Order Number 9224009

Quaternary stratigraphy near Cincinnati, Ohio, and its significance for paleoclimate reconstruction

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QUATERNARY STRATIGRAPHY NEAR CINCINNATI, OHIO, AND ITS SIGNIFICANCE FOR PALEOCLIMATE RECONSTRUCTION

A Dissertation submitted to the

Division of Graduate Studies and Research
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in the Department of Geology
of the College of Arts and Sciences

1992

by

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B.S., Purdue University, 1983
M.S., University of Cincinnati, 1986

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UNIVERSITY OF CINCINNATI

28 January 19 92

I hereby recommend that the thesis prepared under my supervision by Kevin M. Savage

entitled Quaternary Stratigraphy near Cincinnati, Ohio, and its Significance for Paleoclimate Reconstruction

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

Thomas V. Lowell

David B. Nash

M. Brookins

Ice is a plastic art.
No other object more fully
challenges the theory
and practice of esthetics.

Stephen J. Pyne
The Ice (1986)

ABSTRACT

Rare occurences of coeval late Wisconsin glacigenic diamictons and ice-proximal sediments with a diverse faunal assemblage provided an opportunity to test the viability of the glacigenic sediments as proxy paleoclimate indicators.

Physical characteristics and stratigraphic relationships of glacigenic diamictons in southwestern Ohio permit interpretation of ice-marginal glacier dynamics beginning about 19,700 years ago. At sites covered by the late Wisconsin glacier, pre-late Wisconsin (PLW) sediments are overlain by several lithofacies of late Wisconsin diamicton. Sedimentary and deformational structures associated with the diamictons indicate the following sequence: 1) active ice flow over a freezing bed, with entrainment of the PLW sediments, 2) formation of deformation till, and deformation of the underlying substrate beneath basally-melting, active ice, 3) deposition of basal meltout till, and related sediment flow in association with melting, inactive ice, 4) renewed ice flow over a frozen bed, with "thrusting" of megablocks of sediment, and 5) megablock deposition by melting of inactive ice.

Using glaciologic and geologic constraints, basal ice temperatures and ice thicknesses were interpreted for each interval. Estimation of basal shear stress and sliding velocity, and ablation rate allowed estimates of heat flux within the glacier system to be made. Heat fluxes combined with basal temperature and ice thickness estimates allowed ice surface temperatures to be calculated; these calculated temperatures range from a minimum of -14 to -19.5°C during interval 2 to a maximum of >0°C during final stagnation and melting of the glacier.

Sensitivity analyses indicate that the heat flux due to basal sliding is dominant. These analyses also revealed that varying basal shear stress and basal sliding velocity, which control basal sliding heat flux, over a range of glaciologically "reasonable" values results in ice surface temperatures which vary by only 10-12°C.

The estimated ice surface temperatures are in good agreement with temperatures estimated from the local late Wisconsin fauna, as well as with regional temperature estimates based on periglacial geologic, and biota data. The results of this research suggest that the estimation of ice surface temperatures from geologic observations and glaciology theory is a promising technique which should be further explored.

ACKNOWLEDGEMENTS

I would like to express my gratitude and appreciation to my advising committee, Tom Lowell, Dave Nash, Madeleine Briskin, and George Kukla (Lamont-Doherty Geological Observatory) for their interest, advice, and for swift kicks in appropriate places to complete this endeavor. My thanks to Tom for many things, but most importantly for showing me what it takes to be an excellent field geologist, and the importance of personal time management. My thanks to Dave for his constant encouragement, for allowing me to invade his lab space for three years, and for access to his classical music collection. My thanks to Madeleine for showing me the importance of "big-picture" thinking and the global perspective, for some of the most exciting courses, and for Chinese lunches on a semi-regular basis. My thanks to George for tolerating a student who communicaion skills were not always the greatest.

I thank the Geology Department and College of Arts and Sciences for providing financial support and facilities to conduct this research. Thanks also to the Center Hill Research Facility and U.S.E.P.A. for providing support for completion of this document. To many friends at both the Geology Department and Center Hill Facility, I express my thanks for sharing my highs, tolerating my lows, and always providing support. Special thanks to my fellow "Quaternary" students Andrine, Mike, and Rose for sharing ideas, concerns, worries, and dessert at lunch on Wednesdays. To Rich and Sharon, all I can say is thanks for everything. I thank Scott Brockman (Ohio Dept. Natural Resources) for his interest and encouragement of this research, as well as for sharing field notes, slides, and maps; thanks to Ned Bleuer (Indiana Geological Survey) for his support and encouragement throughout this work.

My deepest and most heart-felt thanks go to my wife Becky, my children Nicole and Jacob, my parents Bill and Rafi Savage, and my in-laws Bob and Dotty Bridges for their love, understanding, sacrifices, and support over the past five years.

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CHAPTER 1. INTRODUCTION

INTRODUCTION

Sediments associated with glaciers have been intensively studied in recent years as geologic proxy records of paleoclimatic change. Requirements for completeness of these studies are 1) a proxy record of climate, such as biota with known, and somewhat restricted, paleoclimate ranges, and 2) chronologic control. In many previous studies, proxy climate records have been available, but without the chronologic control. In other cases, material was available for radiometric dating, but detailed proxy paleoclimate indicators were absent. This is the case with most glacial sedimentary sequences; reliable paleoclimate indicators, such as pollen, are not usually present.

A recent study of glacial sediments by Shaw (1987) utilized descriptions of the sedimentologic and structural characteristics of the sediments to interpret glacier conditions. He demonstrated how physical characteristics within the glacigenic sediments could provide specific clues about the glacier and environmental conditions necessary for their formation. However, the climate-related conditions of glaciation can only be interpreted in qualitative terms such as frozen-based, freezing-based, or melting-based ice.

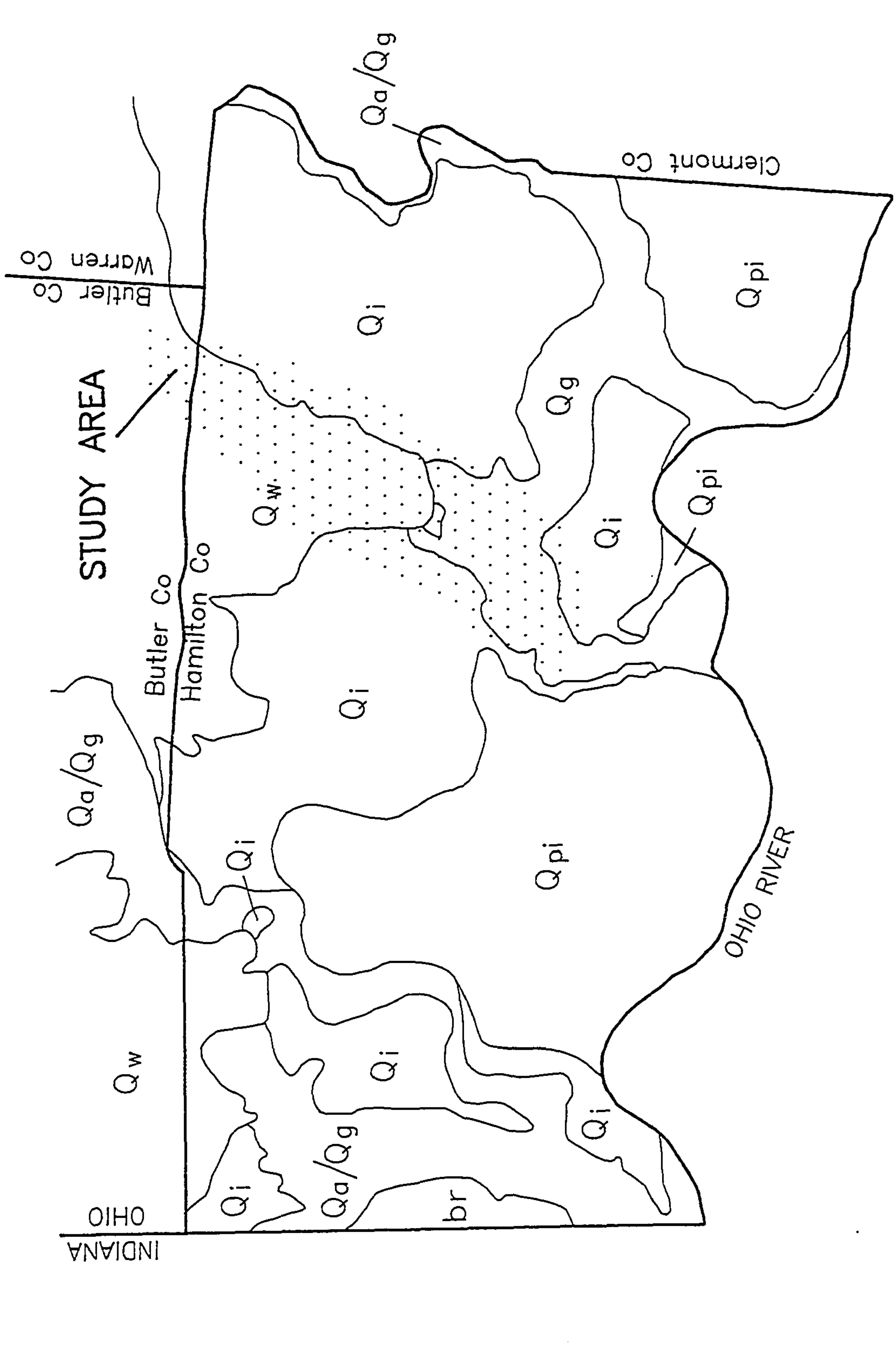
An area which contained detailed proxy paleoclimate data from biota within a tight chronologic and stratigraphic framework, and glacial sediments from the same time interval would provide a unique setting for further testing the usefulness of the sediments themselves as proxy paleoclimate indicators. Unfortunately, few of these comparative studies have been completed.

REGIONAL SIGNIFICANCE OF STUDY LOCALITY

The Mill Creek Valley in Hamilton and southern Butler counties, southwestern Ohio, is located at the southern limit of Laurentide glaciation, as well as the southern limits of both Illinoian and pre- Illinoian glaciation (Fig. 1-1). Within a 20 km north-south transect are sites with sediments of various ages that represent ice-proximal, ice-marginal, and subglacial deposition. Of greatest interest from a paleoclimate perspective are the sediments associated with the last glacier to impact the Cincinnati area, the late Wisconsin Laurentide ice sheet. The ice-proximal sediments of this age contain an extensive peat horizon with a variety of associated floral and faunal records. These materials provide both an extremely detailed paleoclimate signature and tight chronologic control. Associated with the ice-marginal and subglacial sites are temporally-equivalent

Fig. 1-1. Generalized surficial geology of Hamilton and southern Butler Counties. Modified from (Gray *et al.*, 1972). Study area shown with stipple pattern.

Qa - alluvium
Qg - valley-train deposits and outwash
Qw - late Wisconsin ground and end moraine
Qi - Illinoian ground moraine
Qpi - pre-Illinoian ground moraine


STUDY AREA
Butler Co
Hamilton Co
Butler Co
Warren Co
Clermont Co
OHIO
INDIANA
OHIO RIVER
Qa/Qg
Qa/Qg
Qa/Qg
Qi
Qi
Qi
Qi
Qi
Qi
Qi
Qpi
Qpi
Qpi
Qg
Qw
Qw
br

glacigenic sediments which reflect the nature of the glacier, and abundant *in situ* and transported datable organic materials which provide the chronologic control necessary to compare and contrast these sites to the ice-proximal site. It is therefore possible to use the biota-derived paleoclimate signature during late Wisconsin glaciation as a baseline to test the usefulnessness of detailed sedimentologic and structural analysis of glacial sediments for determination of paleoclimate.

REGIONAL QUATERNARY GEOLOGY

Southwestern Ohio lies near the southernmost limit of pre- Illinoian, Illinoian, and late Wisconsin age glaciations (Durrell *et al.*, 1961; Teller, 1970; Goldthwait *et al.*, 1981). Drift attributed to these three glaciations has been mapped in Hamilton County (Goldthwait *et al.*, 1961a; Brockman, 1989). Gooding (1963, 1975) developed a stratigraphic classification for southeastern Indiana and southwestern Ohio; this classification consisted of two Illinoian and seven Wisconsin tills (Table 1-1). Of the Wisconsin tills, four were interpreted to be of late Wisconsin age (younger than about 21,000 years before present (B.P.)). Two of these, the Fayette and Shelbyville tills were interpreted to represent near-maximum (Fayette) and maximum (Shelbyville) advances of late Wisconsin ice. The younger units, the Crawfordsville and Knightstown tills, represent minor readvances during the overall retreat of the late Wisconsin glacier. The southernmost limits of the Crawfordsville and Knightstown tills are 40 to 50 km north of this study area.

Preglacial ("Teays-age") paleodrainage patterns in southwestern Ohio and northern Kentucky were substantially altered by pre-Illinoian and Illinoian glaciation; these changes, still the subject of much debate, are discussed at length elsewhere (e.g., Teller, 1973; Ray, 1974, and references therein). Within the Mill Creek Valley, the location of this research, drainage was to the north from preglacial through pre-Illinoian time, and was quite extensive. Advance of Illinoian ice into the greater Cincinnati area dammed this major north- flowing system, and subsequent breeching of a drainage divide to the south resulted in a reversal of flow direction in this valley. This reversal was contemporaneous with establishment of "modern" Ohio River drainage (Teller, 1973; Ray, 1974). The present-day Mill Creek is a misfit stream (Teller, 1973) occupying a once-major river valley.

Gray *et al.* (1972) mapped glacigenic sediments of the Late Wisconsin Laurentide glacier extending as a tongue southward in to the Mill Creek Valley. The southernmost glacigenic sediments are located near the community of Hartwell; the moraine which is interpreted to mark this southernmost extent is called the Hartwell Moraine. This research was conducted at a number of sites both north and south of the Hartwell Moraine (Fig. 1-2).

TABLE 1-1. Representative stratigraphic sequence of Illinoian and Wisconsin glacial deposits in southwestern Ohio (after Gooding 1963, 1975).

Time-Stratigraphic Classification	Geologic-Climate Classification	Rock-Stratigraphic Classification
Late Wisconsin	Tazewell Stade	Knightstown Till Crawfordsville Till Shelbyville Till
	Connersville Interstade	Connersville organic silts
	Fayette Stade	Fayette Till
Middle Wisconsin	Sidney Interstade	Sidney paleosol and organic deposits
	Unnamed stade(s)	Unnamed till(s)
Early Wisconsin	New Paris Interstadial	New Paris Silt
	Whitewater Stadial	Whitewater Till
	Sanganmon Interstadial	Sangamon paleosol
Illinoian	Richmond Stade	Richmond Till
	Abington Interstadial	Abington Silt
	Centerville Stade	Centerville Till

STUDY OBJECTIVES

The principal objective of this research is to interpret paleoclimate from glacially-related sediments. This objective will be accomplished through the completion of six specific steps:

1) description of geologic units at sites with a variety of positions with respect to the late Wisconsin maximum ice margin,

2) radiocarbon age estimation of *in situ* and transported organic materials to establish chronostratigraphic control at as many sites as possible, and development of a chronostratigraphic sequence for the study area,

3) development of lithostratigraphic sequences at each study locality, and composite lithostratigraphic sequences for each region related to the late Wisconsin ice margin,

4) genetic interpretation of the lithostratigraphic units,

5) interpretation of environmental conditions necessary to produce lithostratigraphic sequence, and

6) interpretation of paleoclimate based on the summary of environmental

conditions.

A second objective will be to compare the geologically-derived paleoclimate signature with independently-developed biota-based paleoclimate signature.

The third objective is to develop a land-surface model for the study area; that is, identify stratigraphic sequences present in each unique geomorphic setting, and combine the stratigraphies to develop one composite stratigraphy for the central and northern portions of the Mill Creek Valley.

STUDY HYPOTHESIS

Statement. The fundamental hypothesis of this work is that identification of glacial environment and ice activity from field study of glacigenic sediments, combined with chronostratigraphy established through radiocarbon age estimation, will permit paleoclimatic interpretation from the sediments.

Implications. A previous biota-based paleoclimate interpretation from one of the ice-proximal sites (Lowell *et al.*, 1990b), provides an independent test of any sediment-based paleoclimate interpretation. If this testing of the stated hypothesis yields positive results (i.e., paleoclimate can be interpreted from the sediments), the method may be applicable in areas where biota traditionally used for paleoclimate interpretation are not available; sites not adjacent to ice margins, or long covered by ice are examples of such areas.

METHODS OF STUDY

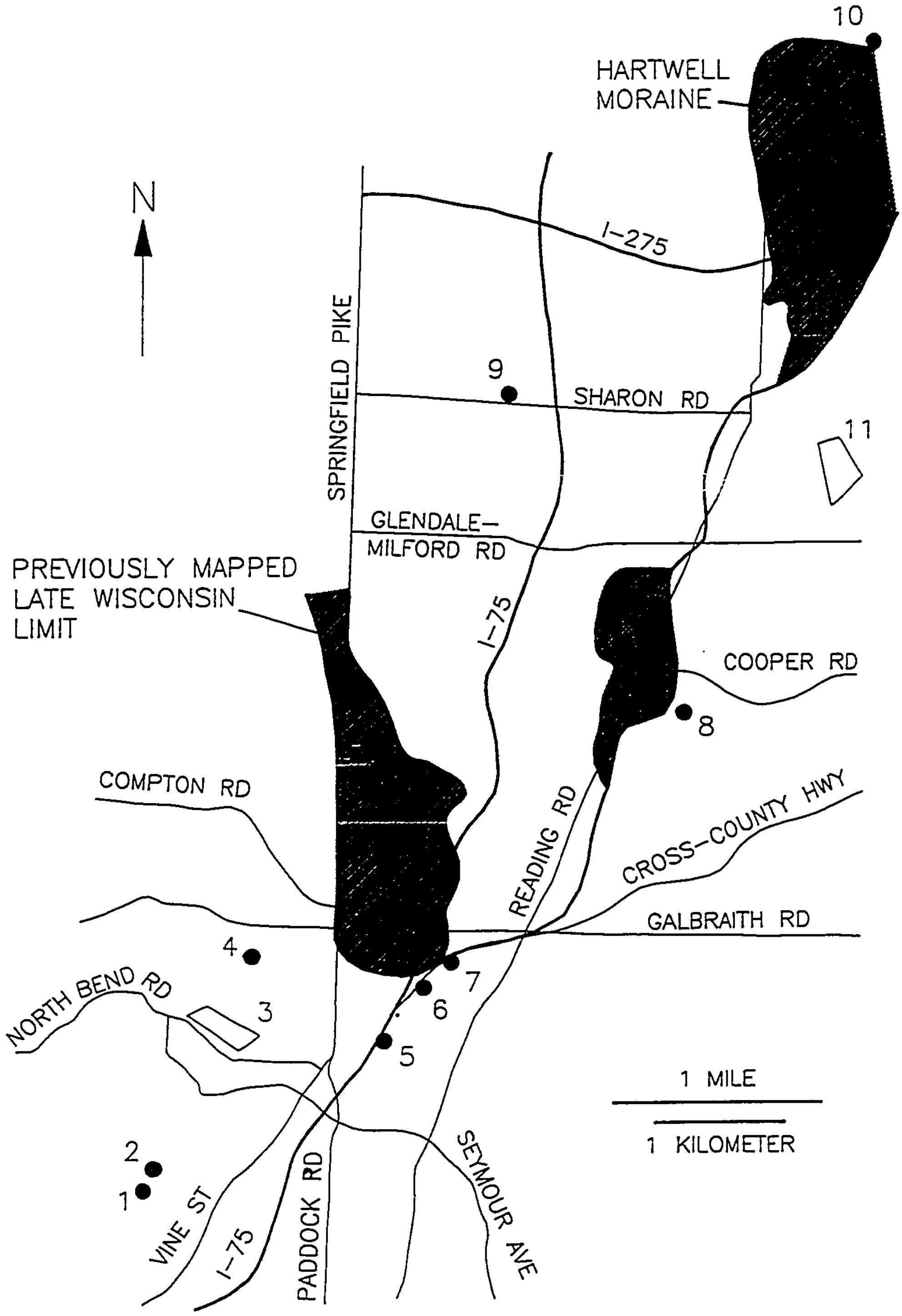
Standard field and laboratory techniques were used throughout the study. These techniques are briefly summarized below.

Field. At each site, the exposure was carefully cleaned with trowels, allowing structural and textural features (Table 1-2) to be recorded and mapped; stratigraphic relationships of the exposed units were recorded. Samples within each unit were collected for laboratory analysis. At the Rack Quarry, measured sections were related spatially by planetable mapping. Also at the Rack Quarry, a Bartington M.S. 2 magnetic susceptibility meter with a M.S.2.F. probe was used to collect susceptibility profiles through the peat and enclosing silty clays. At the Sharonville site, measured sections were related by surveying.

Laboratory. Laboratory analyses completed include grain size, clay mineralogy, and carbonate content. Additionally, lithologic and shape analyses were completed for

Fig. 1-2. Locations of studied sections with respect to the position of the late Wisconsin Hartwell Moraine (mapperd late Wisconsin limit). Modified from portions of the Cincinnati West, Cincinnati East, and Glendale 7.5' topographic quadrangle maps. Position of the Hartwell Moraine after Gray *et al.* (1972).

1. Rack Quarry (multiple sections)
2. ELDA Landfill (multiple sections)
3. Caldwell Park (multiple sections)
4. Satellite dish (KS-88-12)
5. Cross-County South (KS-88-13)
6. Cross-County Main
7. Cross-County North (KS-88-05)
8. Evendale Day Care Center (KS-87-04)
9. Glendale Watse Water Treatment Facility (KS-87-12)
10. Dimmick Road Reservoir (KS-89-06)
11. Sharonville (multiple sections)


N
HARTWELL MORAINE
10
I-275
SPRINGFIELD PIKE
9
SHARON RD
11
GLENDALE–MILFORD RD
PREVIOUSLY MAPPED LATE WISCONSIN LIMIT
I-75
COOPER RD
8
COMPTON RD
READING RD
CROSS-COUNTY HWY
GALBRAITH RD
4
NORTH BEND RD
3
7
6
5
1 MILE
1 KILOMETER
2
1
VINE ST
I-75
PADDOCK RD
SEYMOUR AVE

clast samples. Each of these techniques is summarized in Table 1-1.

