., v. 125, pp. 503-42.

Andrews, J. T., and B. B. Smithson. 1966. Till Fabrics of the Cross-Valley Moraines of North-Central Baffin Island, Northwest Territories, Canada. Geol. Soc. Amer. Bull., v. 77, pp. 271-90.

Armstrong, J. E., and H. W. Tipper. 1948. Glaciation in North Central British Columbia. Amer. Jour. Sci., v. 246, pp. 283-310.

Aronow, S. 1959. Drumlins and Related Streamlined Features in the Warwick-Tokio Area, North Dakota. Amer. Jour. Sci., v. 257, pp. 191-203.

Banham, P. H., and C. E. Ranson. 1965. Structural Study of the Contorted Drift and Disturbed Chalk at Weybourne, North Norfolk. Geol. Mag., v. 102, pp. 164-74.

Baranowski, S. 1970. The Origin of Fluted Moraine at the Front of Contemporary Glaciers. Geog. Annaler Series A, v. 52, pp. 68-75.

Billings, H. P. 1972. Structural Geology. Prentice-Hall, Inc., p. 606.

Boulton, G. S. 1970. The Deposition of Subglacial and Melt-Out Tills at the Margins of Certain Svalbard Glaciers. Jour. Glaciology, v. 9, pp. 231-45.

Carney, F. 1910. Glacial Erosion on Kelleys Island, Ohio. Geol. Soc. Amer. Bull., v. 20, pp. 640-45.

Chamberlain, T. C. 1888. The Rock Scourings of the Great Ice Invasions. U.S. Geol. Survey Ann. Report 7, v. 3, pp. 147-248.

Cowan, W. R. 1968. Ribbed Moraine: Till Fabric Analysis and Origin. Cand. Jour. Earth Sci., v. 5, pp. 1145-59.

Dean, W. G. 1953. The Drumlinoid Landforms of the "Barren Grounds," N.W.T. Cand. Geog., v. 3, pp. 19-30.

Donner, J. J., and R. G. West. 1956. The Quaternary Geology of Brageneset, Nordaust-Landet, Spitsbergen. Norsk Polarinstitutt Skrifter, v. 109, pp. 1-37.

Drake, L. D. 1974. Till Fabric Control by Clast Shape. Geol. Soc. Amer. Bull., v. 85, pp. 247-50.

Dreimanis, A. 1959. Rapid Macroscopic Fabric Studies in Drill Cores and Hand Specimens of Till and Tillite. Jour. Sed. Petrology, v. 29, pp. 459-63.

Dreimanis, A., and G. H. Reavely. 1953. Differentiation of the Lower and Upper Till Along the North Shore of Lake Erie. Jour. Sed. Petrology, v. 23, pp. 238-59.

Dyson, J. L. 1952. Ice-Ridged Moraines and Their Relation to Glaciers. Amer. Jour. Sci., v. 250, pp. 204-11.

Embleton, C., and C. A. M. King. 1968. Glacial and Periglacial Geomorphology. Edward Arnold, Ltd., p. 608.

Evenson, E. B. 1971. The Relationship of Macro- and Microfabric of Till and the Genesis of Glacial Landforms in Jefferson County, Wisconsin. In R. P. Goldthwait, J. L. Forsyth, D. L. Gross, and Fred Pessl, Jr. (eds.), Till, a Symposium. Ohio State Univ. Press, pp. 345-64.

Flint, R. F. 1961. Two Tills in Southern Connecticut. Geol. Soc. Amer. Bull., v. 72, pp. 1687-91.

Flint, R. F. 1957. Glacial and Pleistocene Geology. John Wiley and Sons, Inc., p. 553.

Flint, R. F. 1971. Glacial and Quaternary Geology. John Wiley and Sons, Inc., p. 892.

Galloway, R. W. 1956. The Structure of Moraines in Lyngsdalen, North Norway. Jour. Glaciology, v. 2, pp. 730-33.

Glossary of Geology. 1972. Margaret Gary, Robert McAfee, Jr., and Carol L. Wolf (eds.). Amer. Geol. Inst., p. 805.

Glen, J. W., J. J. Donner., and R. G. West. 1957. On the Mechanism by Which Stones in Till Become Oriented. Amer. Jour. Sci., v. 255, pp. 194-205.

Gravenor, C. P., and W. A. Meneley. 1958. Glacial Flutings in Central and Northern Alberta. Amer. Jour. Sci., v. 256, pp. 715-28.

Harris, S. A. 1967. Origin of Part of the Guelph Drumlin Field and the Galt and Paris Moraines, Ontario: A Reinterpretation: Cand. Geog., v. 11, pp. 16-34.

Harris, S. A. 1968. Till Fabrics and Speed of Movement of the Arapahoe Glacier, Colorado. Prof. Geog., v. 20, pp. 195-98.

Harris, S. A. 1969. The Meaning of Till Fabrics. Cand. Geog., v. 13, pp. 317-37.

Harrison, P. W. 1957a. New Technique for Three-Dimensional Fabric Analysis of Till and Englacial Debris Containing Particles from 3 to 40 MM. in Size. Jour. Geol., v. 65, pp. 98-105.

Harrison, P. W. 1957b. A Clay Till Fabric: Its Character and Origin. Jour. Geol., v. 65, pp. 275-308.