DEFINITION OF GENETIC TERMS

Throughout subsequent chapters of this dissertation, genetic terms will be applied to glacigenic sediments (especially tills) wherever possible. The use of genetic terms in the interpretation of tills is an area open to much debate. Lawson (1981, 1982) and Dreimanis (1988) have discussed this matter in terms of sediment deposited by "primary" processes (sediment deposited by direct release from glacial ice with no subsequent disaggregation and resedimentation (Lawson, 1981, 1982)), and those deposited by the action of "secondary" processes, such as remobilization and subsequent flow. The importance of distinguishing between primary and secondary processes in the analysis of glacigenic sequences, and interpretation of depositional environment was emphasized by Lawson (1988). For this study, the term "till" is used only for those deposits which are believed to have been deposited by primary glacigenic processes.

Definitions of terms used in interpretations below are listed here:

> **lodgement till** - "...deposited by plastering of glacial debris from the sliding base of a moving glacier by pressure melting and/or other mechanical processes." (Dreimanis, 1988, p. 43);
>
> **deformation till** - "...weak rock or unconsolidated sediment that has been detached from its source, the primary sedimentary structures distorted or destroyed, and some foreign matter admixed..." (Elson, 1988, p. 85);
>
> **meltout till** - "...deposited by a slow release of glacial debris from ice that is not sliding or deforming internally..." (Dreimanis, 1988, p. 45).

For resedimented materials, which may be the result of several secondary processes (Lawson, 1979, 1981; Dreimanis 1988), the term **"sediment flow deposit"** is used to describe deposits resulting from those processes. These deposits, while not providing direct information on the glacier itself, may provide information on the local climate and hydrology, as well as other factors affecting the depositional processes (Lawson, 1988).

Additionally, in areas close to marginal moraines, solifluction may be widespread. This process may result in reactivation and movement of older sediments. Clast fabrics within diamictons may permit interpretation of flow; compositional variations may permit interpretation of the parent material of the flow. If the parent material may be determined to be older sediments, the term **"colluvium"** is used to describe them.

TABLE 1-2. SUMMARY OF METHODOLOGIES

FIELD	
Clast fabric	azimuth and plunge of 25 clasts in diamicton with a minimu a:b axial ratio of 2:1; fabric determined using the method of Mark (1973, 1974)
Wood orientation	azimuth and plunge of wood incorporated into diamicton; minimum a:b axial ratio of 5:1
Plane orientation	strike and dip of shear and fracture planes within diamicton
Magnetic susceptibility	five readings recorded at each interval; results plotted with mean and $\pm$ one standard deviation
LABORATORY	
Granulometry	sieve-pipette of Folk (1980); 0.004 and 0.063 mm used as clay-silt and silt-sand boundaries, respectively
Carbonate content	Chittick analysis of <0.063 mm fraction; modified from Dreimanis (1962)
Clay mineralogy	x-ray diffraction of untreated, glycolated, and heated (350^{o}, 550^{o}C) fraction of matrix
Clast lithology	100 clasts minimum with b-axis dimensions 16-64 mm; identified with binocular stereoscope
Clast shape	a, b, and c axis dimensions determined; axial ratios plotted on shape diagram of Zingg (1935); also noted were presenc or absence of striations and facets on each clast; roundness estimations based on Powers (1953)

DISSERTATION ORGANIZATION

Sites studied in this research lie in a generally north-south alignment, and encompass sediments of a number of ages, deposited by a variety of processes. These sites may all be categorized as having positions proximal to, marginal to, or beneath ice of the late Wisconsin Laurentide glacier. Chapters 2 through 5 present descriptions and interpretations in a south-to-north transect in the Mill Creek Valley: Chapter 2 contains the sites proximal to Laurentide ice, Chapter 3 contains the sites marginal to Laurentide ice, and Chapter 5 contains the sites covered Laurentide ice. Chapter 4 is comprised of subsurface data from the zone best-described as marginal to the late Wisconsin ice. Chapter 6 presents an integrated summary and discussion of the geology and the interpreted paleoclimate message.

SIGNIFICANT OUTSIDE CONTRIBUTIONS

Significant contributions to this research, requiring more than a listing in the acknowledgements section of this dissertation, were made by a number of individuals. These contributions are listed here to highlight their importance. Radiocarbon analyses were provided by Robert Stuckenrath (Radiocarbon Laboratory, University of Pittsburgh; "PITT"-dates), and Norton Miller (New York State Museum, Albany, NY; "Beta"-dates). Collection, processing, and analyses of biota within the sediments of interest provided an independent paleoclimate record for comparison with the geologic record. Individuals involved include Andrine M. Dell (University of Cincinnati; gastropods), Norton Miller (New York State Museum; pollen and mosses); Linda Shane (University of Minnesota; pollen); Alan Morgan and Jerry Pilny (University of Waterloo, Waterloo, Canada; beetles); and Greg McDonald (Cincinnati Museum of Natural History; vertebrate paleontology).

The geology and biota-based paleoclimate interpretation of the clay sequence portion of the Rack Quarry site (Chapter 2) have been presented in a multi-authored poster session (Lowell *et al.*, 1990b), and manuscript (Lowell *et al.*, in prep). The subsurface geology presented in Chapter 4 was, in part, presented in two poster sessions (Lowell and Savage, 1987; Savage and Lowell, 1988). The geology of the Sharonville site (Chapter 5) has been presented in a co-authored manuscript (Savage and Lowell, in press).

CHAPTER 2. SITES PROXIMAL TO LAURENTIDE ICE

INTRODUCTION

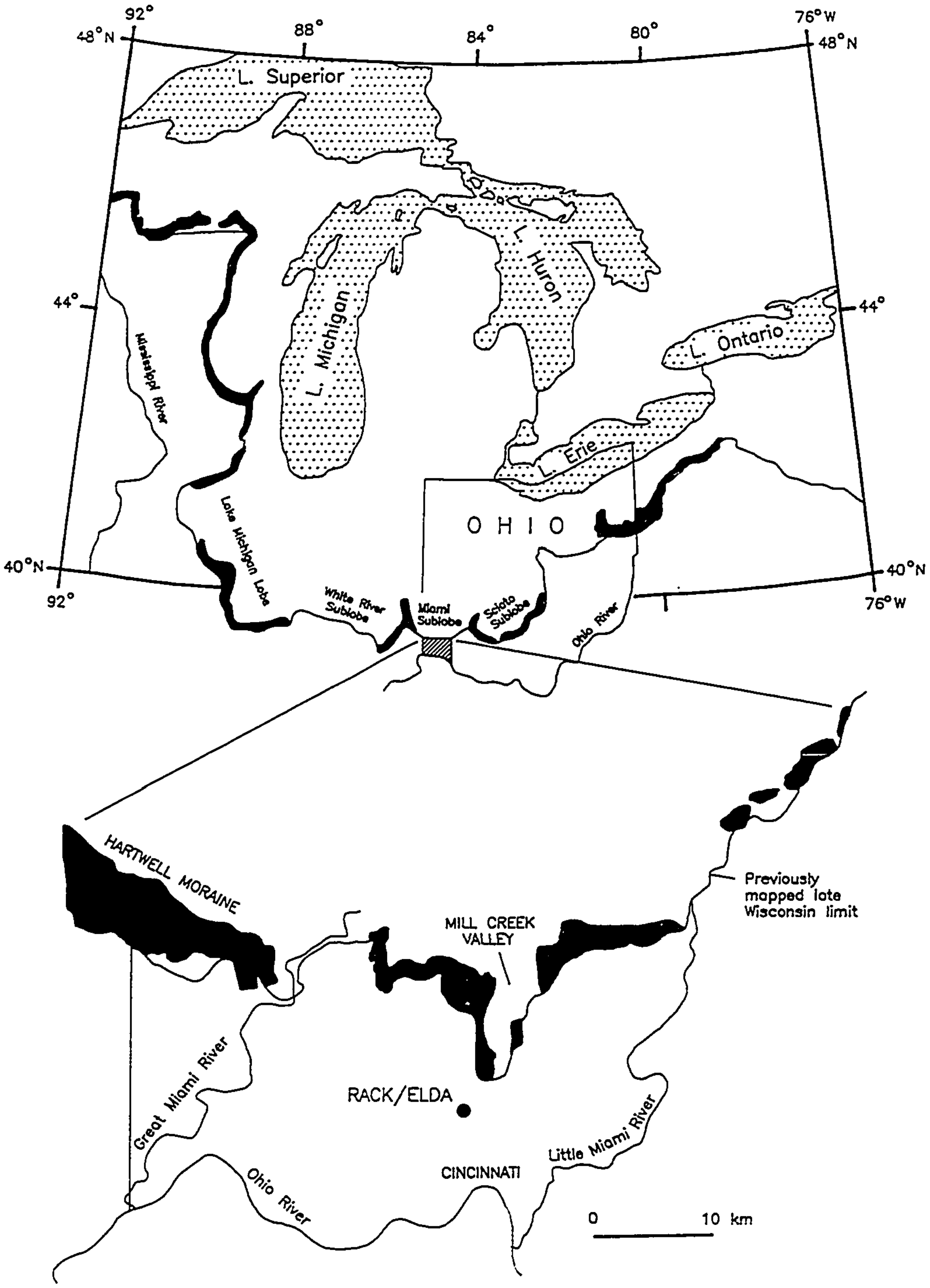
Sediments and biota remains of late Wisconsin age at midcontinent sites near, or proximal to, the late Wisconsin maximum ice margin provide clues to environments and climates present at that time. Unfortunately, these sites are extremely rare, with only three reported: Wolf Creek, in central Minnesota (Birks, 1976), Conklin Quarry, in southeastern Iowa (Baker *et al.*, 1986), and Wedron Silica Sand Company Pit 6 (Garry *et al.*, 1990), in Illinois. Pollen and plant macrofossils at the Wolf Creek site indicate the dominance of tundra conditions from about 20,000 to 14,000 B.P. (Birks, 1976). The Conklin Quarry site contains a diverse faunal assemblage, including pollen, bryophytes (mosses), vascular-plant macrofossils, mammals, molluscs, and insects, which suggest tundra-like conditions from about 18,090 to 16,710 B.P. (Baker *et al.*, 1986). The Wedron pit includes well-preserved pollen, plant macrofossils, and insect remains associated with slackwater gravels, sands, and silts; wood in an organic horizon yielded a radiocarbon age of 21,460±470 yr B.P. (ISGS-1486). The fauna were interpreted to reflect climatic deterioration associated with advancing continental glaciation (Garry *et al.*, 1990).

A fourth late Wisconsin-age site, containing organic remains deposited proximal to the ice margin, located near downtown Cincinnati is reported here. Only the geology and paleoenvironmental interpretations based on sedimentologic and geomorphic constraints are reported here. Other workers analyzed the abundant biota remains from the site. These analyses, summarized at the end of this chapter, provide a check on paleoclimate interpreted from the sediments in the remainder of this study.

LOCATION

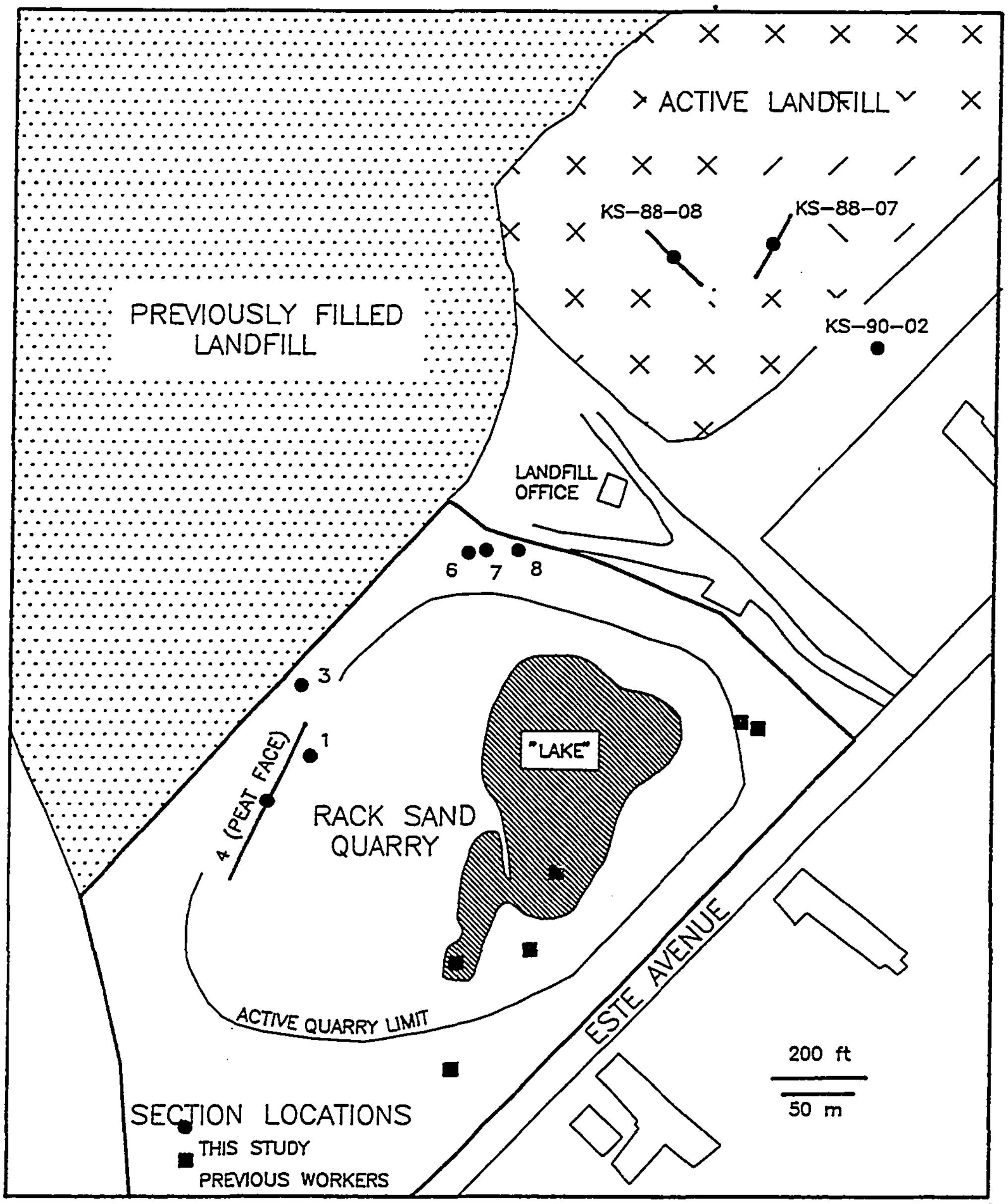
Study locations proximal to the late Wisconsin ice margin are in an active sand quarry operated by the Rack Sand Company, and in an active landfill adjacent to the quarry operated by Waste Management, Inc. (the biota are located in exposures within the quarry). The quarry and landfill are located in the lower Mill Creek Valley, approximately 8 km north of downtown Cincinnati (Fig. 2-1). These sites are located in a terrace that lies at an elevation of approximately 168 m above sea level (ASL); the present valley floodplain is about 16 m below the terrace. Tucker (1962) previously interpreted this terrace to be of Illinoian age. The quarry and landfill lie less than 5 km south of the mapped Hartwell Moraine (Gray *et al.*, 1972), the southernmost end

Fig. 2-1. Location map, showing modern day Ohio River, downtown Cincinnati, late Wisconsin Hartwell Moraine, and the study site.



92°
88°
84°
80°
76°W
48°N
48°N
44°
44°
40°N
40°N
92°
76°W
L. Superior
L. Michigan
L. Huron
L. Ontario
L. Erie
OHIO
Mississippi River
Lake Michigan Lobe
White River Sublobe
Miami Sublobe
Scioto Sublobe
Ohio River
HARTWELL MORAINE
MILL CREEK VALLEY
Previously mapped late Wisconsin limit
Great Miami River
RACK/ELDA
CINCINNATI
Little Miami River
Ohio River
0
10 km

Fig. 2-2. Rack Sand Quarry and Elda Landfill; locations of the studied sections within the quarry and landfill indicated.


ACTIVE LANDFILL
KS-88-08
KS-88-07
KS-90-02
PREVIOUSLY FILLED
LANDFILL
LANDFILL
OFFICE
6
7
8
3
1
4 (PEAT FACE)
"LAKE"
RACK SAND
QUARRY
ACTIVE QUARRY LIMIT
ESTE AVENUE
200 ft
50 m
SECTION LOCATIONS
THIS STUDY
PREVIOUS WORKERS

moraine of late Wisconsin Miami sublobe.

GEOLOGY OVERVIEW

Throughout the quarry, a number of exposures which no longer exist (containing a variety of sediment types and stratigraphic sequences) were studied by previous workers (Fig. 2-2). Durrell *et al.* (1961), Tucker (1962), and Goldthwait *et al.* (1981) reported on exposures in the then-active central and southeastern portions of the pit. Their studies describe and interpret a complex stratigraphy of pre-Illinoian fluvial sands, Illinoian proglacial deltaic sands, Illinoian till, and post-Illinoian fluvial sands.

At present time, two distinct stratigraphic sequences occur in the quarry and landfill (Fig. 2-2). Along the northern boundary of the quarry and throughout the landfill, the diamicton, interpreted by Durrell *et al.* (1961) to be Illinoian in age, unconformably overlies sands at the base of the exposed stratigraphy. Along the northwestern wall of the quarry, the diamicton is not observed, and the sands are overlain by a previously unreported silty clay sequence. Because the two stratigraphic sequences are different, and are likely of different age, each is reported separately. Description and interpretation of the diamicton sequence is presented first, followed by description and interpretation of the silty clay sequence.

DIAMICTON SEQUENCE

Three measured sections in the quarry (6, 7, 8), and the three sections in the adjacent landfill (KS-88-07, KS-88-08, KS-90-02; Fig. 2-2) provide the basis for development of the composite stratigraphy of the diamicton sequence. This generalized stratigraphic sequence (from bottom to top) includes: well-sorted, cross-bedded sand (unit 1) unconformably overlain by rhythmitic-laminated clayey silts with diamicton lenses (unit 2), which are in turn unconformably overlain by one or more facies of diamicton (unit 3). A sequence of interbedded sands and laminated silts and clays (unit 4) overlies the diamicton sequence. The interbedded sand-silt- clay sequence is capped by a final diamicton unit (unit 5).

Unit Descriptions

Unit 1, sand. This unit is exposed throughout the quarry, and in the lowest portions of the active landfill. Within the quarry, it is the object of active quarrying operations, and has an exposed thickness in excess of 15 m. Although the base of this unit is not exposed, driller's logs (which extend to bedrock) within the pit indicate that an additional three to four meters of sand exist below the floor of the active pit, and that the sands are underlain by a thick silty clay unit.

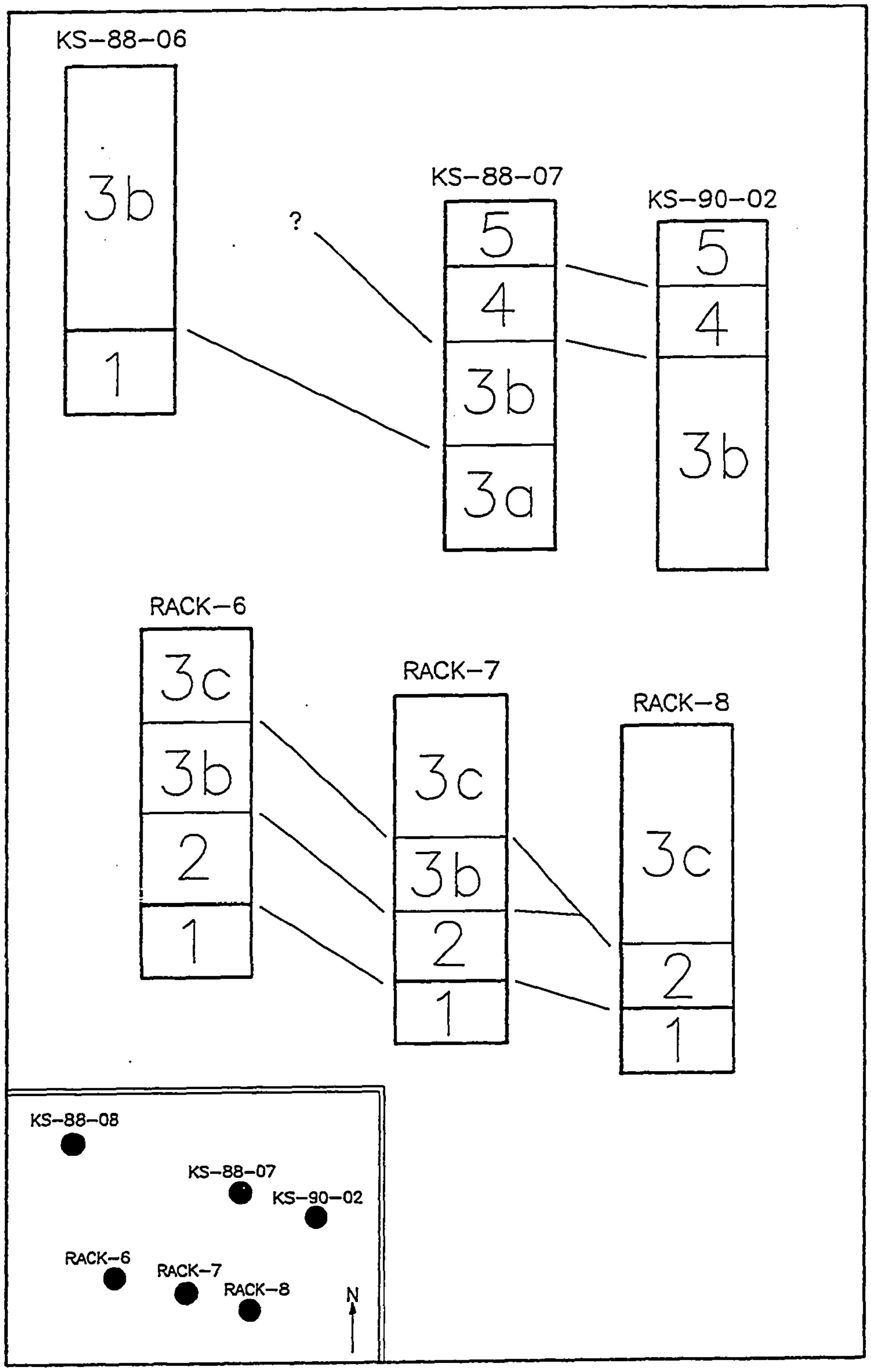
This sand is well-sorted, medium-sized, and has well-developed crossbedding. Silt and clay comprise less than one percent of this unit throughout much of its thickness. Horizontal bedding and trough and hummocky crossbedding are common throughout this unit. In the upper two meters of this unit, however, regular and irregular silt and clay lenses are abundant. The upper limit of the sand is undulatory and erosional; truncated crossbedding is observed everywhere along this contact. Capping this sand is a thin (5 to 10 mm) iron-oxide crust; this crust is ubiquitous, and is observed everywhere along the northwest and northeast faces of the quarry. Approximately two meters below the floor of the active quarry (quarry floor at 136 m ASL), and one and one-half meters below the present local water table, is a calcite-cemented horizon; this cement has been dated by the uranium-thorium (U/Th) method at 46,536+1860, -1830 yrs B.P. (MGS-540).