Heidenreich, C. 1964. Some Observations on the Shape of Drumlins. Cand. Geog., v. 2, pp. 101-07.

Holmes, C. D. 1941. Till Fabric. Geol. Soc. Amer. Bull., v. 52, pp. 1299-1352.

Hoppe, G. 1951. Drumlins in North-East Norbotten, North Sweden. Geog. Annaler, v. 33, pp. 157-65.

Hoppe, G., and V. Schytt. 1953. Some Observations on Fluted Moraine Surfaces. Geog. Annaler, v. 35, pp. 105-15.

Karrow, P. F. 1968. Pleistocene Geology of the Guelph Area. Ontario Dept. Mines Geol. Rept. 61, p. 38.

Kauranne, L. K. 1960. A Statistical Study of Stone Orientation in Glacial Till. Finland, Comm. Geol. Bull., v. 32, pp. 87-97.

Lemke, R. W. 1958. Narrow Linear Drumlins Near Velva, North Dakota. Amer. Jour. Sci., v. 256, pp. 270-83.

Leverett, F., and F. B. Taylor. 1915. The Pleistocene of Indiana and Michigan and the History of the Great Lakes. U.S. Geol. Surv. Mon. 53, p. 529.

Lotan, J. E., and S. G. Shetron. 1968. Characteristics of Drumlins in Leelanau County, Michigan. Papers, Mich. Acad. Sci., Arts, Letters, v. 53, pp. 79-89.

MacClintock, P., and A. Dreimanis. 1964. Reorientation of Till Fabric by Overriding Ice in the St. Lawrence Valley. Amer. Jour. Sci., v. 262, pp. 133-42.

McDonald, B. C. 1969. Surficial Geology of La Patrie-Sherbrooke Area, Quebec, Including Eaton River Watershed. Geol. Surv. Cand. Paper, 67-52, p. 21.

Mark, D. H. 1973. Analysis of Axial Orientation Data, Including Till Fabrics. Geol. Soc. Amer. Bull., v. 84, pp. 1369-74.

Norris, G. 1962. Some Glacial Deposits and Their Relation to Hippopotamus-Bearing Beds at Barrington, Cambridgeshire. Geol. Mag., v. 99, pp. 97-118.

Ostry, R. C., and R. E. Deane. 1963. Microfabric Analyses of Till. Geol. Soc. Amer. Bull., v. 74, pp. 165-68.

Penny, L. F., and J. A. Catt. 1967. Stone Orientation and Other Structural Features of Tills in East Yorkshire. Geol. Mag., v. 104, pp. 344-60.

Prest, V. K. 1967. Nomenclature of Moraines and Ice-Flow Features as Applied to the Glacial Map of Canada. Geol. Surv. Cand. Paper, 67-57, p. 32.

Rains, R. B. 1969. Differentiation of Till Deposits in the Whitemud Creek Valley, Edmonton, Alberta. Albertan Geog., v. 5, pp. 12-20.

Ramsden, J., and J. A. Westgate. 1971. Evidence for the Reorientation of a Till Fabric in the Edmonton Area, Alberta. In R. P. Goldthwait, J. L. Forsyth, D. L. Gross, and Fred Pessl, Jr. (eds.), Till, a Symposium. Ohio State Univ. Press, pp. 335-44.

Reed, B., C. J. Galvin, and J. P. Miller. 1962. Some Aspects of Drumlin Geometry. Amer. Jour. Sci., v. 260, pp. 200-10.

Rudberg, S. 1958. Some Observations Concerning Mass Movement on Slopes in Sweden. Geol. Fören. i Stockholm Förh., v. 80, pp. 114-25.

Schytt, V. 1963. Fluted Moraine Surfaces. Jour. Glaciology, v. 4, pp. 825-27.

Shaw, J., and R. C. Freschauf. 1973. A Kinematic Discussion of the Formation of Glacial Flutings. Cand. Geog., v. 17, pp. 19-35.

Smith, H. T. U. 1948. Giant Grooves in Northwest Canada. Amer. Jour. Sci., v. 246, pp. 503-14.

Stevens, L. A. 1960. The Interglacial of the Nar Valley, Norfolk. Quart. Jour. Geol. Soc. London, v. 115, pp. 291-312.

Walker, M. J. C. 1973. The Nature and Origin of a Series of Elongated Ridges in the Morley Flats Area of the Bow Valley, Alberta. Cand. Jour. Earth Sci., v. 10, pp. 1340-45.

Wardlaw, N. C., M. R. Stauffer, and M. Hoque. 1969. Striations, Giant Grooves, and Superposed Drag Folds, Interlake Area, Manitoba. Cand. Jour. Earth Sci., v. 6, pp. 577-93.

West, R. G., and J. J. Donner. 1956. The Glaciation of East Anglia and the East Midlands: A Differentiation Based on Stone-Orientation Measurements of the Tills. Quart. Jour. Geol. Soc. London, v. 112, pp. 69-91.

Wright, H. E., Jr. 1957. Stone Orientation in the Wadena Drumlin Field, Minnesota. Geog. Annaler, v. 39, pp. 19-31.

Wright, H. E., Jr. 1962. Role of the Wadena Lobe in the Glaciation of Minnesota. Geol. Soc. Amer. Bull., v. 73, pp. 73-99.

Young, Y. A. T. 1969. Variations in Till Macrofabric Over Very Short Distances. Geol. Soc. Amer. Bull., v. 80, pp. 2343-52.

SUMMER PRECIPITATION
IN THE
WASATCH RANGE
AS RELATED TO
SELECTED
MIDDLE AND LOWER
TROPOSPHERIC VARIABLES

By

Russell L. Dodson

A RESEARCH PAPER

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ABSTRACT

Stepwise multiple correlation and regression analysis was used to determine the relationships between measures of approaching 500 mb. short wave troughs, surface and lower tropospheric parameters, and summer precipitation in the Wasatch Mountains of Utah. Variables selected were 500 mb. wind speed, wind direction and pressure height, relative humidity at the surface, stability of the lower troposphere, and areal extent of the summer precipitation. Conclusions of this study were (1) the measures used to indicate approaching 500 mb. short wave troughs exhibited a low correlation with precipitation, (2) the lower tropospheric parameters accounted for more of the variance in precipitation than did the 500 mb. measures, (3) atmospheric stability was the variable most highly correlated with precipitation, and (4) wind speed at the 500 mb. level was negatively, but not strongly, correlated with precipitation.

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INTRODUCTION

Mountainous or hilly areas receive more precipitation than do adjacent lower regions, in part because the initial ascent of air over topographic barriers releases conditional or convectional instability (Barry & Chorley, 1970). The temporal distribution of precipitation in mountain regions is not uniform, however, as not every day brings precipitation. Such periodicity suggests that other factors, when coupled with orographic components, may contribute to the observed precipitation patterns. To this end researchers have included aspects of upper level air flow as well as surface parameters in their investigations (Williams & Peck, 1962).

PURPOSE

This project will attempt to correlate middle and lower tropospheric parameters with the areal concentration of summer precipitation in the Wasatch Mountains of Utah. More specifically, 500 mb. wind direction, wind speed and pressure height, surface humidity, and stability of the lower troposphere will be related to the percentage of selected mountain stations reporting precipitation. Two analyses will be conducted, one to relate precipitation to 500 mb. data only and another which utilizes all of the above variables.

Multiple correlation and regression analysis will be employed in these calculations.

STUDY AREA

The study area consists of the west-central portion of the Wasatch Range in eastern Utah and includes approximately 800 square miles (Figure 1). It was selected for several reasons. First, the range has a north-south trend with a crest averaging over 10,000 feet in elevation and a straight, bold western front (Thornbury, 1965) which is normal to westerly air flow and, therefore, may be appropriate for the study of terrain influences on precipitation (Williams & Peck, 1962). Second, daily precipitation totals for several high altitude stations in the area were available, and third, a first order meteorological station (Salt Lake City) was located just upwind (west) of the study area.

ATMOSPHERIC PARAMETERS

Waves in the Westerlies

The circumpolar westerly wind circulation (mid-latitude westerlies) is characterized at higher altitudes by an oscillatory or wave pattern of flow. These waves, termed long or Rossby waves, change position slowly and have wavelengths which are continental in size. Superimposed on this major circulation pattern and usually obscuring it are eastward-migrating short waves of smaller wavelength (Harman, 1971). Both long and short waves consist of cold troughs and warm ridges with the trough being the equatorward extension and the ridge