Unit 2, rhythmitic-laminated clayey silts. This unit was exposed along the entire northeast wall of the quarry, and had a maximum total thickness of 50 cm. While composed dominantly of rhythmitic-laminated clayey silts, it also contains laterally-extensive lenses of calcareous diamicton (10-15 cm high by several meters long). The upper contact of this unit with the overlying diamicton sequence appears to be conformable at some places, and erosional at others. The nature of the contact is related to the diamicton facies of unit 3 which overlies the silts at any location.

The silt laminations, with a sand:silt:clay (SSC) ratio of 6:63:31, are alternating light and dark in color, and individual laminations range in thickness from less than 1 mm to about 2 mm. The laminations exhibit localized soft-sediment deformation features, including flame structures, folding, and ball and pillow structure. Laminations in the upper 15 cm of the unit are occassionally deformed around small, pebble- sized clasts. Total number of couplets (one couplet = one dark and one light lamination) in the unit were counted at several locations. The total number ranged from 75 to 110. The laminated silts appear to be free of macro-organics.

The diamicton in the lenses is calcareous, sandy (SSC = 30:47:23), and stratified. The basal contacts of the lenses with the underlying laminated silts are generally erosional, as evidenced by truncated laminations; the upper contacts of the lenses are overlain by continuous silt laminations. The diamicton also appears to be free of macro-organics.

Fig. 2-3. Schematic sections showing the composite stratigraphy of the diamicton sequence in the quarry and adjacent landfill.



KS-88-06
3b
1
?
KS-88-07
5
4
3b
3a
KS-90-02
5
4
3b
RACK-6
3c
3b
2
1
RACK-7
3c
3b
2
1
RACK-8
3c
2
1
KS-88-08
KS-88-07
KS-90-02
RACK-6
RACK-7
RACK-8
N

Unit 3, diamicton sequence. At least three different facies of diamicton comprise comprise this unit. Compositionally, the three facies exhibit a decrease in sand and increase in silt up section (Table 2-1); additional distinguishing differences are in the structures within each facies, as described below.

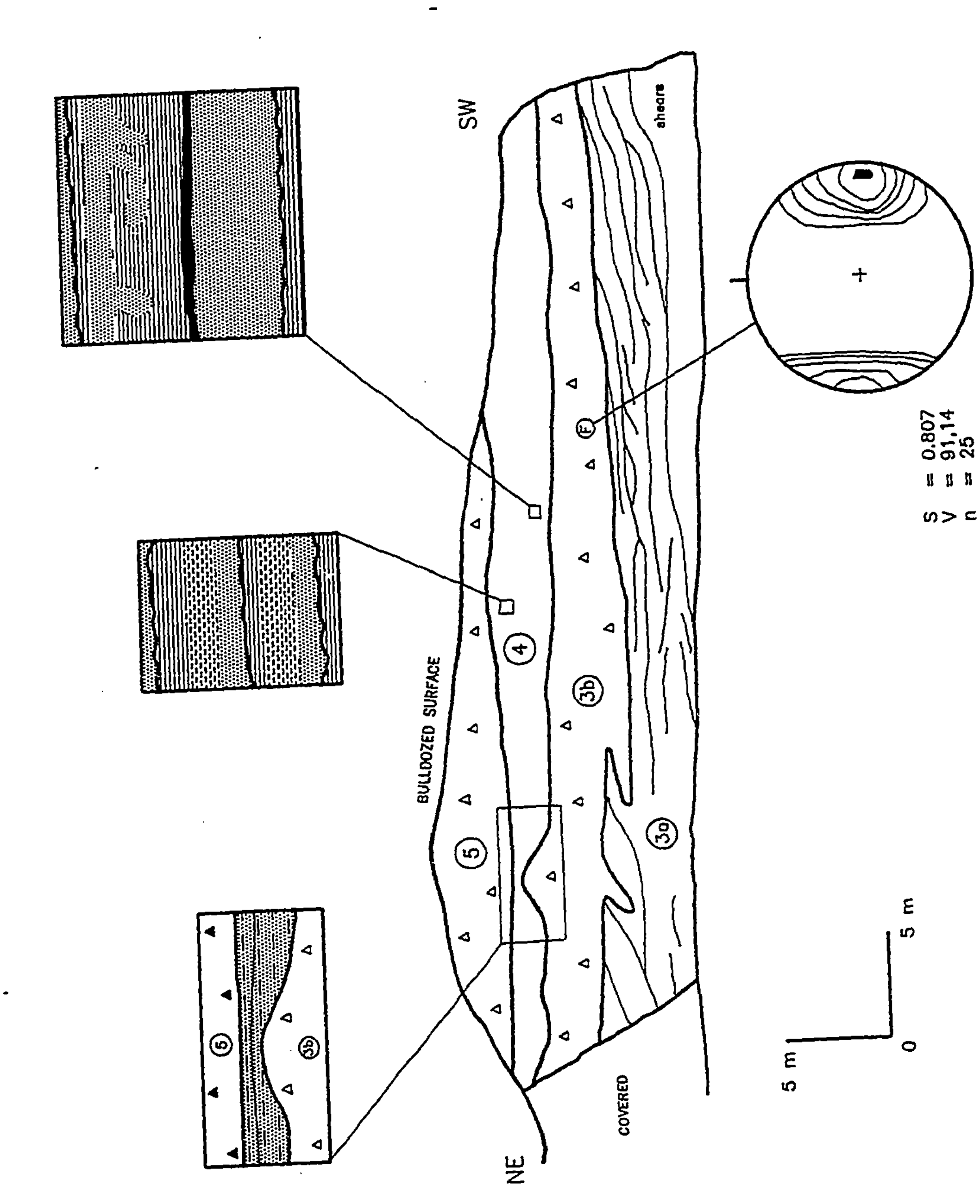
Facies A is found in section KS-88-07 (Fig. 2-3), and contains abundant shear planes, apparently "jumbled" blocks of diamicton, and highly deformed lenses and bodies of sand, with rare deformed lenses of gravel, silt, and clay. This facies has a maximum exposed thickness of about 4 meters, and a lateral exposure of about 40 meters. The contact of this facies with the overlying massive facies is irregular, and the two facies are observed to interfinger over a vertical distance of about 1 m (Fig. 2-4). The lower contact of this facies is not observed within the landfill; additionally, this deformed facies is not observed to overlie the laminated silts of unit 2 in the quarry.

TABLE 2-1. BULK TILL TEXTURE.
Expressed as mean and ± one standard deviation.

Diamicton Facies	n	Sand	Silt	Clay
Facies C	1	13.9	23.1	23.1
Facies B	2	24.7 ± 6.9	49.5 ± 3.1	25.8 ± 3.8
Facies A	1	33.7	42.6	23.7

Facies B is a massive, structureless, matrix-supported diamicton; it is observed at sections 6 and 7 in the quarry, and all three landfill sections (Fig. 2-3). This facies contains rare clusters of flat-lying striated limestone clasts. Striations on these clasts have azimuths between 070-250^{o} and 100-280^{o}. A single clast fabric in this facies is oriented 091^{o} (Fig. 2-4). In the quarry, this facies varies in thickness from 0.25 to about 1 meter, and is observed to unconformably overlie the laminated silts of unit 2, as evidenced by irregular truncation of the laminations. At quarry sections 6 and 7, the stratified diamicton of facies C overlies this facies; the contact appears to be conformable, with no apparent sharp break between the two facies. In the landfill, facies B ranges in thickness from 2.5 to 4 meters, with lateral extents in excess of 40 meters. At section KS-88- 07 (Fig. 2-4), facies B directly overlies the deformed diamicton of facies A. The nature of this contact is highly irregular, as discussed above. At KS-88-08, facies B directly overlies the crossbedded sand of unit 1. This contact is generally

Fig. 2-4. Facemap of KS-88-07 section in the landfill, showing the upper portions of the stratigraphic sequence, along with a clast fabric from unit 3, facies b. The circle represents clast orientation projected onto the lower hemisphere of an equal area net; numbers on the lower side of the circle represent the fabric strength (S_1; 0 = random, 1 = uniform), azimuth and plunge of the mean vector (V_1), and number of clasts (n). Contour interval is 2 standard deviations, with black areas representing the maximum deviation from random. Measures after Lawson (1979).


SW
NE
BULLDOZED SURFACE
COVERED
shears
4
3b
3a
5
F
S = 0.807
V = 91,14
n = 25
5 m
0
5 m

planar, and truncated crossbedding in the sand indicates that it is erosional. At this second location the upper limit of the facies is not observed; any units overlying facies B have been removed by bulldozing.

Facies C, a stratified, matrix-supported diamicton, is observed in only in quarry sections 6, 7, and 8, and has a minimum observed thickness of 3.5 m. Individual "sub-units" that make up the stratification are highly variable in thickness, and range from 5 to 25 cm. Within some of these sub-units, fining-upwards grain-size trends are noted. This facies contains rare pieces of heavily oxidized wood. Clast fabrics in this facies are variable, but are generally north- northeast. At sections 7 and 8, the sub-units have been deformed by folding. Where facies C overlies facies B, the contact is as described above. Facies C also is observed to directly overlie the laminated silts of unit 2 at section 8; here, the contact is sharp and unconformable, although the degree of truncation of the underlying laminations appears less than where facies B overlies unit 2.

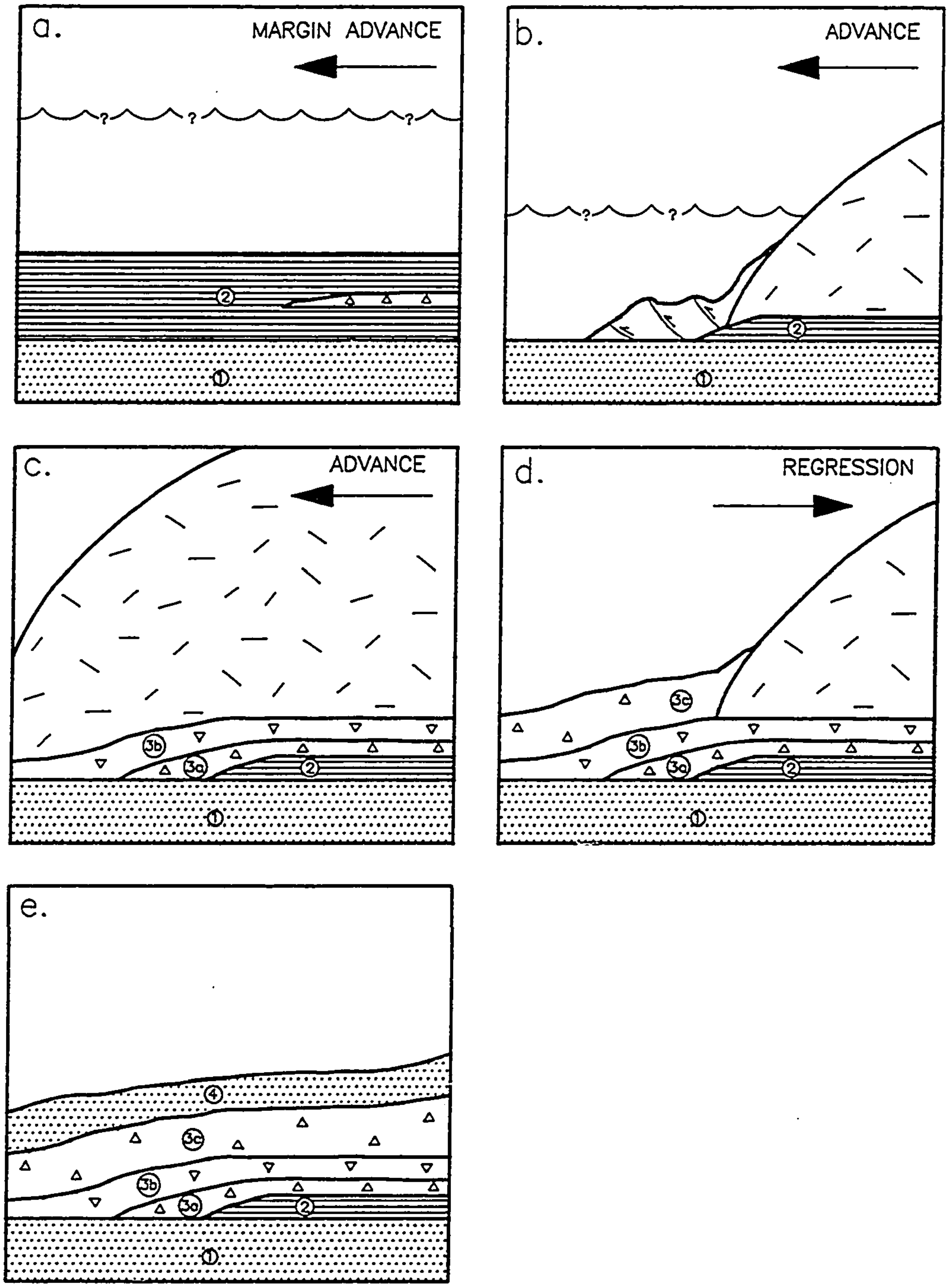
Unit 4, interbedded sand, silt, clay. Unit 4, observed in landfill sections KS-88-07 and KS-90-02, is comprised of repetitive sequences of sand, silt, and clay, and has a maximum lateral extent of 30 m. In the basal 1 m of the unit, the observed sequence is: silty sand overlain by clay with silty sand lenses; each sequence is 25 to 30 cm thick. The upper limit of each sequence is erosional, as evidenced by truncated laminations within the clay cap. In the upper 1 to 1.5 m of the unit, the sequences become well-developed, fining-upward packages of sand, silt, and clay. The packages are slightly thinner than those at the base of the unit, averaging about 20 cm, but are also continuous throughout the entire exposure. The upper limits of these packages, like those below, are erosional and are marked by truncated laminations in the clay caps (Fig. 2-4).

Unit 5, massive diamicton. A massive diamicton forms the uppermost stratigraphic unit in both the quarry and landfill. Within the quarry, this diamicton overlies the stratified diamicton of unit 3, facies C. The contact between these units is easily discernable, and may be unconformable. Within the quarry, this diamicton has a maximum observed thickness of about 4 meters. In the landfill, this facies unconformably overlies the sand-silt-clay sequence of unit 4; the unconformity is evidenced by the irregular erosion of the uppermost clay unit in unit 4. The diamicton is exposed only at the top of one section, and was inaccessable for detailed study.

Diamicton Sequence Interpretation

Unit 1, sand. Tucker (1962) completed extensive mechanical and compositional

Fig. 2-5. Depositional model for units 2, 3, and 4 of the diamicton sequence at Rack/ELDA; a) deposition of silts and clays in proglacial lacustrine environment of advancing glacier; b) glacial margin advance, with "bulldozing" of underlying sediments and deposition of diamicton facies 3a; c) glacier advance over the site, with deposition of diamicton facies 3b; d) glacier margin retreat, with deposition of sediment flow facies 3c; e) ice absent from immediate vicinity of site, with deposition of fluvial facies 4.


a.
MARGIN ADVANCE
?
?
?
2
1
b.
ADVANCE
?
?
2
1
c.
ADVANCE
3b
3a
2
1
d.
REGRESSION
3c
3b
3a
2
1
e.
4
3c
3b
3a
2
1

analyses on the sands of unit 1, and interpreted them to represent braided fluvial sands deposited contemporaneously with Illinoian glaciation. Crossbedding suggests highly variable flow directions, which Tucker interpreted to represent proglacial deltaic sedimentation. No field evidence was observed in this study which requires modification of Tucker's interpretation.

Unit 2, rhythmitic-laminated clayey silts. These laminated silts are interpreted to be cyclic, lacustrine-type sediments deposited in a quiet water basin (Fig. 2-5a). No attempt was made to determine the periodicity of the cycles; each dark-light couplet may represent an annual cycle of deposition ("varves"), or each couplet may simply reflect an episode of sediment influx into the basin. In either case, the number of couplets suggests that the basin was probably present for at least a period of several years, if not several tens of years. The lenses of stratified diamicton are interpreted to be subaqueous debris flows associated with an advancing ice margin, as discussed in greater detail for unit 3. These sediments suggest an interpretation of an ice- marginal lake as the depositional setting (Smith and Ashley, 1985). In all cases where the diamicton lenses are observed, there are 30 to 50 laminae couplets present beneath the lenses. This suggests a period of time where the glacier either had not advanced into this marginal lake, or the ice-lake margin was far enough removed from the exposures that debris flows did not reach the position of these exposures. The diamicton lenses reflect ice movement to a position closer to the position of the exposures, with ice-derived debris being sourced close enough to flow over the laminated sediments. Pebbles associated with deformed laminae in the upper 15 cm are interpreted to be dropstones from ice-rafted debris in the lake.

Unit 3, diamicton sequence. The sequence of diamicton facies within this unit records what is interpreted as a single ice advance over the quarry and landfill sites. The observed grain size trend likely reflects the degree of incorporation of the underlying sand in each facies. Facies A, with its shears, deformed lenses, and "jumbled" blocks of diamicton is interpreted to have been deposited at the leading edge of the advancing ice. The presence of lenses and blocks of sorted sediments and diamicton suggest that these units were not deposited in a subglacial position; Boulton (1987) has discussed poor preservation potential of sorted sediment bodies during subglacial deposition. This facies is interpreted to represent "bulldozing" of sediments by advancing ice. These sediments may have been debris flows shed off the front of the advancing ice.

The massive diamicton of facies B is interpreted to be a subglacial till, with deposition probably by lodgement. Rare clusters of striated, flat-lying limestone clasts, and consistent striation and clast fabric orientations support a hypothesis of ice flow from the east. The folded and interfingered contact of this facies with the underlying facies A indicates incorporation of the underlying substrate contemporaneous with deposition of this facies, also supporting the subglacial interpretation (Boulton, 1987).

Facies C stratified diamicton is interpreted to be comprised of sediment flow deposits derived from a glacial marginal source. Grain size trends within individual stratified packages, and the extremely low abundance of clasts in the pebble-size class suggest that the sediment flows occurred in an aquatic setting (Smith and Ashley, 1985). Folding of these stratified packages may have been the result of soft-sediment deformation. Clast fabrics reflect only the direction of sediment flow in this facies, and indicate that the sediment source was to the north-northeast.

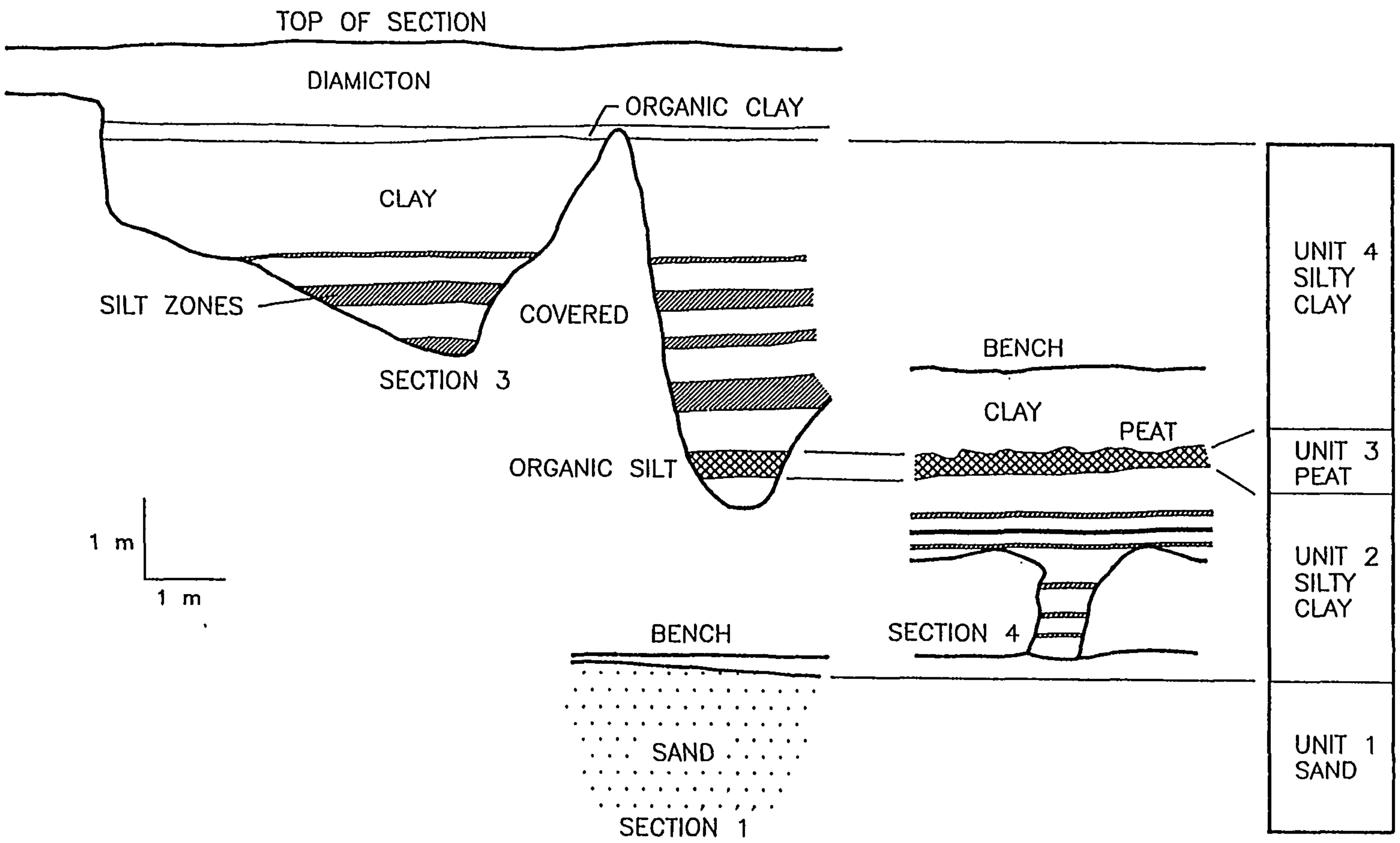
Unit 4, interbedded sand, silt, clay. The fining-upwards packages within this unit are interpreted to be of fluvial origin. Each package reflects an episode of fluvial activity, with basal sands reflecting active fluvial deposition, and the silt and overlying clay components reflecting a slowing and finally cessation (or nearly so) of the fluvial activity. The unconformity at the top of each package reflects erosion (presumably fluvial) prior to the onset of deposition of the succeeding package. The uniformity of thickness of these packages suggests a cyclic nature to the fluvial activity. This apparent cyclicity may be related to meteorologic or climatic cyclicity (e.g., diurnal temperature fluctuations, seasonal temperature fluctuations), or may be related to fluctuations in the nature of the fluvial system. If this unit is associated with the melting of ice responsible for deposition of the unit 3 diamicton facies, then the packages are likely related to cyclic melting of the ice on either a daily or seasonal scale. The thickness of each packages may favor seasonal cyclicity.