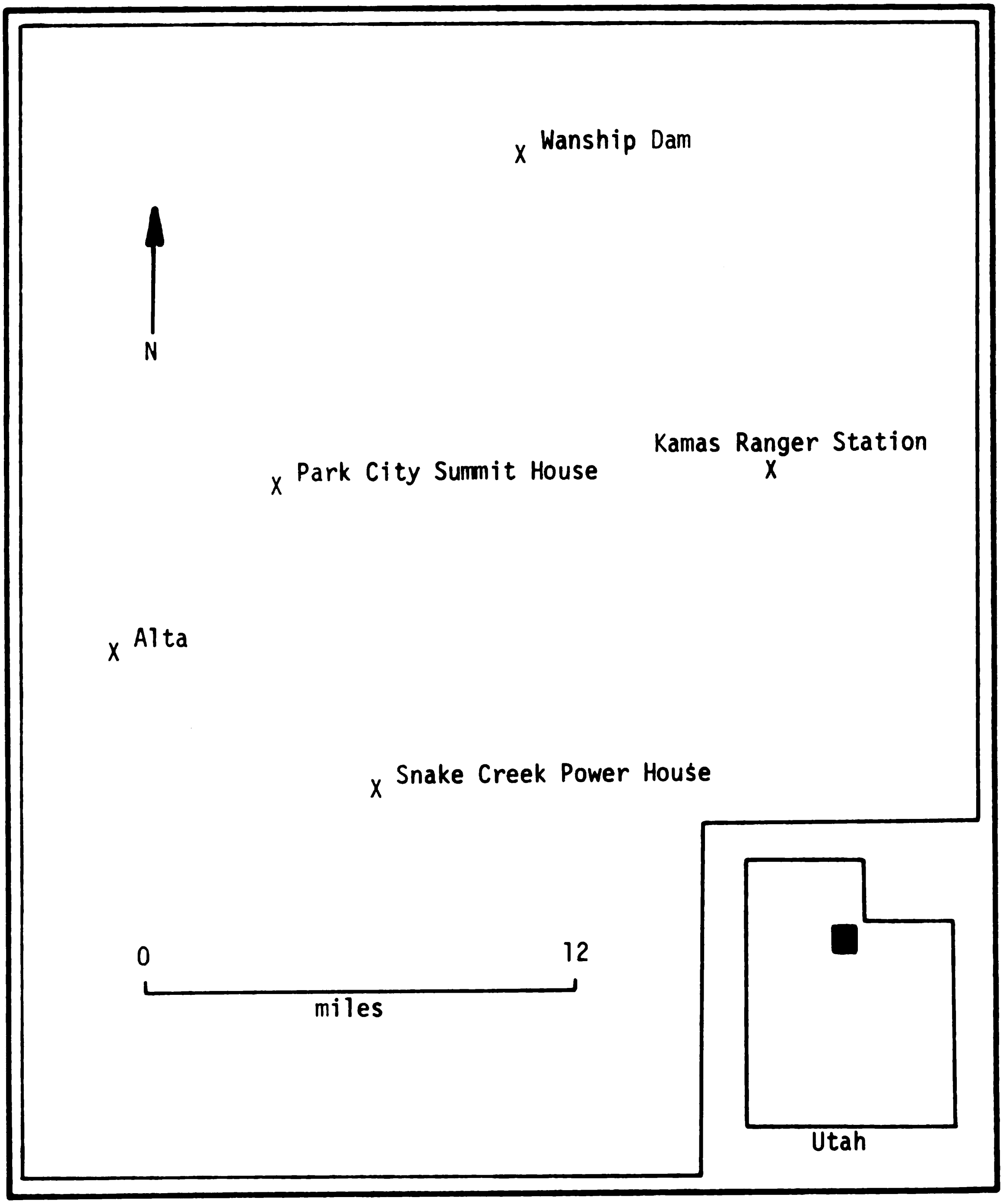

Figure 1: Study area.

the poleward extension of the wave.[1] Since cold air is more dense than warm air, the troughs are characterized by lower pressure heights than are the ridges, so that pressure heights are useful in determining wave positions.

Upper level divergence and consequent upward vertical motions occur east of the trough axes while west of the trough axes upper level convergence and downward vertical motions exist (Palmen & Newton, 1969) (Figure 2). As short waves migrate to the east, surface stations are alternately influenced by upward and then downward vertical motions occurring east and west of the trough axes, respectively. The direction of these vertical motions may be inferred from the 500 mb. wind flow as southerly flow is characteristic of the eastern portion of the troughs while northerly flow is associated with their subsident western part. Also, the magnitude of these vertical motions is partially dependent on the baroclinity of the basic current (Palmen & Newton, 1969), thus, increased upper level wind speeds are associated with increased vertical motions. Since Curtis and Panofsky (1958) conclude that large-scale vertical motions are an important predictor of precipitation it is apparent that the vertical motions associated with the passage of upper level waves are responsible for much of our weather.

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[1] These relationships apply to the northern hemisphere.