Unit 5, massive diamicton. This unit was generally inaccesible for detailed study. No obvious sedimentologic or structural features were observed to support any interpretation of genesis. Rather than speculate on the genesis, no interpretation of this unit is presented here.

Summary of Interpreted Sequence

Unit 2 is comprised of sediments which reflect the first recorded advance of ice into the area of the study sites. The laminated silts and diamicton lenses record the development of a proglacial lake, with active supply of glacially-derived debris into the lake (Fig. 2-5a). The laminated silts at the base and top of the unit indicate periods,

Fig. 2-6. Composite stratigraphy and correlation of clay sequence units at Rack Quarry sections 1, 3, and 4.


TOP OF SECTION
DIAMICTON
ORGANIC CLAY
CLAY
SILT ZONES
COVERED
SECTION 3
ORGANIC SILT
1 m
1 m
BENCH
CLAY
PEAT
SECTION 4
BENCH
SAND
SECTION 1
UNIT 4
SILTY
CLAY
UNIT 3
PEAT
UNIT 2
SILTY
CLAY
UNIT 1
SAND

however, with limited sediment supply and sediment flow of the diamicton into all parts of the basin. Unit 3 diamicton facies reflect erosion and transport of substrate sediments at the margin of the advancing ice (facies A, Fig. 2-5b), subglacial deposition by active, basally-melting ice (facies B, Fig. 2-5c), and finally melting of the ice and contemporaneous or subsequent flow of the sediments (facies C, Fig. 2- 5d). Unit 4 reflects onset of cyclic fluvial process; these may be related to continued melting of the glacier responsible for unit 3 sediments (Fig 2-5e).

CLAY SEQUENCE

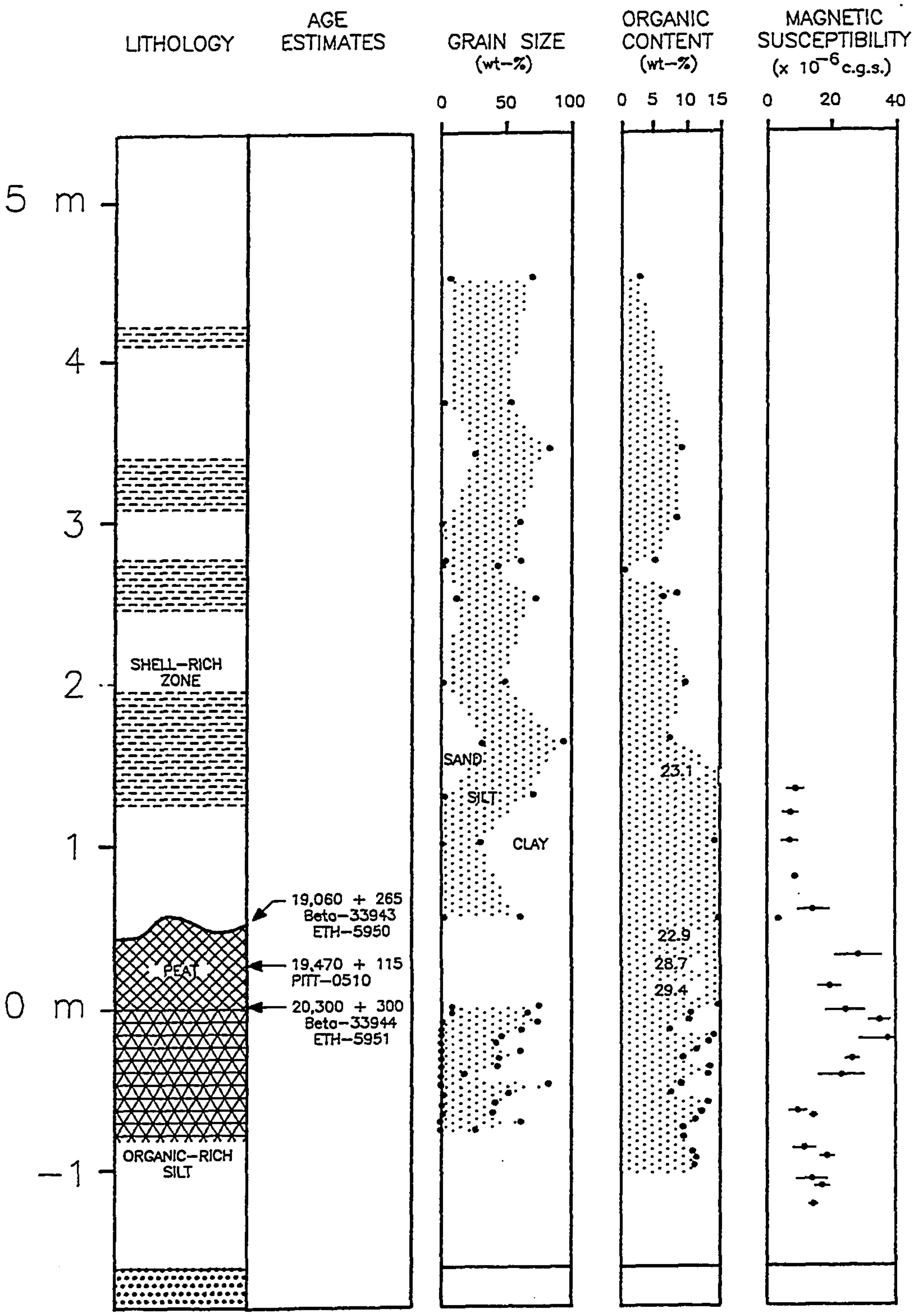
Having examined the first stratigraphic sequence at the quarry and landfill sites, the silty clay sequence shall now be discussed. Five sections along the northwest perimeter of the quarry were measured and mapped over a two year period from January 1988 to February 1990 (Fig 2- 2). Quarrying operations as of July 1990 have destroyed all of these exposures. The generalized stratigraphy of the clay sequence (from bottom to top) includes (Fig. 2-6): well-sorted, crossbedded sand (unit 1) unconformably overlain by coarsely-laminated silt and clay (unit 2), which grades upwards into a well-developed bryophyte peat horizon (unit 3). This peat is in turn overlain by a second unit of coarsely- laminated silt and clay. Hardwood fragments (N.G. Miller, pers. comm.) in the peat yielded radiocarbon age estimates indicating that the silt and clay portion of the sequence is of late Wisconsin age (Table 2-2).

Unit Descriptions

Unit 1, sand. This unit, exposed at quarry sections 1 and 2, is the same as unit 1 described in the diamicton-sequence, and is not re-described here.

Unit 2, silty clay. Unit 2 is a calcareous, silty clay, and is found in quarry sections 1, 2, 3, 4, and 5; maximum exposed thickness of this unit is 4.5 meters at section 5. Although generally massive in appearance, this unit contains zones of rhythmitic bedding, as well as very fine sand and coarse silt interbeds and partings. The rhythmitic bedding and silt/sand beds are generally planar, with only minor deformation; this deformation includes small-scale folding and flame structures. Zones of rhythmitic bedding range in thickness from less than 5 to about 30 cm in thickness. The silt/sand beds range in thickness from 0.2 to 1.5 cm, and are spaced 5 to 10 cm apart. These beds are free of any organic materials. In the upper 2.5 meters at one section, however, some of these silts were observed to contain disseminated plant and moss debris, such as

Fig. 2-7. Composite stratigraphic column of the clay sequence, showing generalized lithology, radiocarbon age estimates, grain size, organic content, and magnetic susceptibility.


LITHOLOGY
AGE ESTIMATES
GRAIN SIZE (wt-%)
0 50 100
ORGANIC CONTENT (wt-%)
0 5 10 15
MAGNETIC SUSCEPTIBILITY (x 10^{-6} c.g.s.)
0 20 40
5 m
4
3
2
1
0 m
−1
SHELL−RICH ZONE
PEAT
ORGANIC−RICH SILT
19,060 + 265 Beta−33943 ETH−5950
19,470 + 115 PITT−0510
20,300 + 300 Beta−33944 ETH−5951
SAND
SILT
CLAY
23.1
22.9
28.7
29.4

that comprising the overlying peat. The upper 0.5 to 0.75 m of this unit becomes very silt- rich and massive, and the organic content in this upper portion increases upwards. At section 4, this unit is overlain by the thick peat of unit 3; at section 3, very organic-rich silt is the overlying sediment. At both of these sections, the contact with the overlying sediments is transitional but distinct.

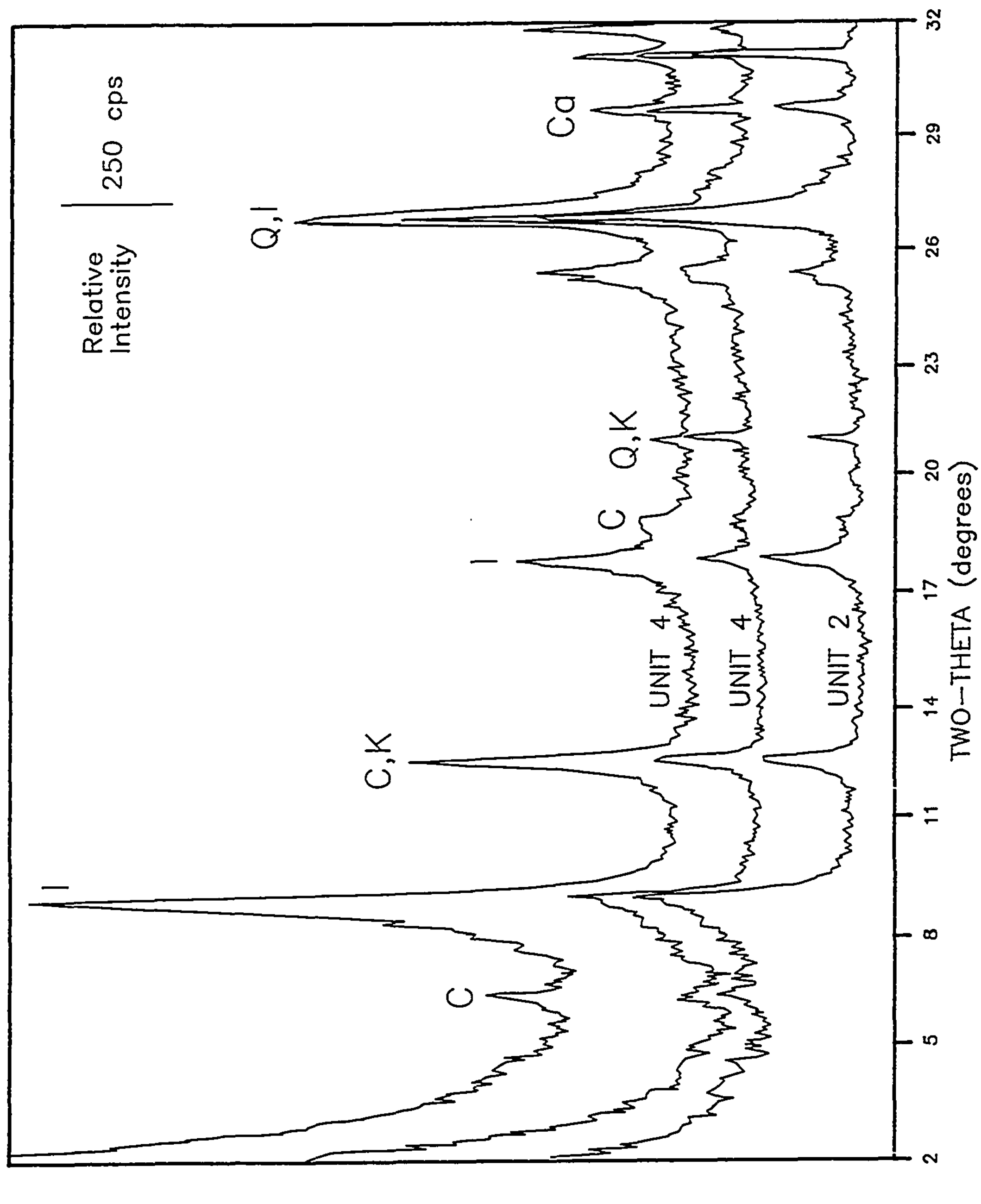
The clay-dominated portions of this unit have an average SSC ratio of 1:48:51 (Fig. 2-7). The average SSC ratio of the silt/sand interbeds is 1:68:31. Diffraction analysis of the clay-sized material indicates the presence of chlorite, illite, and kaolinite, as well as very fine quartz and calcite (Fig. 2-8).

Unit 3, peat. This unit was exposed along section section 4 for a distance of just over 100 m, and varied in thickness between 0.4 and 0.5 m (Fig. 2-7). The unit is comprised of a dense mat of calcareous aquatic bryophytes and sedges (Table 2-3; N.G. Miller, pers. comm.), with some incorporated fine sands, silts, and clays. The mat is generally massive, although sand and silt drapes highlight structures locally. Associated with the mat are a wide variety floral and faunal remains, including at least five gastropod, over seven dozen beetle, and eight bryophyte species. Pollen is abundant throughout this unit, and is dominantly sedge, spruce, and pine (Fig. 2-10). Other remains identified include pelecypods, oribatid mites, and at least one fish (Lowell *et al.*, 1990b). These biota are the subject of ongoing research and are not presented here. Radiocarbon analyses on sedge and juniper fragments twigs found within the peat yielded an age estimates (Table 2-2) which indicate that this unit is coeval with the late Wisconsin glacial maximum advance in this area (Lowell *et al.*, 1990a).

The upper surface of the peat was hummocky, and the contact between the peat and the overlying silts and clays was quite sharp. Nearly- horizontal, planar silt partings 10 to 15 cm above the upper surface of the peat suggest that the hummocks probably represent the actual peat surface just prior to deposition of the overlying sediments. At the tops of several hummocks, individual blades of sedge were observed to penetrate the lower 2 to 5 cm of the overlying sediments.

Unit 4, silty clay. Unit 4 is a calcareous, silty clay, and is exposed at sections 3, 4, and 5; the maximum thickness of 5 m is in section 5. The unit is dominantly massive, with thin silt interbeds and lenses rich in shell material. These beds and lenses range in thickness from only a few millimeters to about 0.5 meters, are vertically spaced at 0.2 to 0.4 meter intervals, and are comprised of dominantly structureless silt. The lower bounds of these zones are generally sharp and well-defined; the upper bounds are poorly-

Fig. 2-8. Typical x-ray diffraction patterns of glycolated <2 um fraction of unit 2 (lowest curve), and unit 4 (upper 2 curves); C = chlorite, I = illite, K = kaolinite, Ca = calcite, Q = quartz.


Relative Intensity
250 cps
I
C
C,K
I
C
Q,K
Q,I
Ca
UNIT 4
UNIT 4
UNIT 2
2
5
8
11
14
17
20
23
26
29
32
TWO-THETA (degrees)

defined and the silts grade upwards in silty clay. Very rarely, contorted bedding is noted in the silt zones, and horizontal laminations are noted in the intervening silty clays. The silt zones are rich in gastropod, pelecypod, and ostracod tests. The silty clay contains fewer gastropods and pelecypods, but is rich in ostracods. The upper 1 to 2.5 meters of unit 4 are heavily oxidized.

The silty clay has an average SSC ratio of 1:35:64; the silt zones have a SSC ratio of 3:63:34 (Fig. 2-7). In both cases, 70 to 85 weight-percent of the sand-sized material is shell material, either as whole tests or fragments. In general, diffraction analysis again indicates the presence of chlorite, illite, and kaolinite, as well as very fine calcite and quartz (Fig. 2-8).

The geometry of this unit varies between the sections, and provides clues as to the depositional setting of units 2, 3, and 4 (discussed in greater detail below). At sections 3 and 4, this unit overlies the unit 3 peat or organic rich silt. At section 5, however, the peat/organic silt of unit 3 is absent, and unit 4 directly overlies the silty clay of unit 2. The boundary between units 2 and 4 at this section is indistinct, and is based on the "first occurrence" of shell material in the silt zones; this occurrence is approximately 2 to 2.5 m below the elevation of the base of the peat at section 4. Along the scarp of a slump between sections 4 and 5, the geometry of the peat was exposed in the third-dimension. Along this face normal to section 4, the peat was observed to dip to the northwest ("into" the quarry wall), thinning as it got deeper, and eventually pinching out; this pinching out resulted in the unit 4-over-unit 2 geometry discussed above.

Clay Sequence Interpretation

The interpretation of unit 1 as proglacial deltaic sands has been discussed in the interpretation of the diamicton sequence section above. Although the units overlying the sand in each sequence are interpreted to be of different ages (and therefore are not conformable), the sand in each sequence is interpreted to be the same unit.

Unit 2 is interpreted to represent quiet water deposition, such as in a backwater fluvial setting. Rhythmitic bedding of clay-rich zones within the unit indicates periods of little or no major water movement. Other textural characteristics, most notably the high silt content and presence of sorted sand lenses and stringers, indicate periods of water movement. These features are consistent with backwater fluvial deposits reflecting episodic sediment influx. Organic-rich silt stringers in the upper portion of the unit at section 5 are interpreted to represent debris derived from the peat at nearby locations, and transported within this quiet water system. There is no evidence to indicate subaerial exposure anywhere within this unit.

The biota of unit 3 suggest a rich, open fen setting, probably near treeline (Lowell *et al.*, 1990b). The transitional nature of the lower contact with the underlying silty clay suggests a gradual shallowing of the water responsible for unit 2 deposition, with stabilization of water level at the level of the peat. The abrupt contact with the overlying unit 4, and the occurrence on sedge protruding into these overlying sediments suggests a very rapid rise in water, with increased sedimentation rate.

Unit 4 is interpreted to also represent quiet water deposition. The nature of the unit 3 - unit 4 contact indicates an abrupt increase in water level at the site, and an initial period of fairly high sedimentation. Cyclic sedimentation observed at section 5 may also reflect episodic sediment/water influx. The sharp lower - gradational upper bounds of the silt zones suggest that these represent sediment flows (Collinson and Thompson, 1982), with the transport of shelled fauna from shallow to deeper water. Numerous pelecypods have been found with the nacrum intact, suggesting transport and burial while the organism was alive. No escape burrow structures have been identified, however. The thickness of the unit indicates a minimum overall increase in water depth of at least 5 meters for deposition of the unit.

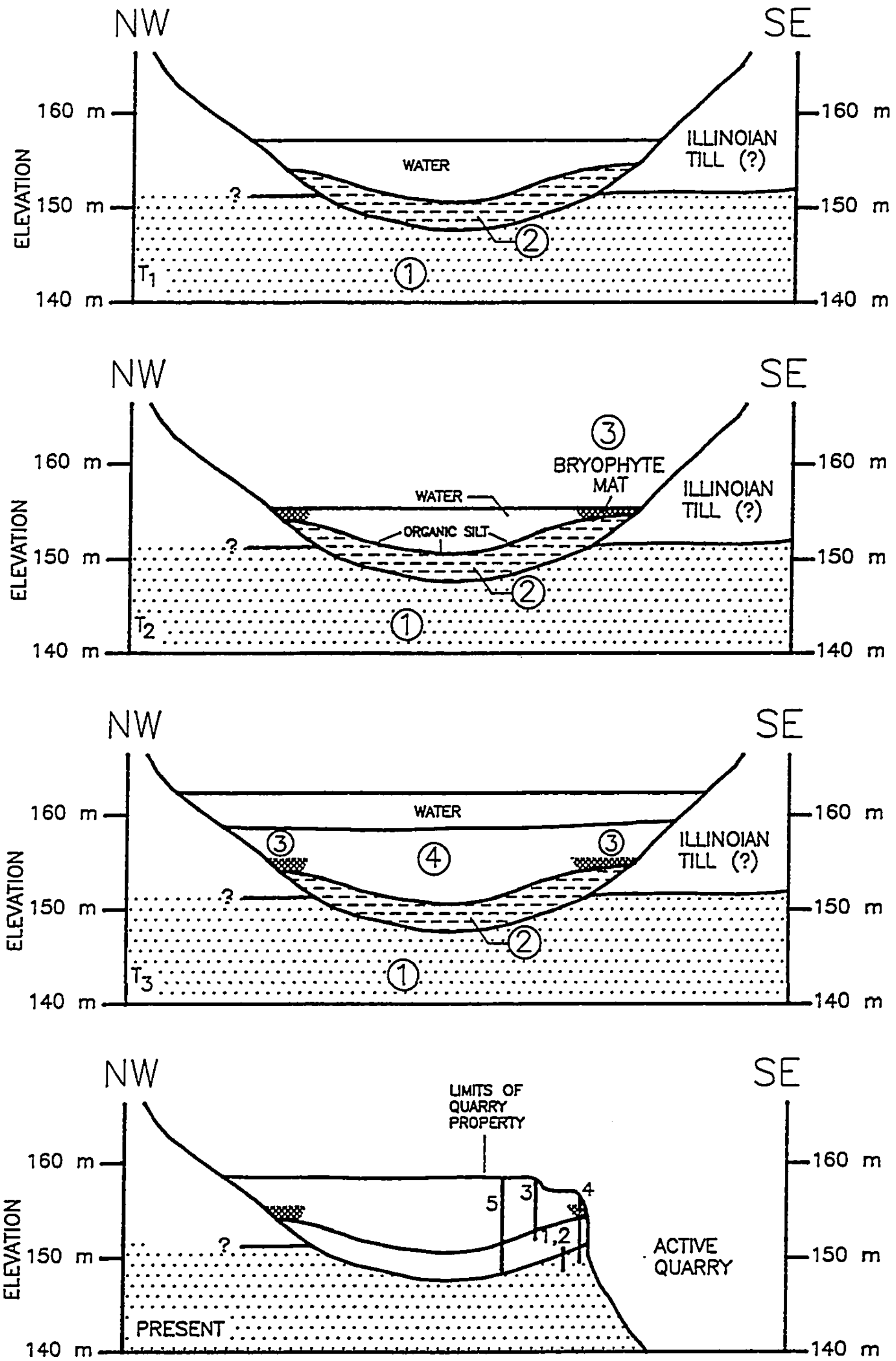
TABLE 2-2. RADIOCARBON AGE ESTIMATES - RACK QUARRY.
Expressed with $\pm$ one standard deviation

Stratigraphic Position Within Peat	Material Dated (a)	Age Estimate	Lab Number	Method
top	wood-juniper	19,060 + 265	Beta-33943 ETH-5950	AMS[b]
middle	wood - sedge	19,470 + 115	PITT-0510	conventional
base	wood-juniper	20,300 + 300	Beta-33944 ETH-5951	AMS

a - wood identifications by Donna Christenson, U.S. Forestry Dept., Woods Laboratory, Madison, WI.

b - AMS radiocarbon analyses provided by N.G. Miller, New York State Museum, Albany, NY.