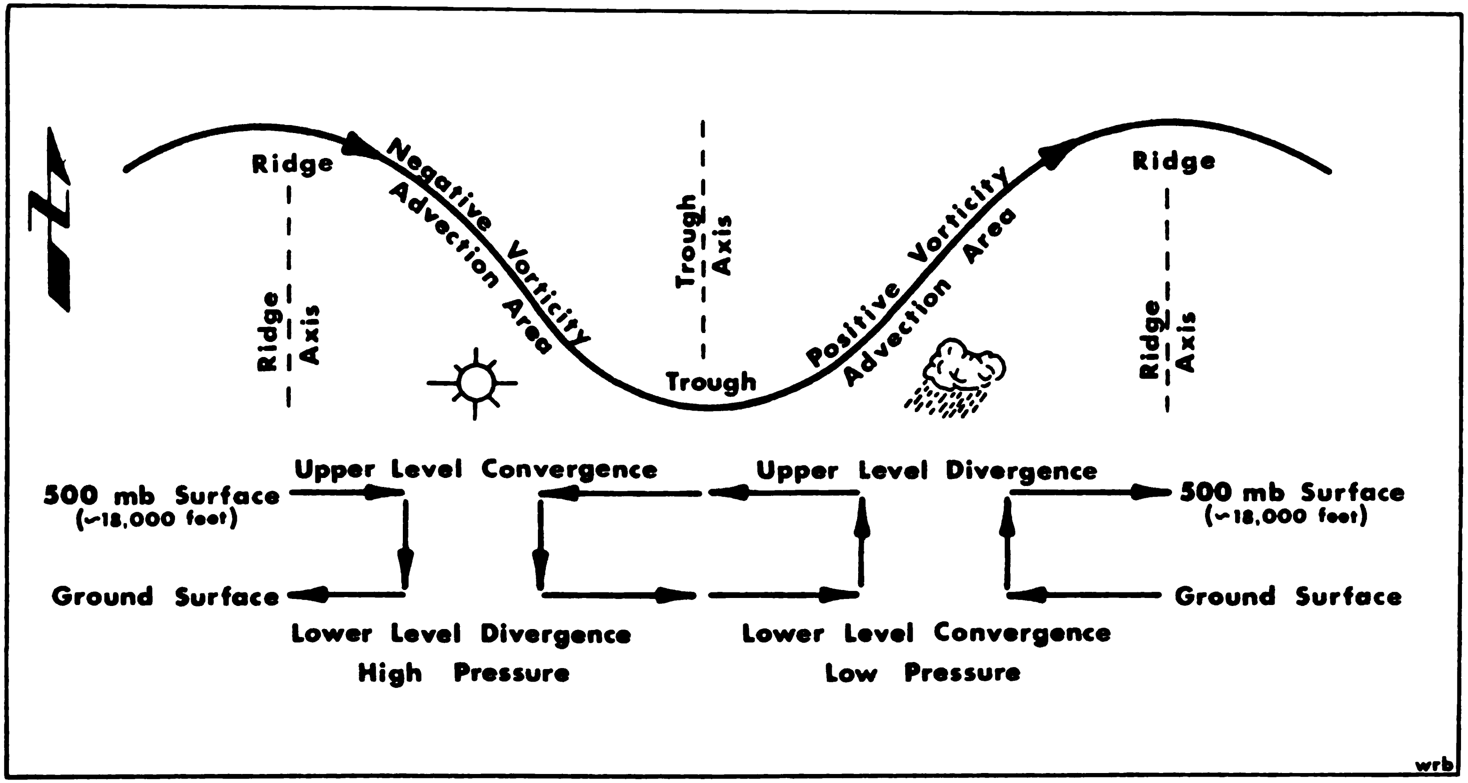

Figure 2: A schematic diagram of a tropospheric wave and associated vertical atmospheric motion (from Buckler, 1973).

Atmospheric Stability

Air which is conditionally or convectively unstable may, depending on its humidity, become unstable and undergo convection if forced to rise (Normand, 1938). Mechanisms by which this instability may be released include orographic effects (Barry & Chorley, 1970), dynamic effects associated with the jet stream (Beebe & Bates, 1955), and valley winds resulting from solar heating of mountain peaks (Flohn, 1969). Since conditionally or convectively unstable air is common in temperate latitudes in the summer (Normand, 1938), the degree of instability in the atmosphere is an important factor in summer precipitation in temperate latitudes.

Humidity

Humidity refers to the water vapor in the atmosphere and may be expressed in several ways; relative humidity, the percent saturation of the air (Strahler, 1969), is one of these. The percent saturation may be increased through cooling resulting from orographic or convective lifting; with a given ascent of air, the higher the initial relative humidity the lower the lifting condensation level. Thus relative humidity may indicate the height at which clouds may form, although it is not a measure of precipitable water. Also, relative humidity appears to be highly correlated with both daytime convective precipitation (Curtis & Panofsky, 1958) and general air mass showers (Chalker, 1949).

HYPOTHESES

Movement of air over mountain regions results in upward vertical motions in the lower troposphere (Sawyer, 1956). Because the Wasatch Range presents an abrupt front perpendicular to the prevailing winds, it should particularly enhance these motions. Since this process may not be sufficient to initiate precipitation during summer, it is assumed that the additional upward vertical motions associated with approaching 500 mb. short wave troughs in many cases will assist in initiating precipitation. It is also assumed that increased 500 mb. wind speeds, because of their relation to vertical motions, will likewise assist in the initiation of precipitation. Thus, it is hypothesized that measures which indicate the approach of 500 mb. short wave troughs and the presence of faster winds at that level will exhibit a relatively high positive correlation with the areal distribution of precipitation in the study area.

Although vertical motions are an essential component of weather, humidity and stability of the lower troposphere are important variables also. Other factors being equal, the more humid or unstable the air the higher the likelihood of precipitation. It is hypothesized, therefore, that inclusion of humidity and stability measurements will result in a substantially higher positive correlation with observed precipitation than do 500 mb. data alone.

DATA SOURCES

Atmospheric data were obtained from soundings at Salt Lake City, Utah, which were transmitted on 500 mb. (1200 Zulu) and surface (1200 Zulu) facsimile charts prepared by the National Meteorological Center. Maps of the Daily Weather Map series (7:00 AM) were utilized to obtain occasionally missing data. Rainfall statistics were obtained from Climatological Data.

DATA ANALYSIS

Stepwise multiple correlation and regression analysis was employed to determine the relationships between the variables. This program yields not only the multiple correlation coefficient but also the significance added by the successive inclusion of each independent variable into the regression equation.

VARIABLES

Wind Direction

The azimuths of daily 500 mb. wind directions at Salt Lake City were used as a general measure of vertical motions (Figure 3). Northerly flow was assigned the lowest value while southerly flow was given higher rankings. Easterly flow was ranked highest because inspection of the facsimile charts revealed occasional recumbent troughs whose axes usually exhibited a northwest-southeast orientation. Days with no wind (due to a 500 mb. ridge over the study area) were assigned a value of zero.

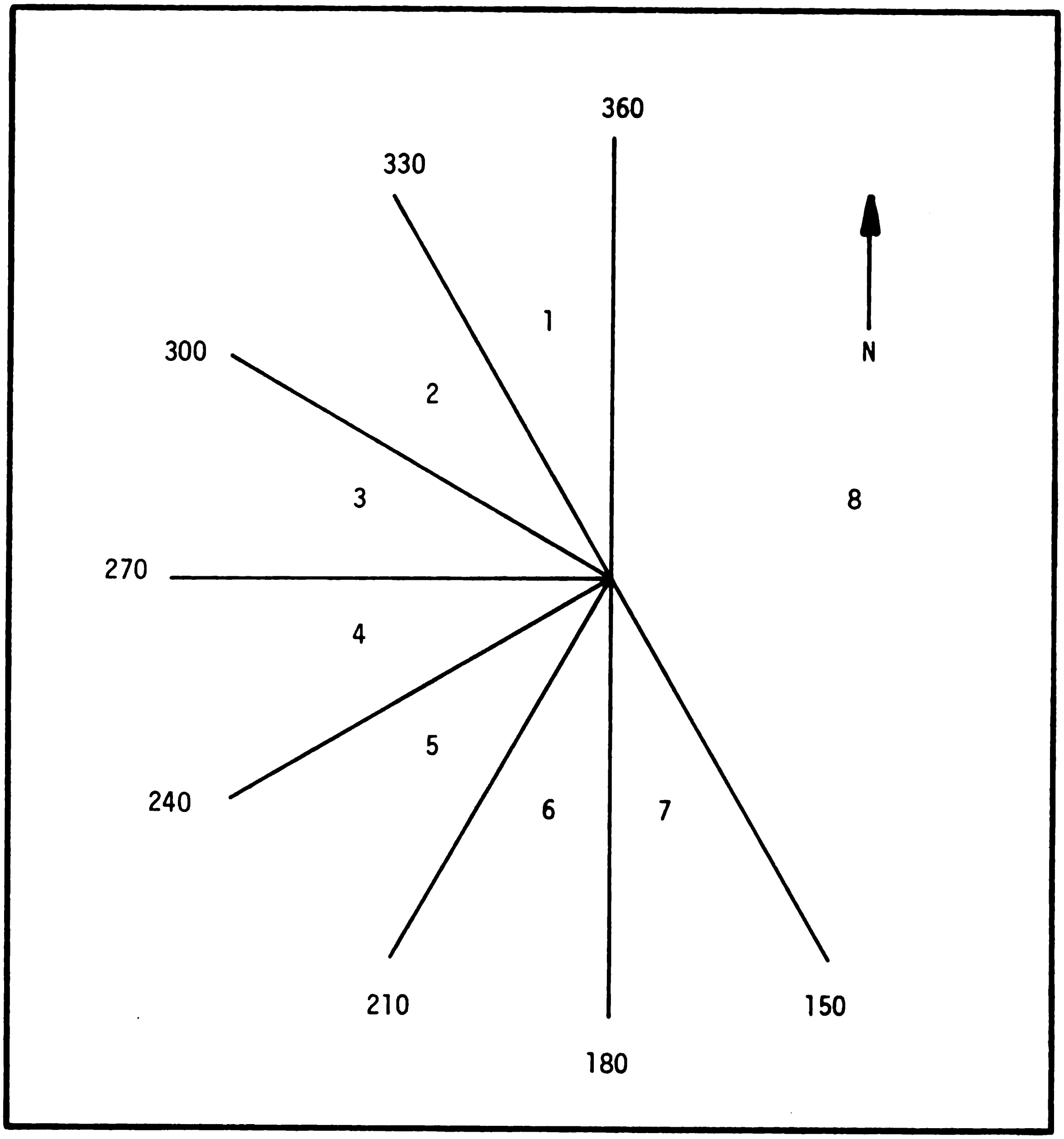

Figure 3: Index of vertical motions as indicated by 500mb. wind direction.

Pressure Heights

Height of the 500 mb. surface at Salt Lake City was recorded for each day. High pressure heights indicate ridge conditions and low heights trough conditions.

Wind Speed

Velocity of the 500 mb. wind at Salt Lake City was used to indicate the intensity of vertical motions associated with migrating tropospheric waves. Low wind velocities occurred when the jet stream was either not well developed or not positioned over the study area.

Relative Humidity

Relative humidity (R.H.) may be computed by dividing the mixing ratio (r) by the saturated mixing ratio (r_s); thus R.H. = $\frac{r}{r_s}$ (Cole, 1970). Through use of a pseudo-adiabatic diagram, the mixing and saturated mixing ratios were determined from the surface dew point and surface temperature, respectively, and the relative humidity calculated.

Atmospheric Stability

Through the use of a pseudo-adiabatic diagram, the surface air at Salt Lake City was lifted dry adiabatically until saturated and then wet adiabatically to the 700 mb. level. The temperature of the environment at 700 mb. was then subtracted from the temperature determined by adiabatic ascent and the result used as an index of atmospheric stability.[2] The higher the index the greater the potential instability of the air.

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[2] This method is similar to that of Elliot and Shaffer (1962).

Rainfall

Five stations were utilized in this study and although all had an elevation of 5,900 feet or more, most were located in valleys (Table 1). Areal extent of rainfall was determined by calculating the percentage of stations reporting .01 inches or more precipitation for each day.

RESULTS

It was hypothesized that approaching 500 mb. short wave troughs (as indicated by 500 mb. wind direction and pressure height) and higher 500 mb. wind speeds would be statistically related to the areal extent of precipitation in the study area. Examination of the simple correlations between these variables and rainfall (Table 2) reveals low values and indicates that, by themselves, none of the measures are a good indicator of precipitation in the study area. Results of stepwise multiple correlation and regression (Table 3) show an R^2 of .18 which indicates that only 18 percent of the variance in rainfall is "explained" by the 500 mb. indices.