Fig. 2-9. Schematic diagram showing changes in water levels during deposition and growth of units 2, 3, and 4; t_1) water level above an elevation of 155 m, with deposition of silts and clays of unit 2; t_2) water level at approximately 154.5 m elevation, with prolonged growth of the bryophyte mat of unit 3; t_3) water level rise to at least 161 m elevation, with deposition of silts and clays of unit4; bottom panel reflects extent of modern quarry activity, and relative stratigraphic position of the five measured clay-sequence sections.


NW
SE
160 m
150 m
140 m
ELEVATION
WATER
ILLINOIAN TILL (?)
?
T_1
1
2
NW
SE
3
BRYOPHYTE MAT
WATER
ORGANIC SILT
ILLINOIAN TILL (?)
160 m
150 m
140 m
ELEVATION
?
T_2
1
2
NW
SE
WATER
3
4
3
ILLINOIAN TILL (?)
160 m
150 m
140 m
ELEVATION
?
T_3
1
2
NW
SE
LIMITS OF QUARRY PROPERTY
160 m
150 m
140 m
ELEVATION
5
3
4
1,2
?
ACTIVE QUARRY
PRESENT

Summary of Landscape Change

The stratigraphic sequence of silty clay - peat - silty clay reflects a "regressive - transgressive" sequence; that is, a shallowing of water at the time of transition from unit 2 to unit 3, and a subsequent deepening of water at the transition from unit 3 to unit 4.

Thin stringers of transported plant and moss debris in unit 2 probably indicates the presence of a stable shoreline environment with moss and other plant growth. Because no stable shoreline environment was found at the same elevation as the stringers, it is concluded that this shoreline must have been topographically above the unit 3 peat horizon (Fig. 2-9, t_1); the portions of the quarry where this horizon might have been observed were removed sometime prior to this study, however. Elevation of the top of this unit is approximately 154.5 m ASL, and our interpretation requires a water surface elevation above that.

The extensive peat horizon reflects a prolonged shoreline at about 154.5 m ASL. A falling water level for the upper portion of unit 2 to allow the growth of the bryophyte mat (unit 3) (Fig. 2-9, t_2); peat growth was initiated at about 20,200 BP (Table 2-2) and continued for approximately 1100 radiocarbon years to about 19,100 BP. It must certainly be emphasized here that the likelihood of water level remaining stable for more than 1000 years in an area so close to an advancing ice margin is highly unlikely. Water levels in the adjacent Mill Creek valley were likely affected by volumes of meltwater and calved ice, and by water level in the Ohio River 5 to 10 km downstream. The level represented by the peat horizon is therefore an average water level over a period of time which may have lasted from 500 to 1000 years. Contamination associated with radiocarbon age estimation may have resulted in such a lengthy interval.

Unit 4 silts and clays reflect a rise in water level beginning about 19,100 radiocarbon years BP ; the nature of the upper peat - silty clay contact, as previously discussed, indicates an abrupt initial increase in water level. The maximum elevation of this unit is approximately 161 m ASL, requiring a water rise of 5 to 5.5 m (Fig. 2-9, t_3).

Elevation of the present-day alluvial valley floor is about 152 m ASL. Unit 2 requires that the slackwater surface elevation be at least 2.5 m above the modern valley floor. The bryophyte horizon indicates a stabilization of the water level 2.5 m above the modern valley floor, and unit 3 indicates a subsequent water level at least 9 m above the modern alluvial valley floor.

This entire sequence is interpreted to represent fine sediments deposition in a valley marginal embayment flooded by water associated with late Wisconsin glaciation, and possible aggradation in the Ohio River system at this time (Rogers, 1990; flooding and aggradation discussed at length in chapter 4 of this dissertation).

Additional scenarios related to growth and development of the peat horizon merit attention. Because of the possibility of radiocarbon sample contamination, it is possible that the peat horizon predates the maximum ice advance by several hundred years. If ice were not in the vicinity water levels could have been more stable. An important paleoclimate implication of this scenario is that the cold local climate reflected by the biota associated with the peat (see **Summary of Paleoclimate Based on Biota** at the end of this chapter) was established before the glacier was in the vicinity.

The second possibility is that the peat may have been formed during an interstade, such as the Connersville of Gooding (1963, 1975). Ekberg (1991) reported marginal recession and readvance near Oxford, Ohio (30 km NW) at approximately the same time. Again, the recession of ice from the immediate area may have allowed water levels to stabilize. An interstadial at this time has been reported in the Perigord Cave sediments in France (G. Kukla, pers. comm.)

CONCLUSIONS

The following conclusions are offered for the two sequences at the Rack Sand Quarry and adjacent ELDA Landfill:

Diamicton Sequence

1. The sequence of sediments reflects an advance of wet-based ice over the study sites; ice-flow indicators within these sediments indicate that ice-flow was from the east;

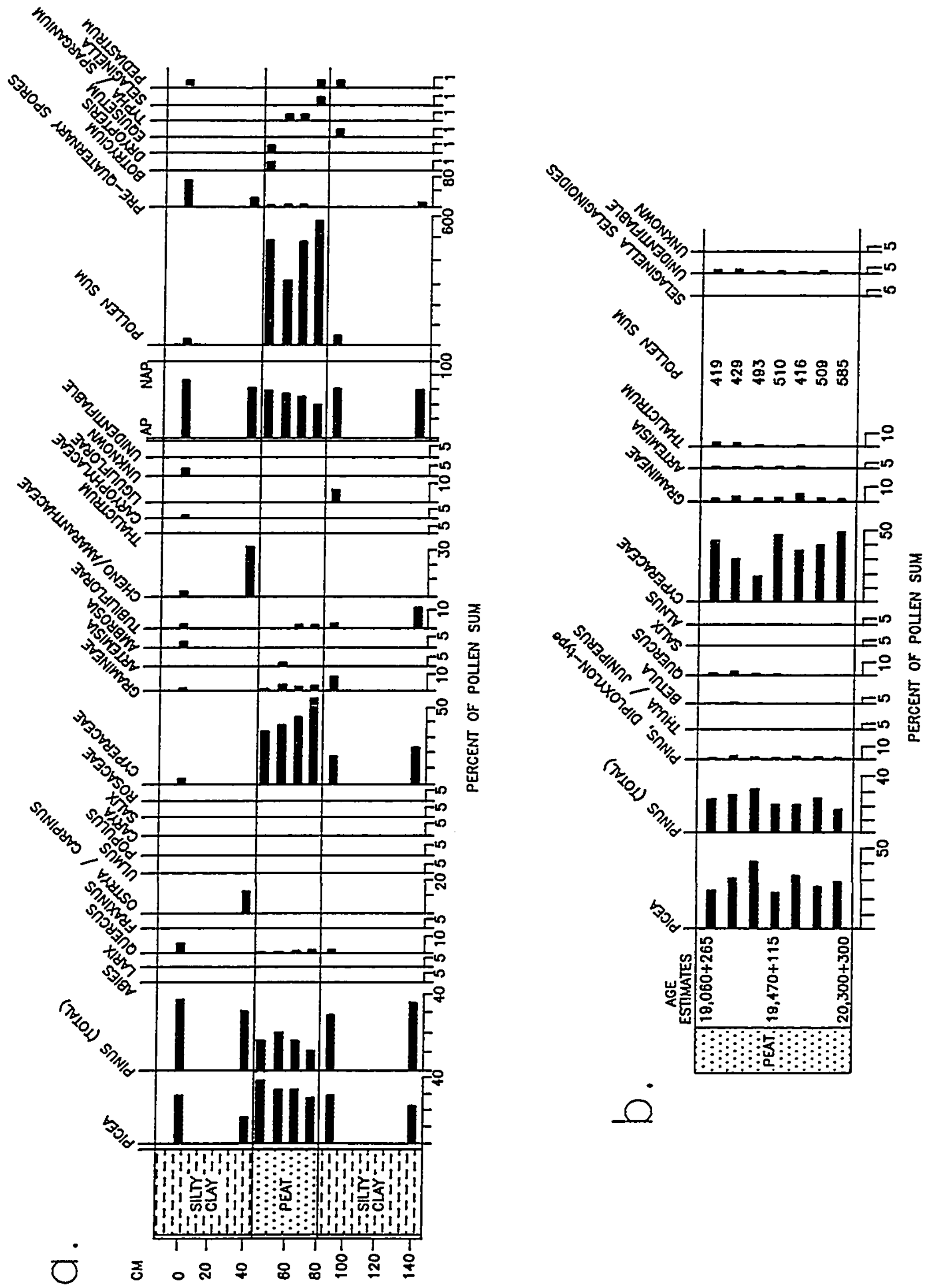
Clay Sequence

1. The radiocarbon age estimates from the bryophyte-peat unit indicates that bryophyte growth occurred at approximately the same time as the late Wisconsin glacial maximum reported 5 to 10 km north in the valley (Lowell *et al.*, 1990a),

2. Conformable upper and lower contacts between the peat and the under- and over-lying silty clays indicates that these units are probably also associated with the late Wisconsin glacial maximum.

3. Grain size and clay mineralogy of the silty clays above and below the peat are indistinguishable; the observation that the clays below the peat are free of any shelly material, and the clays above the peat are rich in shelled fauna indicates a change in the biota at the site. This change may have resulted from physical changes, such as water chemistry or water turbidity, and was not detected by any analytic work. Alternatively, the difference may have been the result of a climatic variation.

Fig. 2-10. Pollen abundance diagrams from analyses immediately below, within, and immediately above the peat horizon; a) analysis by L. Shane, b) analysis by N.G. Miller. Radiocarbon age estimates within the peat are shown in (b); the same ages would apply to the peat interval shown in (a). All samples in (b) were collected within the peat horizon; position of samples in (a) with respect to the peat horizon are shown graphically.


a.
b.
PICEA
PINUS (TOTAL)
CYPERACEAE
GRAMINEAE
ARTEMISIA
THALICTRUM
POLLEN SUM
AP
NAP
PERCENT OF POLLEN SUM
SILTY CLAY
PEAT
CM
AGE ESTIMATES
19,060±265
19,470±115
20,300±300
419
429
493
510
416
509
585

4. Reconstruction of depositional setting suggests deposition in a flooded embayment located along the margin of the main valley; minimum water surface elevations required for silt and clay deposition reflect fluctuating water levels in the embayment of at least 10 meters.

5. Reconstruction of the paleogeography of the clay sequence indicates that the diamicton sequence sediments formed the entire valleyward boundary of the embayment; the requirement that the diamicton sequence preceded the clay sequence deposition indicates that the diamicton sequence represents an ice advance older that the one reflected in the clay sequence biota.

SUMMARY OF PALEOCLIMATE BASED ON BIOTA

As previously mentioned, a diverse biota assemblage was associated with the peat horizon, and the overlying clay/silt unit. The biota provide a picture of paleoclimate associated with the late Wisconsin maximum glacial advance to a position approximately 5 km from the quarry. Analyses of the biota were completed by specialists at a number of institutions; individuals who conducted these studies are Linda Shane (Limnological Research Center, University of Minnesota; pollen), Norton Miller (New York State Museum, Albany; moss, pollen), Alan Morgan and Jerry Pilny (University of Waterloo, Canada; beetles), and Andrine Dell (University of Cincinnati; gastropods). Only individual summaries and a composite paleoclimate signal are presented here. Readers interested in a more detailed discussion of the biota studies should see Lowell *et al.* (in prep.). It should be noted that the biota summaries below were developed by the above-mentioned workers.

Moss. The peat horizon is composed primarily of calcareous bryophytes (mosses). Eight moss species were identified (Table 2-3); five of these eight species are members of Ohio's extant moss flora, in which they occur rarely in rich-fen plant communities. *Byrum neodamense* is possibly extirpated in North America, although it persists in Europe. All other species are frequent in calcareous wetlands, from the boreal forest region of Canada northward into the Arctic.

Pollen. The pollen assemblage is dominated by sedge, spruce, and pine (Fig. 2-10). Climatic interpretation of this record is of a dry, cold climate. The use of response surface graphs (Bartlein *et al.*, 1986) offers some estimates of temperature and precipitation. The high sedge pollen frequencies (35-54 percent) suggest mean annual precipitation of 50 cm or less, and mean January and July temperatures of -10 to -20^{o}C, and +5^{o}C, respectively. Using the precipitation range suggested by the sedge frequencies, the spruce and pine response surfaces would imply mean January temperatures of -10 to -30°C, and mean July temperatures of +10 to +15°C. Also, the consistently high percentages of pine (probably mostly of the *Pinus banksiana* (jack-pine) type), suggests the trees were close to the Rack site.

Beetles. Beetles recovered from the site represent a numerically rich, taxonomically diverse assemblage (over 500 individuals from at least 87 species and at least 16 families). The paleoenvironmental reconstruction from the beetle remains indicates a sedge-rich fenland with muddy substrates and shallow pools, located close to, but inside, treeline. Most of the species identified from the site are present-day residents of the boreal zone of North America. A few species are found in localities which are today confined to the southernmost boreal ecotone, and south of it. Not one of the species may be regarded as an obligate tundra resident (i.e., requires a tundra environment), although a few species have been recorded from sites beyond modern tree limit. This assemblage reflects temperature conditions found in the central to southern part of the boreal zone, with interpreted mean July temperatures of +10 to 12°C.

Gastropods. The gastropod assemblages found within and immediately above the peat (Table 2-4) indicate the presence of a shallow marshy environment. The assemblage includes several marginal semiaquatic species, and others which have been transported in from a nearby wooded area. The assemblage found in the silts above the peat indicates a change from a quiet, shallow body of water to a deeper one. The gastropod assemblages indicate a cooler climate, consistent with the other biota data.

Summary. These biota provide a detailed "snapshot" of paleogeography and paleoclimate at a time when the late Wisconsin glacier was about 5 km away. The mosses reflect an open, rich-fen setting; pollen indicates open areas with trees at some distance from the fen. The beetles support a fenland setting near treeline. Gastropods within the peat reflect closely associated terrestrial and aquatic environs. Paleoclimatically, the biota indicate mean annual precipitation of 50 cm or less, and mean January temperatures of -30 to -10°C. For mean July temperatures, the pollen suggest about +5°C, while the beetles suggest +10 to +12°C. For comparison, modern averages of these variables in the Cincinnati area are mean annual precipitation of 100 cm, mean January temperature of -2°, and mean July temperature of 24° (data from the National Weather Service, Cincinnati, OH).

TABLE 2-3. SUMMARY OF MOSS ABUNDANCES WITHIN PEAT.
Expressed as percents; the four samples represent the same stratigraphic interval.
Analyses by N.G. Miller, New York State Museum, Albany, NY.

Moss Type	Sample			
	1	2	3	4
Scorpidium scorpoides *	35	30	35	30
Drepanocladus revolvens *	35	25	30	30
Meesia triquetra	5	30	30	5
Campylium stellatum *	20	---	---	20
Cinclidium stygium	trace	5	trace	5
Calliergon giganteum *	5	---	trace	5
Byrum neodamense **	---	10	5	5
Byrum pseudotriquetrum *	trace	---	---	---

* - extant in Ohio

** - extirpated in North America

SIGNIFICANCE OF SITE TO STUDY OBJECTIVES

The Rack - ELDA study locations provides interpretations of 1) a pre-late Wisconsin glacial advance, 2) paleoenvironmental changes associated with late Wisconsin maximum glaciation, and 3) late Wisconsin paleoclimate conditions 5 km from the ice margin at the time of maximum glaciation. The interpretation of late Wisconsin glacial maximum paleoclimate is the most inportant of the three, and provides a paleoclimate "baseline" for comparison for the rest of this study.

TABLE 2-4. GASTROPOD ASSEMBLAGES. Asterisk indicates presence of the species listed. Analyses by A.M. Dell, University of Cincinnati, Cincinnati, OH. (Dell, 1991)

Species	Position		
	Peat	Clay Just Above Peat	Upper Clay
Carychium exile	*	*	
Catinella sp.	*		
Discus cronkhitei		*	
Discus sp.		*	
Fossaria cf. *decampi*		*	
Fossari obrussa			*
Fossaria sp.		*	
Gastrocopta pentodon		*	
Gyraulus parvus	*	*	*
Lymnaea stagnalis			*
Physa sp.		*	*
Pomaptiopsis lapidaria		*	
Pupilla muscorum			*
Nesovitrea electrina		*	
Stagnicola caperata	*		
Stagnicola elodes	*	*	
Stenotrema leai		*	
Stenotrema sp.	*		
Succinea sp.	*	*	
Vallonia excentrica		*	
Valvata sincera	*		*
Valvata tricarinata			*
Vertigo elatior	*	*	
Vertigo modesta		*	

CHAPTER 3. SITES MARGINAL TO LAURENTIDE ICE

INTRODUCTION

A number of sites in the Mill Creek Valley are located in positions that are best described as being marginal to Laurentide ice (Fig. 3-1). This is not meant to imply that late Wisconsin sediments are present at each of these sites, but only to indicate their position with a known ice margin. Within the stratigraphic sequences at these sites are both non-glacigenic and glacigenic sediments of uncertain age.

The sites are presented in a south to north transect. The transect begins with two sites along the western edge of the Mill Creek Valley, the Caldwell Park and satellite dish sites (Fig. 3-1). The transect continues eastward to excavations in the Cross-County Highway - I-75 construction area in the middle, and along the eastern margin of the Mill Creek Valley (Fig. 3-1). The final site is the Day Care Center site located along the eastern margin of Mill Creek Valley (Fig. 3-1).

CALDWELL PARK

Location. The site is a park operated by the City of Cincinnati Park Board, and consists of 20 exposures in three southeast-flowing tributary streams to Mill Creek (Fig. 3-2). The park lies approximately 2 km north of the Rack Quarry and ELDA Landfill sites along the western margin of the Mill Creek Valley, and is approximately 1.5 km south of the mapped Hartwell Moraine (Fig. 3-1). The streams of interest are incised into terraces of unconsolidated materials, primarily diamicton and sand, and bedrock is exposed at the upstream end of the southernmost stream. Landslides and slumps of various sizes are common throughout the park, and are in some cases responsible for exposures of the sediments. The exposures vary in height from 2 to 22 m, and from 5 to 20 m in length.

Stratigraphy. Five stratigraphic units are exposed in Caldwell Park: 1) Ordovician limestone and shale bedrock, 2) massive diamicton, 3) well-sorted, medium sand, 4) stratified diamicton with interbedded sand and gravel, and 5) well-sorted medium sand.

Unit 1, bedrock. The Ordovician bedrock is exposed only at the upstream end of the southern most stream, but is exposed in the stream bed over a distance of about 75 m. Maximum exposed thickness within the park is 2.5 to 3 m. The upper surface of the exposed bedrock is free from striations, and the bedrock overall appears to be free of fold- or fault-type deformation.

Fig. 3-1. Map of central Mill Creek Valley, showing locations of sites in positions marginal to Laurentide ice. Location of the Hartwell Moraine (mapped limit of Laurentide ice) after Gray *et al*. (1972).

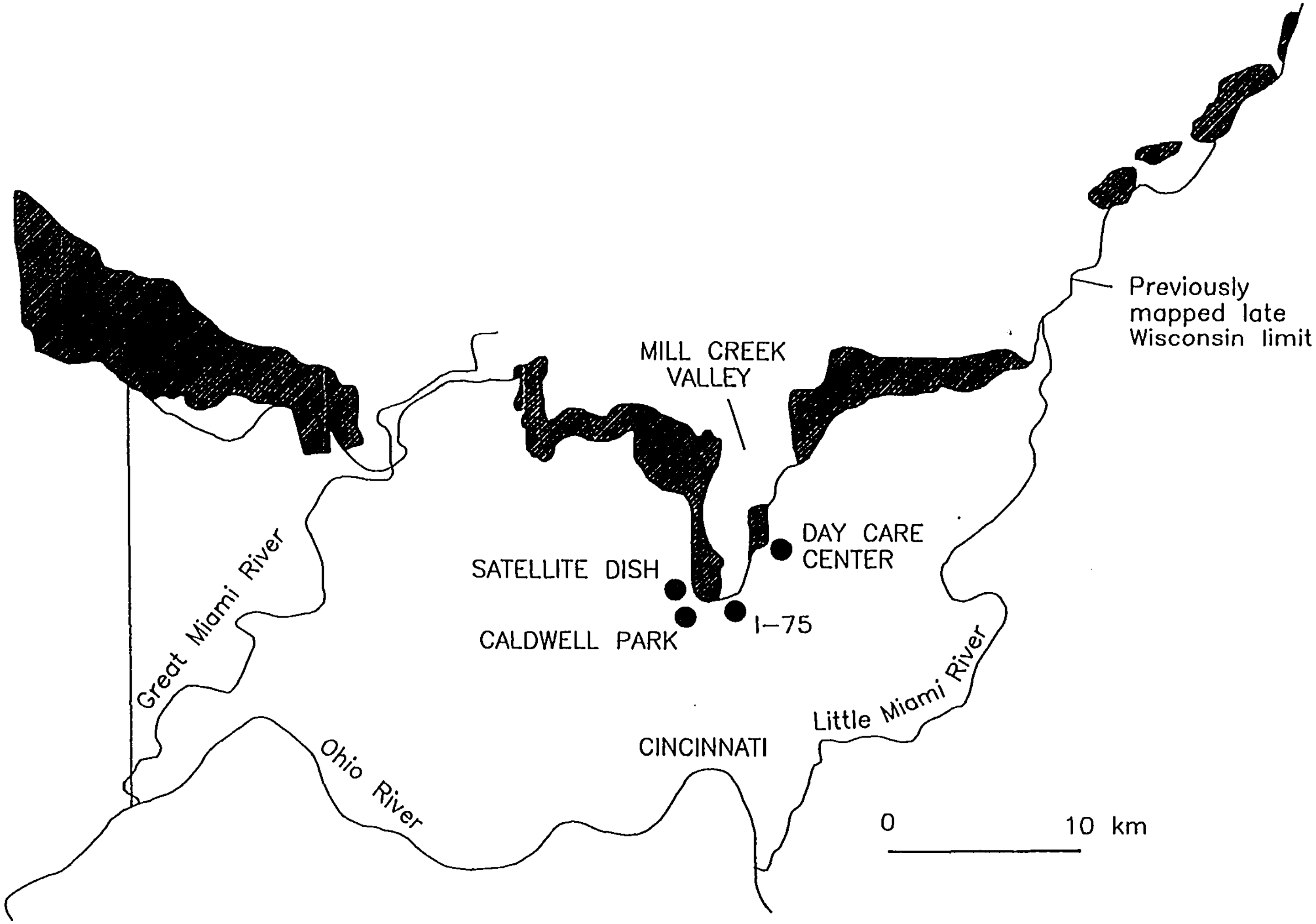
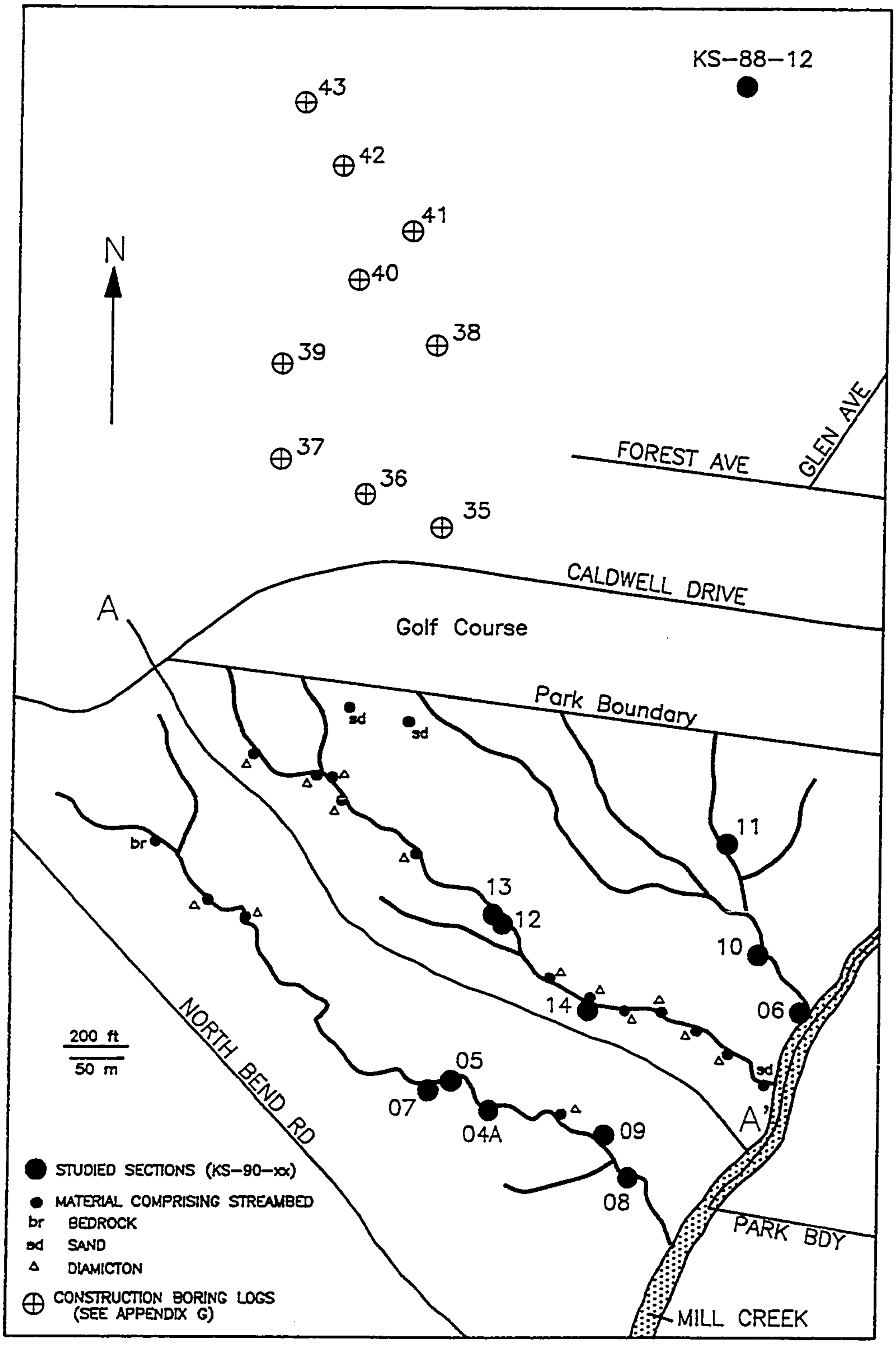

MILL CREEK VALLEY
Previously mapped late Wisconsin limit
DAY CARE CENTER
SATELLITE DISH
CALDWELL PARK
I–75
Great Miami River
Little Miami River
Ohio River
CINCINNATI
0
10 km

Fig. 3-2. Locations of studied sections in Caldwell Park, and driller's logs from an adjacent area. Base map is 1:2400 Cincinnati and Hamilton County Topographic Survey Map 363. Driller's logs listed in Appendix F.


KS-88-12
43
42
41
N
40
38
39
37
36
35
FOREST AVE
GLEN AVE
CALDWELL DRIVE
A
Golf Course
Park Boundary
sd
sd
br
11
13
12
10
14
06
200 ft
50 m
NORTH BEND RD
05
07
04A
09
sd
A'
08
PARK BDY
MILL CREEK
STUDIED SECTIONS (KS-90-xx)
MATERIAL COMPRISING STREAMBED
br BEDROCK
sd SAND
DIAMICTON
CONSTRUCTION BORING LOGS
(SEE APPENDIX G)

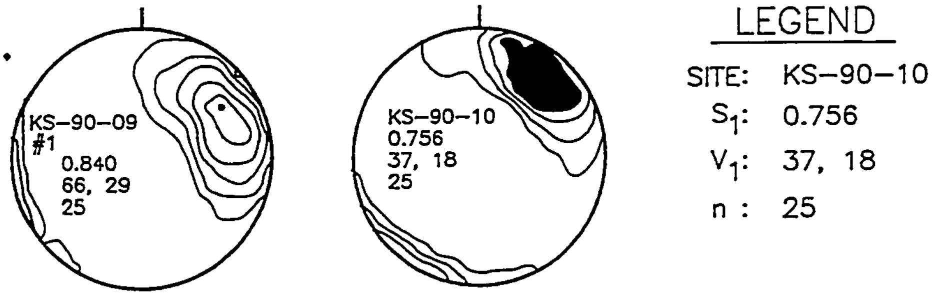
Unit 2, massive diamicton. Massive diamicton overlies bedrock; this diamicton is exposed in the bed of all three streams, and is generally traceable throughout the lengths of all three streams. Less than 1.5 m of this unit are typically exposed, but the unit has a maximum exposed thickness of about 6 m in the lower reaches of the streams. This diamicton has a SSC ratio of 31:46:23, and is calcareous throughout. The unit is everywhere massive, and free from apparent deformation features. Clast fabrics in this unit are to east, and are in agreement in orientation (Fig. 3-3). The basal contact of this unit with the underlying bedrock is sharp and distinct. Although the upper contact of this unit with overlying sands of unit 3 is generally sharp, a 0.3 to 0.6 m thick zone of interbedded diamicton and sand is observed two localities in the lower part of the southernmost stream.

Unit 3, sand. This unit is comprised of well-sorted, medium sand. The sand commonly has well-developed crossbeds, and individual packages of crossbeds vary in thickess from several tens of centimeters to about 2 m. Crossbed orientations, while highly variable, are generally indicate paleocurrent flow from the south to the north or northeast. This unit is extremely variable in thickness, ranging from 1.5 to over 14 m. In the basal 2 m, small concentrations of granule-sized coal and/or charcoal pieces are present. In the downstream ends of the streams, the basal 5 m of the unit contains deformed and undeformed lenses of diamicton. These lenses range in thickness from a few centimeters to a maximum of about 1 m, and range in length from 0.5 to 5 m. Deformation in these lenses is by folding. The largest of these diamictons commonly contain folded lenses of well-sorted sand; bedding in theses sand lenses is preserved, and folded. Individual coarsening- and fining-upwards sequences are observed in different bedded packages throughout this unit, but there is no consistent overall trend. Iron-oxide and manganese staining is common throughout the units; localized areas where the staining is especially heavy have a crustose texture. The upper contact of this unit with overlying stratified diamicton of unit 4 is indistinct. At some locations, the contact is sharp and distinct, at other locations there is a zone 1 to 1.5 m thick comprised of interbedded sand and stratified diamicton. This contact varies over an elevational range of 7 to 8 m throughout the park.

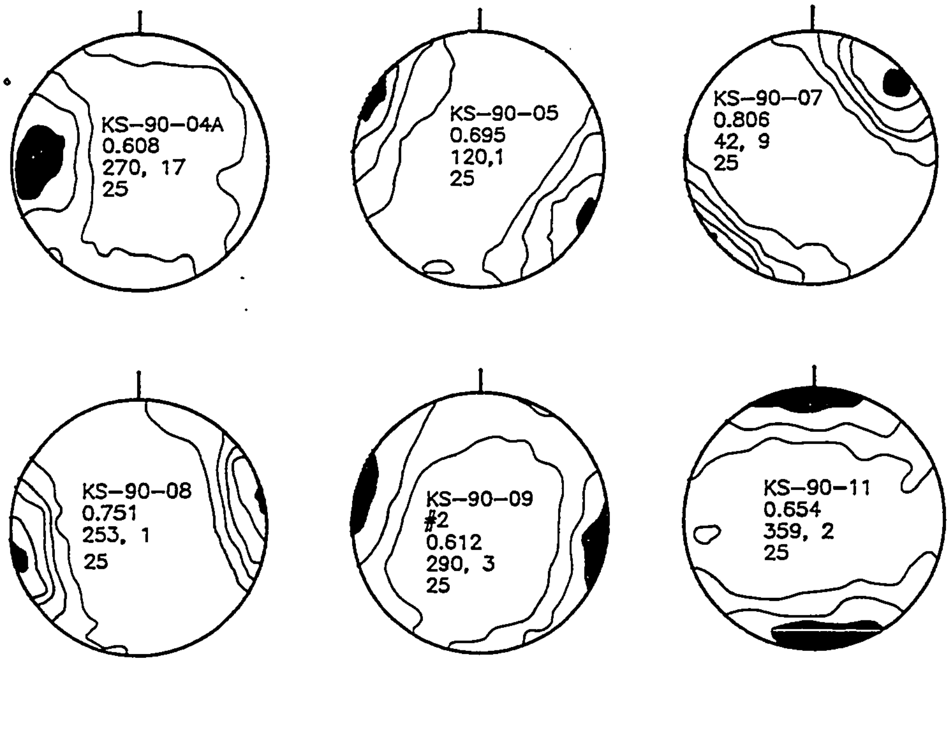
Unit 4, stratified diamicton. Stratified diamicton makes up most of unit 4. This diamicton is matrix-supported, calcareous, slightly sandier in composition than the diamicton of unit 2 (SSC = 35:38:27), and is interbedded with sand and gravel. The unit is extremely variable in thickness, and ranges from 3 to 15 m. At individual exposures, this unit varies in composition from 100 percent stratified diamicton to about 50 percent stratified diamicton/50 percent sand or gravel. Individual stratified "beds"

Fig. 3-3. Clast fabrics from diamicton units at Caldwell Park: a) massive diaicton of unit 2, b) stratified diamicton of unit 4. Numbers at upper portion of each circle indicate the section number of the fabric; each circle represents clast orientation projected onto the lower hemisphere of an equal area net; numbers on the lower side of each circle represent the fabric strength (S_1; 0 = random, 1 = uniform), azimuth and plunge of the mean vector (V_1), and number of clasts (n). Contour interval is 2 standard deviations, with black areas representing the maximum deviation from random. Measures after Lawson (1979).

a.


KS-90-09
#1
0.840
66, 29
25
KS-90-10
0.756
37, 18
25
LEGEND
SITE: KS-90-10
S_1: 0.756
V_1: 37, 18
n : 25

b.


KS-90-04A
0.608
270, 17
25
KS-90-05
0.695
120,1
25
KS-90-07
0.806
42, 9
25
KS-90-08
0.751
253, 1
25
KS-90-09
#2
0.612
290, 3
25
KS-90-11
0.654
359, 2
25

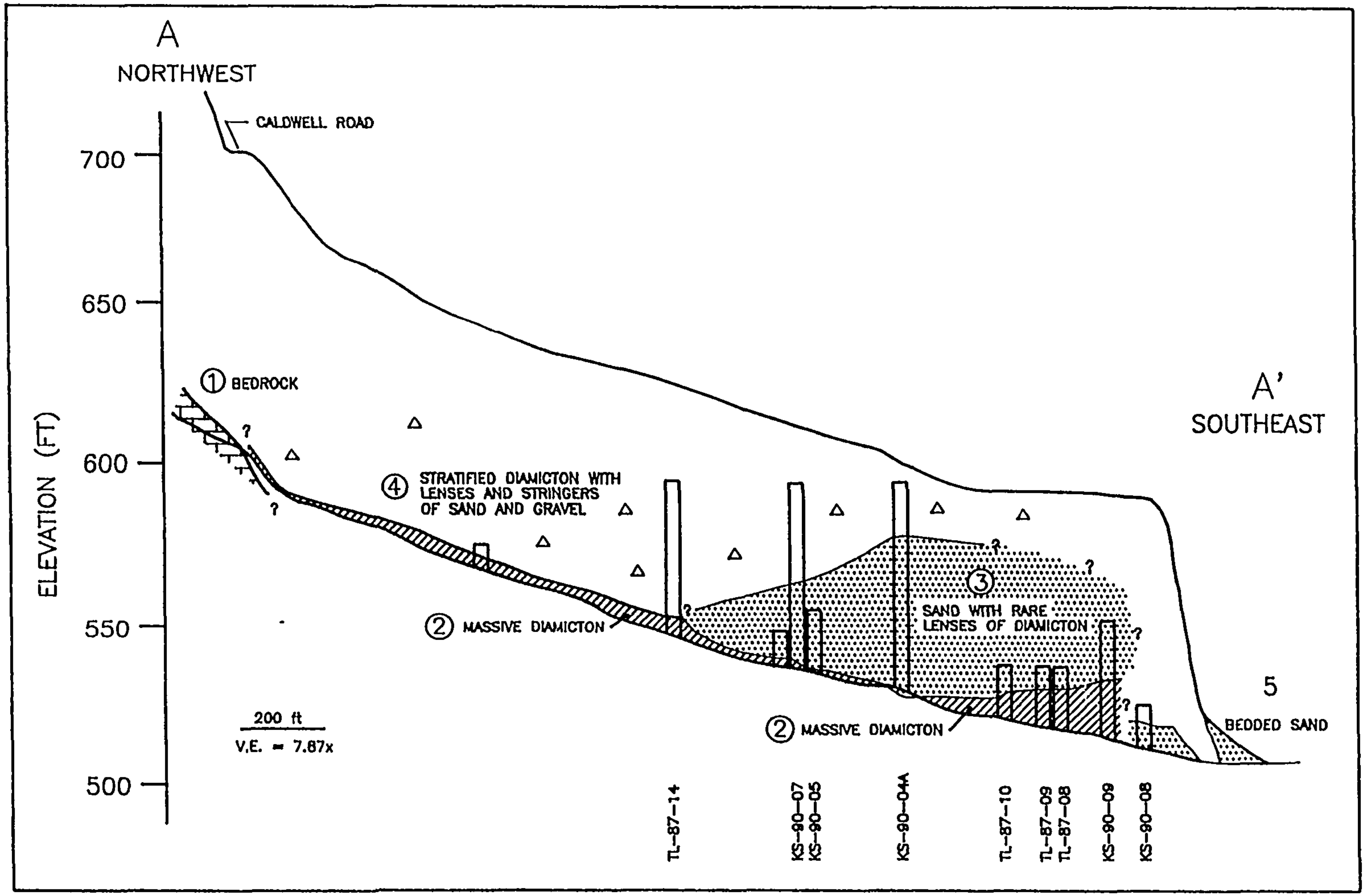
range in thickness from 10 to 45 cm, and may be capped by very fine sand or silt stringers. Some stratified beds exhibit grain-size trends, but most are massive, with no apparent grain size trends. Clast fabrics from this unit are highly variable, and show no consistent patterns or trends (Fig. 3-3b). The upper limit of this unit is not observed; at two exposures, the unit continues upwards to the modern hillside surface, 2 to 3 m below the upper surface of the terrace. Sediments identified in driller's logs at a construction site adjacent to the park (see Fig. 3-2 for well locations) indicate interbedded diamicton and sand of this unit extends into the upper portions of the terrace immediately adjacent to bedrock (shown schematically on Fig. 3-4).

Unit 5, sand. The uppermost stratigraphic unit at Caldwell Park is a well-sorted medium sand with thin silt/clay interbeds. These sands are cross-bedded, with the cross-bedding indicating stream flow to the south, same as the present-day Mill Creek. Maximum thickness of these sands is 3 to 3.5 meters, with a maximum lateral exposure of 50 to 60 meters. This unit is exposed only where the tributary streams empty into Mill Creek, and forms the cores of small terraces that are 3 to 4m in height. Abrupt lateral termination of this unit (and the terraces it forms) against the massive diamicton of unit 2 is noted in all three streams.

Composite Stratigraphy. Because of the variable size and distribution of the studied exposures, not all units were exposed at each location. Units identified at the studied exposures were therefore combined to form a composite stratigraphy for the park (Fig. 3-4; Table 3-1). As previously discussed, Ordovician bedrock (the oldest stratigraphic unit) is observed only the the upstream end of the southernmost stream. Units 2, 3, and 4 form the body of the incised terrace, and make up nearly all of the studied sediments. Unit 5, the well-sorted, cross-bedded sand, is found only at the confluences of the streams with Mill Creek.

Interpretation. Unit 2, the massive diamicton, is interpreted to be a subglacially deposited till. Consistent, parallel alignment of clast fabrics is a characteristic of both lodgement and meltout tills (Dreimanis, 1988), and is not considered conclusive for either type. Other features "characteristic" of lodgement tills (e.g., clast clusters, striated boulder pavements, "smudges" of substrate materials; see Boulton (1972b), Kruger (1979), Dreimanis (1988)) are generally absent, as are "characteristic" features of meltout tills (e.g., lenses of sorted sediments, drapes of sorted sediments over large clasts; see Haldorsen and Shaw (1982), Bouchard *et al.* (1984), Van der Meer *et al.* (1985)). The interbedded nature of the upper portion of the unit with sands of unit 3

Fig. 3-4. Profile along the southernmost stream, Caldwell Park, showing the distribution of units. Terrace profile along line A- A' shown on Fig. 3-2. Locations of studied sections indicated along base of profile, and unit contacts dashed where infered. Projections from nearby driller's logs as shown.


A
NORTHWEST
CALDWELL ROAD
700
650
600
550
500
ELEVATION (FT)
① BEDROCK
④ STRATIFIED DIAMICTON WITH LENSES AND STRINGERS OF SAND AND GRAVEL
② MASSIVE DIAMICTON
③ SAND WITH RARE LENSES OF DIAMICTON
② MASSIVE DIAMICTON
5
BEDDED SAND
A'
SOUTHEAST
200 ft
V.E. = 7.87x
TL-87-14
KS-90-07
KS-90-05
KS-90-04A
TL-87-10
TL-87-09
TL-87-08
KS-90-09
KS-90-08

suggests that the upper portion may have been deposited by meltout or sediment flow. Deposition by either lodgement or meltout indicates an episode of glacial advance of wet-based ice over the site; clast fabrics indicate that the ice flow was from the east.

TABLE 3-1. UNIT OCCURRENCE AND COMPOSITE STRATIGRAPHY, CALDWELL PARK. Asterisk indicates presence of a given unit at a specific locality; MCO indicates the unit is observed only at the tributary - Mill Creek confluence. Localities shown on Fig. 3-2. Note that Unit 1 (bedrock) is observed only at the upstream end of the southernmost tributary stream.

Unit	-04A	-05	-06	-07	-08	-09	-10	-11	-12	-13	-14
5			MCO		*						
4	*			*		*	*	*	*	*	
3	*	*		*		*	*	*	*	*	*
2	*					*			*	*	*
1											

Sands of unit 3 are interpreted to be fluvially-deposited. The absence of gravel from these sands suggests that they are not outwash derived from the underlying till. The overall thickness and continuity of the unit suggests that these sands were likely not deposited in a subglacial or englacial channel. Paleocurrent directions from the crossbeds indicates flow from the south. The presence of charcoal/coal, present at the surface in Kentucky, but not Ohio, also supports a southerly source. (It is, however, acknowledged that these could have been reworked from older deposits.) If these sands are sourced from the south, it requires at least a small marginal retreat of the ice to allow water to flow between the valley wall and ice margin.

The stratified diamicton of unit 4, and its associated interbeds of sand, and sand and gravel, are interpreted to represent sediment flow deposits, and sediment flow deposits intermixed with fluvial sediments. The highly variable clast fabrics in the diamicton portions of the unit indicate the sediment flows were sourced from several locations. West- and northwest-trending fabrics suggest flows of material from the adjacent valley wall; fabrics from the east may indicate flows derived from a nearby ice margin within the valley to the east. The intermixing of the flows with fluvial sediments indicates the processes were contemporaneous, and may indicate that fluvial activity may have been responsible for initiation of some flow activity.

The well-sorted, crossbedded sands of unit 5 are interpreted to be of fluvial origin.

Crossbed orientations indicate flow to the south. The locations of exposures of this unit, and their abrupt lateral terminations against unit 2 indicate that these sands were deposited after the unit 2-3-4 sequence.

Summary of Interpreted Sequence. Units 2, 3, and 4, are interpreted to represent a single ice advance across the Caldwell Park area. Unit 2, interpreted as a subglacial till, records the advance of ice across the site. Unit 3 sands reflect a marginal recession, and fluvial activity which may derive its water from non-glacial sources to the south. Unit 4 reflects ablation of the ice, with sediment flows derived from sediments on the valley wall, as well as those covering stagnating ice. The lack of radiometric dating at this site makes assignment of the age of this advance uncertain. Clast fabrics in the till unit, indicating ice flow from the east, are consistent with those recorded at the Rack Quarry and ELDA Landfill sites, and with structural data reported by Tucker (1962) from till at the Rack Quarry. Ice flow from the east is consistent with interpreted flow direction of the Illinoian Clermont Lobe of Tucker (1962).