In terms of each variable, 500 mb. wind direction was most highly correlated with precipitation (.06) and was entered into the regression equation first. Next was 500 mb. pressure height and then wind speed, with pressure height adding .04 and wind speed .078 to the "explanation." Both pressure height and wind speed were negatively, but weakly, correlated with precipitation in the final regression equation and indicate not only that higher pressure heights but also increased 500 mb. wind speeds were associated with lessened

Table 1: Rainfall recording stations.

Name	Elevation	Location	County	Type of Site
Alta	8,760 feet	40° 36' N. 111° 38' W.	Salt Lake	Valley
Kamas Ranger Station	6,495 feet	40° 39' N. 111° 17' W.	Summit	Valley
Park City Summit House	9,270 feet	40° 38' N. 111° 32' W.	Summit	Peak
Snake Creek Power House	5,950 feet	40° 33' N. 111° 30' W.	Wasatch	Valley
Wanship Dam	5,900 feet	40° 48' N. 111° 24' W.	Summit	Valley

Table 2: Simple correlations between 500 mb. variables and rainfall.

	Rainfall	Wind Direction	Wind Speed	Pressure Height
Rainfall	1.00000	.24684	-.07062	-.23326
Wind Direction	.24684	1.00000	.21013	-.13986
Wind Speed	-.07062	.21013	1.00000	-.55697
Pressure Height	-.23326	-.55697	-.55697	1.00000

Table 3: Results of stepwise multiple correlation.

Variable Entered	Proportion Reduced	Cumulative Proportion Reduced
Wind Direction	.061	.061
Pressure Height	.040	.101
Wind Speed	.078	.180

precipitation. The relationship between 500 mb. wind speed and precipitation is the opposite of that hypothesized.

It was also hypothesized that inclusion of lower tropospheric parameters (relative humidity and atmospheric stability) into the regression equation would substantially increase the "explanation" of precipitation. A program was thus run which included both 500 mb. and lower tropospheric parameters. Lower tropospheric parameters exhibited a much higher correlation with precipitation than did any of the 500 mb. measures (Table 4). The significance added and the order of entry of each variable in the regression equation is as follows: atmospheric stability .419, relative humidity .058, 500 mb. pressure height .031, 500 mb. wind direction .011, and 500 mb. wind speed .011. As is shown, the stability index is the most significance indicator of precipitation.

The multiple correlation coefficient for this second program (R^2 = .53) exhibited a significant increase in the "explanation" of precipitation over that indicated by 500 mb. data alone and in this regard confirmed the hypothesis. However, because the 500 mb. data were such a poor indicator of precipitation the multiple correlation coefficient was not as high as initially anticipated. As was the case in the first regression analysis, 500 mb. wind speed was negatively, but not strongly, correlated with precipitation and as such was opposite to the relationship hypothesized.

Because of the lower than expected multiple correlation coefficients, several additional programs were run in an attempt to evaluate alternative measures of some variables. Modifications from the original program included the use of surface dew point as a measure of atmospheric moisture, restriction of the study to only those days

Table 4: Simple correlations between all variables and rainfall.

	Rainfall	Wind Direction	Wind Speed	Pressure Height	Relative Humidity	Stability
Rainfall	1.00000	.24684	-.07062	-.23326	.49359	.64601
Wind Direction	.24684	1.00000	.21013	-.13986	-.10804	.26764
Wind Speed	-.07062	.21013	1.00000	-.55697	-.10704	-.14749
Pressure Height	-.23326	-.13986	-.55697	1.00000	-.22231	-.00456
Relative Humidity	.49359	-.10804	-.10704	-.22231	1.00000	.42777
Stability	.64601	.26764	-.14749	-.00456	.42777	1.00000

with rain, and restriction of the study to days in which the stability index was at or above its mean value. This last modification was run twice, first with 500 mb. variables and then with all variables included. Only the program utilizing 500 mb. data associated with a high stability index exhibited a multiple correlation coefficient higher than the comparable program using the original measures. The increase was negligible, however, as R^2 was raised only from .18 to .21.

Since precipitation can be measured in terms of its amount as well as its areal extent, several of the above programs were again run with the total amount of precipitation at all stations for each day as the dependent variable. None of these programs exhibited an "explanation" higher than the comparable program using areal extent of precipitation.

DISCUSSION OF RESULTS

The low multiple correlation coefficients do not support the initial hypothesis relating summer precipitation in the study area to parameters associated with 500 mb. dynamics. Visual inspection of the facsimile charts on days with high residuals, however, reveals that one or two of the measured variables often account for the observed precipitation. The relative difference between the variables rather than their absolute magnitude may be most important then, although this distinction would escape detection by regression analysis.

In addition, three other factors might account for the low correlations. First, multiple correlation and regression analysis assumes normally distributed data and independent variables

(Blalock, 1972), and neither of these assumptions was strictly met. Second, the data may not be valid, i.e., they did not sample the intended variable.[3] For example, 500 mb. wind direction was intended as a surrogate measure of vertical motions associated with short wave troughs. However, since different troughs migrate at different rates and because wind direction was sampled in the morning only, the measure may not represent the entire day. Also, the selected mountain stations may not be a representative sample of the study area. If the data are not valid, the hypotheses may be acceptable even though correlations are low. Third, factors other than those measured may exist which when incorporated into the analysis would significantly increase the "explanation" of variance of precipitation in the study area. These might include measurements of vorticity, insolation, or surface windflow. I believe that some, or all, of these reasons partially account for the low multiple correlation coefficients obtained in this study and, therefore, do not reject that portion of the initial hypothesis relating precipitation to approaching short wave troughs.