Deposition of unit 5 occurred after the advance of the Illinoian ice. Exact timing is unclear, and the sands of this unit may be related to fluvial activity of 1) post-Illinoian, pre-late Wisconsin, 2) late Wisconsin, or 3) post-late Wisconsin age.

SATELLITE DISH SITE

Location. This site is a excavation created by the building of an access road to a construction site; the site is located approximately 750 m north of the center of Caldwell Park, and is about 1 km outside of the mapped late Wisconsin Hartwell Moraine (Fig. 3-1). This site is a single trench exposure 3.5 m high by 2 m wide.

Stratigraphy. Deeply weathered diamicton is the only unit exposed at this site. The upper 1.5 m both oxidized and leached. The lowest exposed 2 m of the unit is oxidized, but calcareous, with a SSC ratio of 31:41:28. These 2 m are generally massive, although isolated weak stratification, denoted by silt partings, is present. Two clast fabrics in the lower portion of the diamicton are oriented to the northwest. The boundary between the upper leached and lower calcareous zones is marked by 15 cm thick unit enriched in silt and clay (SSC = 13:54:33). The upper limit of the exposure is the present-day land surface; the lower limit is at the level of the adjacent construction road.

Interpretation. This unit is interpreted to be a sediment flow deposit. There is insufficient data to determine if this flow deposit is glacigenic in nature. The clast fabrics indicate that the flow was probably derived from higher up on the adjacent valley wall. Although no chronologic control is available for this unit, the extensive degree of weathering suggests an interpretation of pre-late Wisconsin for the age.

I-75 AT CROSS-COUNTY HIGHWAY

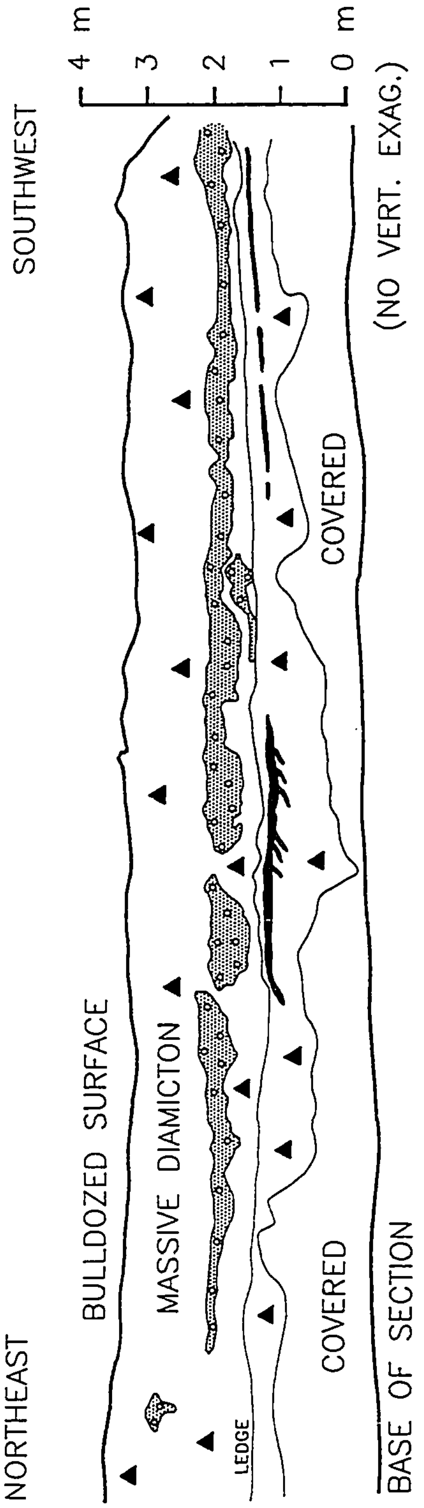
Location. This location consists of three main exposures associated with the construction of the interchange between Cross-County Highway and I-75. The general construction area is from the central portion of Mill Creek Valley eastward to the east valley wall just south of Galbraith Road. The southernmost exposure, KS-88-13, lies approximately 2 km east of Caldwell Park (Fig. 3-1); the central exposure, Main Cut, is approximatly 800 m northeast of KS-88-13. The final section, KS-88-05, is approximately 600 m northeast of the main exposure. The Main Cut and KS-88-05 section lie along the mapped Hartwell Moraine of Gray *et al.* (1972). Units exposed at the these sections are utilized to construct a composite stratigraphy for the construction area.

Stratigraphy. Three units comprise the stratigraphy in the construction zone: 1) medium sand, 2) calcareous diamicton, and 3) massive calcareous clay.

Unit 1, sand. This unit is exposed at the base of both the KS-88-13 and Main Cut sections. At KS-88-13, 1 m of the sand is exposed in a trench 15 m in length; approximately 5 m of this unit are exposed along the base of the main cut, with exposures of the sand occurring over 300 to 400 m laterally. The sand is very well-sorted medium sand with well-developed crossbedding; crossbed orientation is variable, indicating deposition by flow to the south and west. The upper contact of this unit with the overlying diamicton is irregular, and appears transitional over a vertical distance of 20 to 50 cm. Within this transition zone, lenses of diamicton occur within zones composed dominantly of sand, sand lenses occur in zones composed of diamicton, and in some places the diamicton and sand are interfingered.

Unit 2, diamicton. Sandy diamicton overlies the sand of unit 1. At KS-88-13, about 2 m of this unit are exposed, and form the uppermost unit at the section. At the main cut, 3 to 4 m of the diamicton were exposed. The diamicton, matrix-supported and calcareous, contained lenses of sand and gravel up to 60 cm in height and several meters in length (Fig. 3-5). Within some of these lenses, well-developed crossbedding is preserved. Along the base of some of the lenses are "tails" of the sorted sediment which dip upvalley to the north. As mentioned above, the lower contact of the diamicton with the underlying sands is transitional and irregular. The upper contact of the diamicton

Fig. 3-5. Facemap of a portion of Main Cut, I-75 at Cross-County Highway, showing lenses of sorted sands and gravels in the diamicton of unit 2.


NORTHEAST
SOUTHWEST
BULLDOZED SURFACE
MASSIVE DIAMICTON
LEDGE
COVERED
COVERED
BASE OF SECTION
4 m
3
2
1
0 m
(NO VERT. EXAG.)

with ther overlying clays is irregular, but distinct.

Unit 3, clay. Massive to laminated clays of unit 3 overlie the unit 2 diamicton. Over 5 m of laminated clay is exposed along the main cut; approximately 2 m of massive and laminated clays are exposed at KS-88-05. Laminations are marked by alternating light and dark layers; the dark layers are dense and clayey, the light layers are enriched in silt. Hand samples of this unit tend to break horizontally along the silt layers. In the lower 2-3 meters of the unit, the dark layers are 7 to 10 cm thick, and the intervening light silt layers are about 1 cm thick. This spacing appears relatively uniform over the lateral extent of the exposed cut. In the clay exposed at KS-88-05, the dark, clay-rich layers range from 2 to 10 cm in thickness, and the light silt layers are only 2-5 mm in thickness. Also at this exposure, channel-shaped lenses of coarse sand and gravel are found within the clay. Along the undersides of these sand and gravel lenses, the clay has been eroded, as evidenced by truncated, horizontal laminations; clay over these lenses exhibits continuous laminations draped over the irregular upper surface. This unit forms the uppermost land surface in the construction area.

Interpretation. The observed stratigraphy is interpreted to represent sediments deposited in response to a single ice advance. The sands of Unit 1 is are interpreted to be braided fluvial outwash sands associated with the advancing glacier. The overlying diamicton is interpreted to be a subglacial till; the nature of the contact with the underlying sand suggests deformation, with incorporation of the sand, and mixing of the sand and diamicton at the time of diamicton deposition. Preserved bedding in some of the channel-shaped sand bodies suggests the formation of subglacial drainage channels in previously deposited diamicton, so-called "Nye"-channels (Nye, 1973). The large sand and gravel channels which exhibit no internal structures are all nearly horizontal, and may also be Nye-channels. The deformation in the lower portions suggests a lodgement or deformation origin. The abundance and size of sand/gravel bodies, themselves interpreted to be subglacial channel deposits, reflect the presence of abundance quantities of meltwater; it is reasonable to suggest that localized deposition by meltout may also have been occurring. The clays, found only at the sites adjacent to the mapper Hartwell Moraine are interpreted to be lacustrine sediments; this lake basin was likely formed by recession of the glacier, and ponding of meltwater between the ice margin and the moraine.

Although no material for radiometric dating was collected from these sites, it is interpreted that these units are late Wisconsin in age. This interpretation is based primarily upon the correlation of the diamicton to diamicton units inside of the Hartwell

Moraine. These correlations are discussed in detail in chapter 4, and will not be covered here.

DAY CARE CENTER

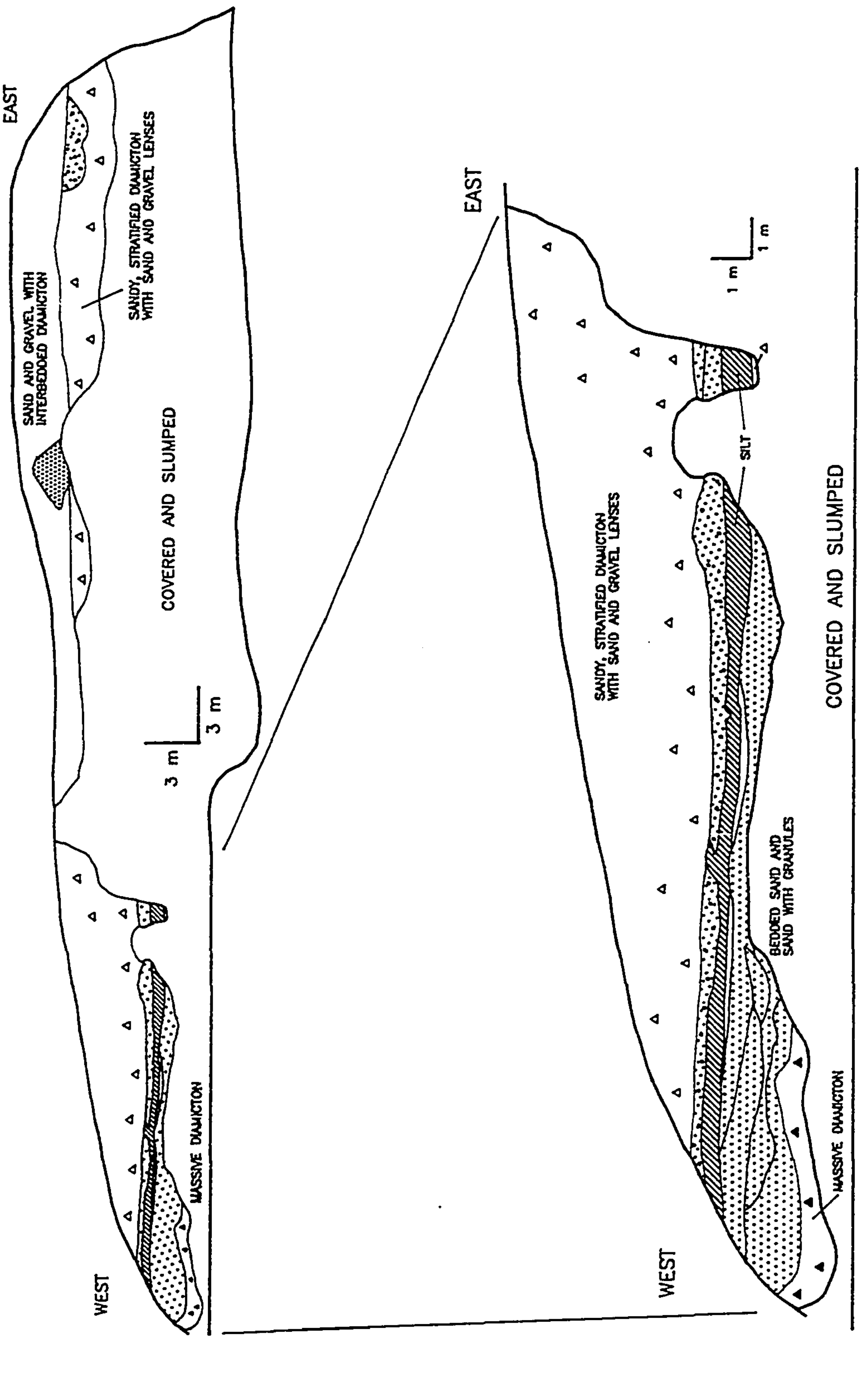
Location. This section is located on the north bank of an unnamed stream approximately 800 m east of Reading Road in Evendale (Fig. 3-1), along the east wall of the Mill Creek Valley. The exposure is approximately 4 km north-northeast of Cross-County Highway section KS-88-05, and at the edge of the mapped late Wisconsin Hartwell Moraine. The exposure is about 15 m high and 70 m long; sediments are well exposed for 15 to 20 m at each end, but the central 30 to 40 m is largely covered by a slump. Only the uppermost units are exposed above the slump. Less than 100 m to the west from the exposure, up to 2 m of Ordovician limestone and shale bedrock is exposed above stream level.

Stratigraphy. The stratigraphy at the site is made up of five units: 1) massive diamicton, 2) channelized and bedded sands and fine gravel, 3) silt, 4) sand and gravel, 5) stratified diamicton, and 6) mixed diamicton and sand and gravel. Units 1 through 5 are exposed at the west end of the exposure; units 5 and 6 are exposed at the east end of the exposure (Fig. 3-6).

Unit 1, diamicton. This unit is a massive, calcareous diamicton exposed at the base of the western end of the section. The diamicton has an exposed thickness of about 1 m, and is exposed over a lateral distance of about 6 m. The unit contains no apparent structures; a single clast fabric in this unit is oriented to the northeast (azimuth = 055°). The unit is overlain by the sands of unit two. The upper surface of the diamicton is irregular; the contact between the diamicton and the overlying sands is sharp and distinct.

Unit 2, sand. Bedded sands and small gravel forms unit 2. This unit, exposed only at the western end of the exposure, has an overall channel-shaped geometry (Fig. 3-6). Within the unit, are numerous individual packages of bedded sand and small gravel. Crossbed orientations within several of these channels reflects deposition by a north-flowing ("into the exposure") system. The boundaries of each package are readily discernable, and are marked by truncated bedding. The individual packages are up to 70 cm in thickness, and several meters in length. Individual packages contain varying amount of silt and clay; within a couple of the packages, clay drapes are common. The unit is capped by a discontinuous stratified diamicton up to 20 cm thick. Overlying the diamicton (where present) and sand of unit 2 is the silt of unit 3. This contact is sharp,

Fig. 3-6. Facemap, Day Care Center.


EAST
SAND AND GRAVEL, WITH INTERBEDDED DIAMICTON
SANDY, STRATIFIED DIAMICTON WITH SAND AND GRAVEL LENSES
COVERED AND SLUMPED
3 m
3 m
MASSIVE DIAMICTON
WEST
EAST
1 m
1 m
SILT
SANDY, STRATIFIED DIAMICTON WITH SAND AND GRAVEL LENSES
COVERED AND SLUMPED
BEDDED SAND AND SAND WITH GRANULES
MASSIVE DIAMICTON
WEST

distinct and traceable over 15 to 20 m at the western end of the exposure.

Unit 3, silt. A uniform silt layer, 30 to 50 cm thick and 15 to 20 m long makes up unit 3. This unit is massive in appearance, with no apparent internal structures. This unit has isolated zones which contain gastropods. The upper surface of the unit is gently undulatory, and the unit is overlain by sands and gravels of unit 4.

Unit 4, sand and gravel. Sand and gravel of generally uniform thickness overlies the silts of unit 3. Unit 4 sand and gravel ranges from 40 to 60 cm in thickness, and extends over 15 to 20 m at the western end of the exposure. This unit is heavily oxidized; is some spots the sediments are moderately-well cemented by precipitated iron oxide. Near the center of the western end exposure, the silts of unit 3 "bulge" through unit 4; no other structures were noted within the unit.
The upper contact of this unit with the overlying stratified diamicton of unit 5 is sharp and easily traceable over 15 to 20 m of exposure.

Unit 5, stratified diamicton. Stratified diamicton makes up unit 5. This unit reaches up to 8 m in thickness, and extends to the top of the exposure at the west end of the section. Within this unit are thin interbeds of fine sand and silt; these interbeds are less than 10 cm in thickness, but may extend laterally for up to 5 m. The basal 25 cm of this unit are completely oxidized, but are not leached. The remainder of the unit is calcareous, although field testing with hydrochloric acid indicates that the upper 2 m of the unit at the west end are less calcareous than the base of the unit. A single clast fabric near the base of the unit at the western end of the exposure is very weakly oriented to the southwest. At the east end of the exposure, this unit contains abundant wood. Conventional radiocarbon age estimation of two samples collected 1 m below the top of the unit yielded ages of 35,550$\pm$880 (PITT-0928) and 39,830$\pm$1450 (PITT-0929). Also at the east end, channel-form sand and gravel deposits are inset into the top of the unit. The contact between the diamicton and the sand/gravel deposits is erosional, as evidenced by truncated stratification in the diamicton. In the central and eastern portions of the exposure, this unit is overlain by mixed diamicton and sands and gravels of unit 6. The sharp and irregular contact between these units suggests that it is erosional as well. Additional supporting evidence for an erosional contact is the apparently truncated upper surface of the channel-form sand and gravel bodies inset into the diamicton.

Unit 6, diamicton/sand and gravel. This unit is present in the central and eastern portions of the exposure. At its westernmost extent, the basal limit of the unit becomes indistinct, and units 5 and 6 appear to merge and become a single unit. The maximum exposed thickness of the unit is approximately 3 m; the unit extends laterally for a distance of about 40 m. Within this unit are zones where diamicton is dominant with interbeds of sand and gravel; in other positions, sand and gravel are dominant and contain interbeds of diamicton. Rare pieces of wood are present in the diamicton portions of the unit.

Interpretation. Unit 1 is interpreted to be a subglacial till of undetermined genesis deposited by ice flowing from the northeast; this ice flow direction is, in general, consistent with east-to-west flow directions interpreted for tills at the Rack, ELDA, and Caldwell Park sites. This unit is interpreted to be correlative to the tills at these locations, and is therefore interpreted to be of Illinoian age. The overlying sands of unit 2 reflect fluvial downcutting into the till of unit 1. It is interpreted that these sands represent downcutting and subsequent sand deposition in a subglacial position. If this is the case, these sands represent Nye-channel (Nye, 1973) deposits. The presence of "packages" of sand within this unit indicate multiple episodes of erosion and deposition, as well as some migration of the active fluvial channel. Cross-cutting relationships between some of the packages, and the general shape of some individual packages suggests erosion and deposition in a conduit-type of system, such as might be expected in a Nye channel. The intermittent capping diamicton represents diamicton deposition over the sands in the waning stages of the life of the channel. The silts of unit 3 have moderate clay content and are interpreted to have been deposited in an aquatic environment. The presence of isolated zones with gastropods indicates that this aquatic environment was not subglacial; this requires the melting of the ice responsible for units 1 and 2. (These gastropods offer the best opportunity for future workers to "date" the unit using amino acid racemization (Miller *et al.*, 1987).) Sand and gravel of unit 4 are interpreted to have been deposited in a fluvial setting; the timing of this deposition uncertain.

The unit 5 stratified diamicton is interpreted to be a thick sequence of sediment flow deposits. A key question with regard to this unit is its "age". The radiocarbon age estimates of wood would suggest that the deposit is too young to be Illinoian in age, but too old to be late Wisconsin in age (if it is glacigenic). One factor to consider is the potential for contamination of the sample. Olsson (1974) reported that for "infinite"-aged material, 1 percent contamination by modern carbon can produce "finite" ages on the order of 37,000 radiocarbon years. If this type contamination is present, these samples could actually be "infinite" age, and the deposit related to the underlying Illinoian sediments. This is the prefered interpretation of this deposit. An alternative explanation is that the sediment flows are completely unrelated to any glacial episode, and that the estimates reflect the age of debris flows on the land surface. The wood in this scenario would be trees growing on the landscape at the time the flow was initiated. The stratified nature of this unit is inconsistent with slope failure of non-saturated material (Johnson, 1970); also, if the wood were derived from trees alive on the land surface, it is expected that stumps and/or roots of these trees would be present. All wood observed in the unit was broken and transported; no roots or stumps were observed. This unit is problematic, because the site lies on the mapped limit of the late Wisconsin Hartwell Moraine. Sediment flow deposits along the margin of an active glacier would be expected. Additional age estimates in this unit and the underlying units would help decipher this problem.

Unit 6, the uppermost unit at this exposure, is interpreted to represent the final sediments deposited in the sediment flow sequence responsible for the underlying unit 5. The lateral merging of the two units supports this interpretation. The increased sorting in this unit (evidenced by sand and gravel zones) reflects water flowing over the unit, either as channelized fluvial-type flow, or perhaps as sheet-flow over the surface of the flow deposits. Either of these mechanisms could result from the dewatering of the sediments during flow (Lawson, 1979).

SUMMARY OF SITES

The Caldwell Park, satellite dish, and Day Care Center sites are all dominated by sediment flow deposits, certainly common in any glacial environment. At the Caldwell Park and Day Care Center sites, these flow deposits overlie basal tills interpreted to be of Illinoian age. The position of the sites with respect to the late Wisconsin glacial limit leaves these interpretations open to debate. Age estimates would be extremely helpful in solving this question; unfortunately, these deposits have not been found to contain datable materials. As discussed for the Day Care Center site, even having age estimations from these deposits does not always clear up the problem.

Sediments exposed at the I75 - Cross-County Highway exposures are interpreted to be late Wisconsin in age, based on correlation with units within the late Wisconsin limit. These correlations are discussed at length in the following chapter.

TABLE 3-2. STRATIGRAPHIC CORRELATIONS - ICE MARGINAL SITES.

Age	Caldwell Park	Satellite Dish	I-75	Day Care Center
Late Wisconsin			3 - clay 2 - diamicton	
?	5 - sand		1 - sand	
Illinoian	4 - stratified diamicton	1 - diamicton		5 - stratified diamicton
	3 - sand			4 - sand & gravel 3 - silt 2 - sand
	2 - diamicton			1 - diamicton
Ordovician	1 - bedrock			(bedrock)

SIGNIFICANCE OF THE ICE-MARGINAL SITES

These sites provide valuable stratigraphic information with regards to the development of a "land-surface" model. Unfortunately, these sections provide little or no information for paleoclimate interpretation.