As stated earlier, the weak negative correlations between 500 mb. wind speed and precipitation were opposite to the relationship hypothesized. Yeh, Carson and Marciano (1951) similarly reported a negative correlation beween summer precipitation in Hawaii and the position of the jet stream at 700 mb. They attributed periods of lower precipitation to subsiding motions south of the jet stream axis.

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[3] Alternative measures of some variables (atmospheric moisture and precipitation) were examined but all produced lower multiple correlation coefficients than programs using the original parameters.

Unfortunately, the present study did not consider jet stream position but a cursory inspection of 500 mb. charts for days with high residuals revealed no apparent relationships betweeen jet stream position and precipitation. Possibly the morning measurements of 500 mb. wind speed were not representative of the entire day and resulted in weak correlations with afternoon weather.

The second hypothesis, that inclusion of lower tropospheric parameters should substantially increase the correlation with precipitation, is accepted. Thus, surface and lower tropospheric conditions, especially stability of the lower atmosphere, appear to be important determiners of weather in the study area during summer.

CONCLUSIONS

Based on this study the following conclusions appear appropriate.

1. Measures intended to indicate vertical motions associated with 500 mb. short wave troughs (i.e., 500 mb. wind direction, wind speed and pressure height) exhibited a low correlation with summer precipitation in the study area.
2. Lower tropospheric parameters accounted for more of the variance in rainfall than did the 500 mb. measures.
3. The measure of atmospheric stability was the most significant variable correlated with observed precipitation.
4. Wind speed at the 500 mb. level was negatively, but not strongly, correlated with precipitation.

SUGGESTIONS FOR FURTHER STUDY

Because of the low correlations alternative measures and methods of investigation should be examined. Utilization of different variables to indicate vertical motions associated with 500 mb. flow, such as vorticity values, use of more than one observation time per day, or investigation of only those days exhibiting some particular atmospheric situation, for example diffluent flow aloft, are possible alternatives. Although none of these measures or methods were employed in this study they may represent useful lines of inquiry.

LIST OF REFERENCES

Barry, R. G. and R. J. Chorley. 1970. Atmosphere, Weather, and Climate. Holt, Rinehart and Winston, Inc. New York, 320 pp.

Beebe, R. G. and F. C. Bates. 1955. A mechanism for assisting in the release of convective instability. Monthly Weather Review, 83(1): 1-10.

Blalock, H. M., Jr. 1972. Social Statistics. McGraw-Hill Book Company. New York, 583 pp.

Buckler, W. R. 1973. Variations in water level and precipitation in the Lake Michigan basin. Unpublished Masters thesis, Michigan State University.

Chalker, W. R. 1949. Vertical stability in regions of air mass showers. Bulletin of the American Meteorological Society, 30(4): 145-147.

Cole, F. W. 1970. Introduction to Meteorology. John Wiley and Sons, Inc. New York, 388 pp.

Curtis, R. C. and H. A. Panofsky. 1958. The relation between large-scale vertical motion and weather in summer. Bulletin of the American Meteorological Society, 39(10): 521-531.

Elliot, R. D. and R. W. Shaffer. 1962. The development of quantitative relationships between orographic precipitation and air-mass parameters for use in forecasting and cloud seeding evaluation. Journal of Applied Meteorology, 1: 218-228.

Flohn H. 1969. Local wind systems, 139-171. In H. E. Landesberg (editor in chief), World Survey of Climatology, volume two, General Climatology. Elsevier Publishing Co. New York.

Harman, J. R. 1971. Tropospheric waves, jet streams and United States weather patterns. Association of American Geographers, Commission on College Geography, Resource Paper No. 11. Washington, D. C., 37 pp.

Normand, C. W. B. 1938. On instability from water vapor. Quarterly Journal of the Royal Meteorological Society, 64: 47-69.

Palmen, E. and C. W. Newton. 1969. Atmospheric Circulation Systems: Their Structure and Physical Properties. Academic Press. New York, 603 pp.

Sawyer, J. S. 1956. The physical and dynamical problems of orographic rain. Weather, 11: 375-381.

Strahler, A. N. 1969. Physical Geography. John Wiley and Sons, Inc. New York, 733 pp.

Thornbury, W. D. 1965. Regional Geomorphology of the United States. John Wiley and Sons, Inc. New York, 609 pp.

Williams, P., Jr. and E. L. Peck. 1962. Terrain influences on precipitation in the intermountain west as related to synoptic situations. Journal of Applied Meteorology, 1: 343-347.

Yeh, T., J. E. Carson and J. J. Marciano. 1951. On the relation between the circumpolar westerly current and rainfall over the Hawaiian Islands. Meteorological Monographs, 1(3): 47-55.

U. S., Department of Commerce. National Oceanic and Atmospheric Administration. Climatological Data. Washington, D. C.: Government Printing Office, 1973.

U. S., Department of Commerce. National Oceanic and Atmospheric Administration. Daily Weather Maps, weekly series. Washington, D. C.: Government Printing Office, 1973.