CHAPTER 4. SUBSURFACE GEOLOGY OF THE CENTRAL AND NORTHERN MILL CREEK VALLEY

INTRODUCTION

Subsurface data of several types are available within the study area. These data consist almost entirely of driller's logs of water wells, and from construction projects. These data have been used to construct a north to south cross-section, and three east to west cross- sections within the study area. The purpose of these cross-sections is two-fold: 1) to delineate the subsurface stratigraphy, and 2) to tie this stratigraphy to outcrop exposures, and thereby tie together exposures throughout the valley.

Driller's logs used in this study are all referenced in English units. In the discussion below, and on the sections, thicknesses and elevations are therefore listed in metric and English units. Listings of the individual driller's logs used in the cross-sections are given in Appendix G.

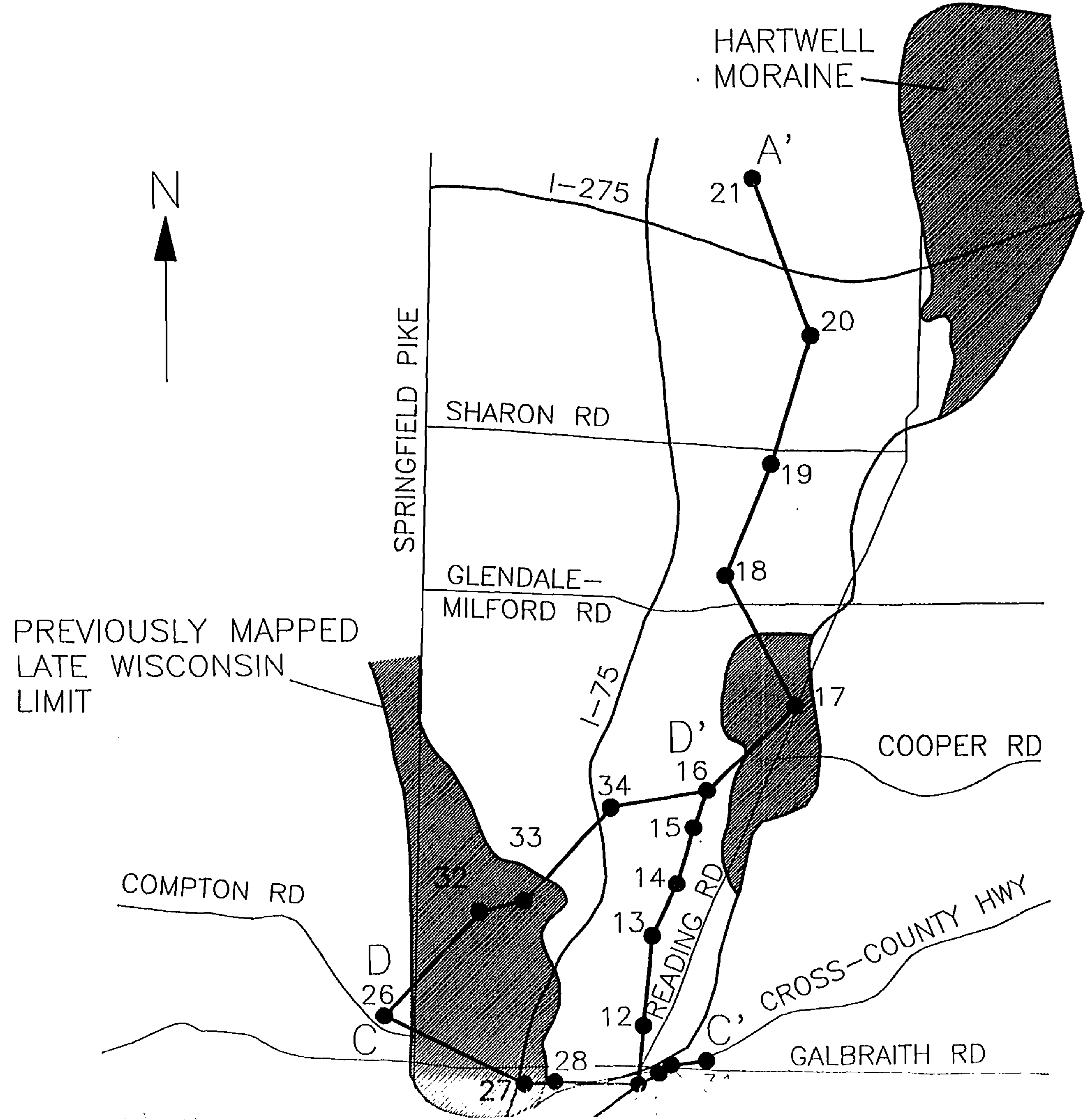
NORTH-SOUTH SECTION, A-A'

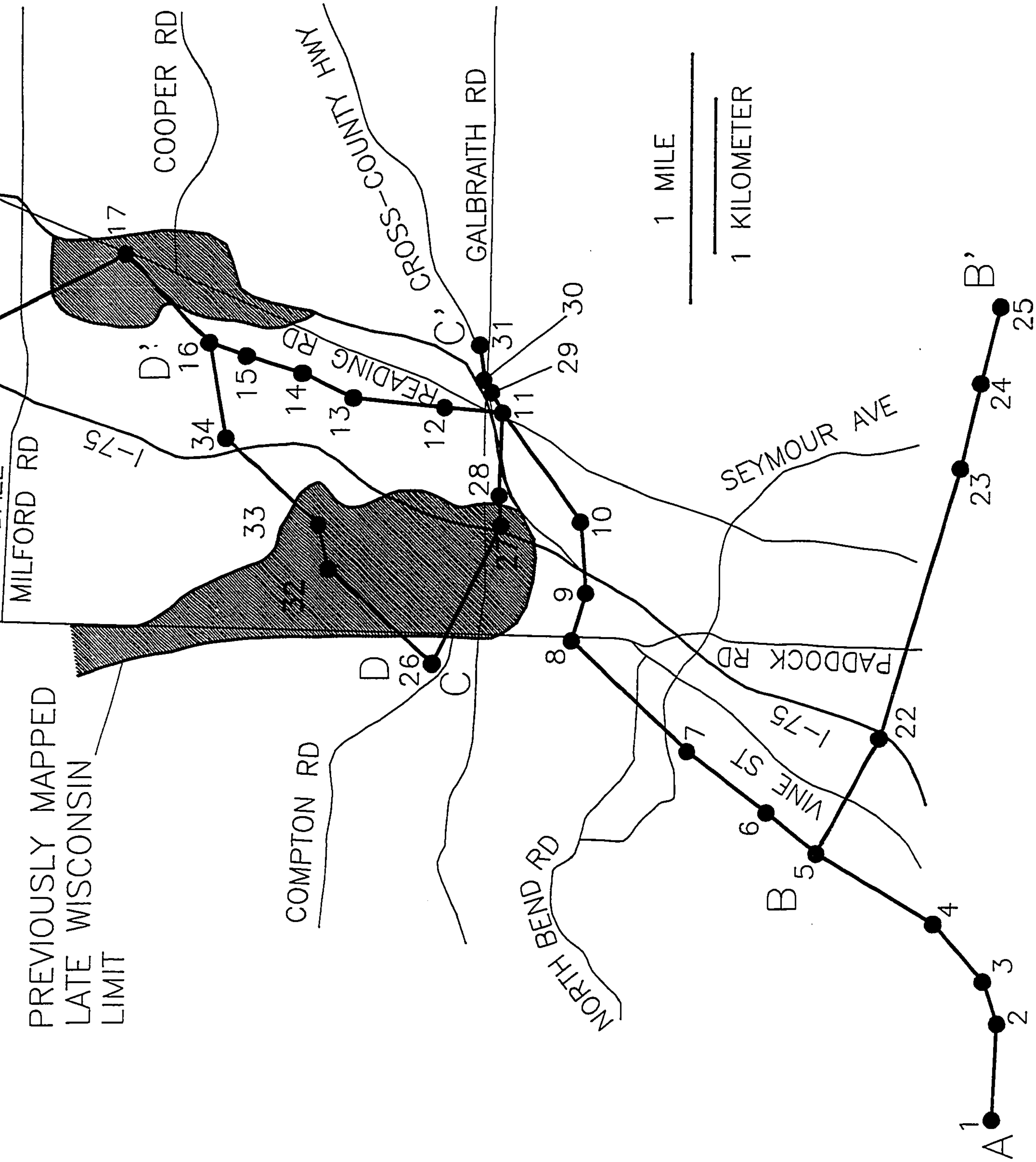
Location. This cross-section extends from approximately 2 km down valley from the Rack-ELDA site northward to near the I75 - I275 intersection, a distance of approximately 19 km (Fig. 4-1), and is composed of 21 logs (Plate 1a; in back pocket). The southernmost 7 km lies along the western margin of Mill Creek Valley; the central 2 km of the section is an east-west oriented section across the valley. The northernmost 10 km lies along the eastern margin of the Mill Creek Valley. The cross-valley portion of the section (wells 8-11) lies just outside of the late Wisconsin Hartwell Moraine (Fig. 4-1).

Stratigraphy. Subsurface stratigraphy in the core of Mill Creek Valley is fairly consistent and correlatable throughout the valley, and is comprised of six units of unconsolidated material. Bedrock is penetrated by wells in the extreme south and north-central portions of the section; in all cases, bedrock is overlain by sand and/or gravel of unit 1.

Unit 1, sand and gravel. Where the wells penetrate to bedrock, this sand and gravel unit ranges in thickness from 3 m (10 ft) to the south, to about 38 m (125 ft) in the north-central portion. The thinning to the south is controlled by bedrock topography; bedrock rises to the south, reflecting the influence of pre-Illinoian, north-flowing drainage in the Mill Creek Valley (Ray, 1974, and references therein). Within this unit are zones of sand only, as well as mixed sand and gravel. Also recorded within this unit

Fig. 4-1. Location of wells used in constructing stratigraphic cross-sections, cross-section lines, and position of the late Wisconsin Hartwell Moraine (mapped late Wisconsin limit). Base map includes portions of the Cincinnati West, Cincinnati East, and Glendale 7.5' topographic quadrangle maps. Position of the Hartwell Moraine after Gray *et al.* (1972).


HARTWELL
MORAINE
A'
21
N
I-275
20
SPRINGFIELD PIKE
SHARON RD
19
18
GLENDALE-
MILFORD RD
PREVIOUSLY MAPPED
LATE WISCONSIN
LIMIT
17
I-75
D'
COOPER RD
16
34
15
33
14
32
READING RD
COMPTON RD
13
CROSS-COUNTY HWY
D
26
12
C'
C
28
GALBRAITH RD
27


PREVIOUSLY MAPPED
LATE WISCONSIN
LIMIT
MILFORD RD
COOPER RD
CROSS-COUNTY HWY
GALBRAITH RD
READING RD
I-75
COMPTON RD
NORTH BEND RD
VINE ST
PADDOCK RD
SEYMOUR AVE
1 MILE
1 KILOMETER
A
B
B'
C
C'
D
D'
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
22
23
24
25
26
27
28
29
30
31
32
33
34

are zones (lenses?) of silt and clay; the zones are usually less than 1 m in thickness, and are not correlatable between adjacent wells.

Unit 2, silt/clay. Silts and clay of unit 2 overlie unit 1. These silts/clays occur in each well, and as with unit 1, are readily traceable throughout the valley. At least one log reports this unit as being "varved" (well 8). This unit ranges in thickness from 6 m (20 ft) to 18 m (60 ft), and generally thickens to the south. At the extreme northern end of the section (wells 19-21), these silts/clays are capped by a sand and gravel wedge approximately 8 m (25 ft) thick. This wedge pinches out to the south and is not observed in wells south of well 19.

Unit 3, diamicton, sand/gravel. The silts and clays of unit 2 are overlain in the northern third of the section (wells 16-21) by a diamicton of highly variable thickness (3-15 m; 10-48 ft). Within this diamicton are zones of sand and/or gravel less than 1 m thick that are not traceable between adjacent wells. Between wells 15 and 16, this diamicton changes facies laterally to sand and gravel. This sand and gravel, 3 to 13 m thick (10 to 43 ft), is traceable across the entire southern two-thirds of the section.

Unit 4, silt/clay. Overlying the diamicton or sand and gravel of unit three is a second package of silts and clays. This unit is generally thinner than unit 2 (3-8 m; 10-25 ft). This unit contains rare zones of non-traceable sand and gravel. In the northern and southern portions of the section the upper surface of this unit has been disturbed by either filling (north), or erosion (south). In the central portion of the section, the unit is overlain by diamicton.

Unit 5, diamicton. Wells in the central portion of the section (wells 11-16), lying adjacent to or within the Hartwell Moraine, indicate that the silts/clays of unit 4 are overlain by diamicton. This diamicton, less than 7 m (23 ft) thick, is terminated to the south at the approximate position of the Hartwell Moraine. To the north, this diamicton is terminated by human-produced fill.

Unit 6, silt/clay. In wells adjacent to the Hartwell Moraine, the diamicton of unit 5 is overlain by silts/clays. This clay forms the uppermost land surface; erosion subsequent to the silt/clay deposition prevents determination of the thickness of this unit, but the maximum observed thickness is about 7 meters (23 ft).

EAST-WEST SECTION, B-B'

Location. This section extends from the Rack-ELDA site in the southern part of the study area, to the mouth of the previously-reported Norwood Trough (Durrell *et al.*, 1961; Ray, 1974), a distance of approximately 6 km. The westernmost log of this

Plate 1 (in back pocket). Geologic cross-sections, central and northern Mill Creek Valley (MCV), Hamilton County, Ohio.

Section A-A'. North-south section in the "core" of MCV; note the near "layer-cake" stratigraphy;

Section B-B'. East-west section which runs from the Rack/ELDA site at the west end to the mouth of the Norwood Trough in the east; at least two erosion surfaces are evident in this section, with a thick sequence of incised sediments in the present MCV; note the correlation of the stratigraphy at the mouth of the Norwood Trough with outcrop stratigraphy from Rack/ELDA;

Section C-C'. East-west section located adjacent to the mapped Hartwell Moraine; layer-cake stratigraphy, such as that observed in section A-A' is evident in this cross-valley profile, along with an incised package of sand and gravel in the present MCV.

Section D-D'. East-west cross-valley section, located entirely within the mapped Hartwell Moraine; generalized stratigraphy is again present across the valley.

section, well 5, is common to this section and section A-A'. Along this section, bedrock is penetrated by only two wells, a well in the bottom of the Rack Quarry, and a well at the mouth of the Norwood Trough (well 23).

Stratigraphy. Three distinct stratigraphies are observed in this section (Plate 1b). Along the eastern end (wells 23-25), three litho- stratigraphic units are observed (from the base up): sand and gravel, silt/clay, and diamicton. This sequence, which represents sediments at the mouth of the Norwood Trough, is observed in logs throughout the trough (these additional logs are not shown here). Observed sand thickness is variable, and ranges from 15 to 34 m (50 to 110 ft). Silt and clay overlies this sand and gravel. The silt/clay sequence is quite thick in this eastern part of the section, and remains thick throughout much of the Norwood Trough. In well 23, the silt/clay sequence shows an extreme thinning. The position of this well (and therefore, the thinning) corresponds to a geomorphic break along the margin of the Mill Creek Valley, and probably truly reflects the mouth of the trough.

The second stratigraphy, based entirely on interpretation, lies in the area between wells 22 and 23. This area is interpreted to consist of the upper- and lowermost units of the previous sequence, the diamicton and the sand/gravel. The sand/gravel unit is interpreted to have a thickness of at least 20 m (65 ft). The overlying diamicton is believed to have a thickness of about 30 m (100 ft). The silt/clay unit observed within the trough is believed to be absent in this area, resulting in the diamicton directly overlying the sand. This interpreted stratigraphic sequence would then correlate with the diamicton-over-sand sequence observed in outcrop exposure at the Rack and ELDA sites, as shown along the western edge of the section.

The third stratigraphy is exhibited in wells 5 and 22, and is comprised of four units (from the base up): sand and gravel, silt/clay, sand and gravel, and a gravel. The basal sand/gravel unit has a minimum thickness of about 10 m (30 ft), based on adjacent logs (one in the Rack Quarry, the other is well 5). The silt/clay which overlies the sand has a penetrated thickness that ranges from 17 to 24 m (55 to 80 ft); this unit is capped by an upper sand and gravel unit penetrated by well 22. In the lowest part of the valley in this section (well 5), the upper sand and gravel is missing, and the silt/clay unit is reduced in thickness. The stratigraphy in this zone is markedly different than either of the previous two, and indicates a different episode of deposition.

EAST-WEST SECTION, C-C'

Location. This section is located approximately 4 km upvalley from section B-B', and lies adjacent to the the mapped late Wisconsin Hartwell Moraine (Fig. 4-1). The western portion of the section lies within the Hartwell Moraine, the eastern portion lies just outside of the moraine. Well 11 in the eastern part of the section is common to this section, and the north-south section A-A'.

Stratigraphy. Wells at the eastern edge of the section penetrate bedrock, and delineate the eastern valley wall at this location. Overlying bedrock is a stratigraphic sequence that matches the sequence observed in the central portion of section A-A'. This sequence consists of 1) sand and gravel (lowest penetrated unit) overlain by 2) silt/clay, which is, in turn, overlain by 3) diamicton, and 4) silt/clay. In the center of the section (wells 27 and 28), the diamicton and upper silt/clay units are not observed; the lower silt/clay is capped by a sand and gravel unit (unit 5).

Unit 1, sand and gravel. This unit is extremely thick in the western portion of the valley, with a maximum penetrated thickness of 37 m (120 ft). The lower silt/clay unit recognized in section A-A' is observed in well 11 of this section. Along the western margin of the valley, this unit is absent.

Unit 2, silt/clay. This unit is penetrated by all but the easternmost wells. Its thickness across the valley at this position is generally uniform, and ranges from 4.5 to 7.5 m (15 to 25 ft). The unit is thickest in the center of the valley, and thins towards the valley margins.

Unit 3, diamicton. This unit is penetrated by wells on both sides of the valley, but is absent from the two wells in the center of the valley. Along the western side of the valley, the diamicton makes up a segment of the mapped Hartwell Moraine. The diamicton is also present on the eastern side, which lies just outside of the moraine; at the extreme eastern end side of the valley the diamicton directly overlies bedrock. The diamicton is thickest where it forms part of the moraine, and is thinner elsewhere.

Unit 4, silt/clay. On the eastern side of the valley, the diamicton is capped by a second silt/clay unit. This unit is limited in lateral extent at this position, and is observed in only one well.

Unit 5, sand and gravel. Two wells in the center of the valley are capped by sand and gravel. In these wells, the thickness of the unit 2 silts and clays is reduced, and unit 3 diamicton is absent.

EAST-WEST SECTION, D-D'

Location. This section runs in a southwest-northeast line across the valley, and lies entirely within the mapped Hartwell Moraine (Fig. 4-1). The westernmost well (26) is a common well between this section and section C-C'. The easternmost well (16) is common with section A-A'.

Stratigraphy. Bedrock is penetrated by the two eastern wells; overlying bedrock is a stratigraphic sequence somewhat different that found in the other sections. A thick unit of sand and gravel (up to 35 m (115 ft) penetrated) overlies bedrock, and generally thickens to the west. A silt/clay unit overlies the sand and gravel; this unit has a fairly uniform in thickness of 5 to 10 m (16 to 30 ft). At the eastern and western edges of section, the silt/clay unit is overlain by a thick diamicton unit. Incised into this diamicton in the center portion of the section is a sequence that is composed of (from the base up) sand and gravel, silt/clay, sand, and silt/clay.

INTERPRETATION OF SUBSURFACE STRATIGRAPHY

The overall geomorphology of the Mill Creek Valley is one of a valley incised into bedrock, with erosional terraces of older unconsolidated sediments along the valley walls, with younger sediments in fluvially-active "center" of the valley. Section A-A' is interpreted to lie completely within this "center" of the valley; the upper sediments encountered are therefore likely to be the youngest in the valley. Sections C-C' and D-D' cross the valley, exhibiting the same stratigraphy as that observed in section A-A'. Section B-B' is the only section to include both the older terrace sediments, as well as the younger incised sediments.

The basal sand and gravel unit found in all four sections is likely the unit which represents "Deep Stage" (Durrell *et al.*, 1961; Ray, 1974, and references therein) fluvial sediment deposition. Isolated silt/clay zones within this thick unit are interpreted to represent localized overbank deposits, or abandoned-channels fillings within this fluvial system. Cross-bedding measurements in this unit from the adjacent Rack Quarry indicate water flow at the time of deposition was to the north, indicating that modern Ohio River drainage had not yet been established at the time of deposition; this fluvial system was likely a tributary of the north-flowing Teays River system to the east. This sand and gravel unit represents the oldest subsurface unit in the valley.

The next oldest unit is the silt/clay unit observed in the Norwood Trough (east end of section B-B'). This unit is interpreted to represent a damming of the north-flowing fluvial system responsible for deposition of the underlying sands and gravels. This damming has been interpreted by previous workers (Durrell *et al.*, 1961; Tucker, 1962; Teller, 1973; Ray, 1974; Teller and Last, 1981) to be the result of the advance of Illinoian ice, which blocked the north-flowing river system, and created a widespread lake. Lake level rose until a drainage divide south of the study area was breached, draining this lake. The thickness of the lacustrine sediments in the Norwood Trough together with their absence in the Mill Creek Valley suggests several possible scenarios. The first is that these sediments may have been eroded from the Mill Creek Valley during the draining of draining of the lake; it does not, however, explain why the same sediments are preserved in the Norwood Trough. A second scenario is that the sediments were not deposited in the Mill Creek Valley; this scenario does not explain why the same sediments were deposited in the adjacent trough. A third, and perhaps more plausible, scenario is that Illinoian ice advancing from the east (as evidenced by clast fabrics at Rack-ELDA and Caldwell Park, and by structural data presented in Tucker, 1962) covered the lacustrine sediments in the Norwood Trough, depositing a blanket of diamicton (discussed below), and protecting them from fluvial erosion. At the same time, drainage in the Mill Creek Valley would have remained open, subjecting the lacustrine sediments to extensive fluvial erosion. Illinoian ice advancing from the north-northwest (the "Harrison lobe" of Tucker, 1962) could have provided large quantities of meltwater to this Mill Creek fluvial system.

The diamicton mentioned above is the third-oldest unit in the valley. As previously discussed, clast fabrics and other structural data from this diamicton taken at outcrop exposures suggests that ice flow into and over the Mill Creek Valley was from the east. The diamicton overlies the lacustrine sediments in the Norwood Trough; in the Mill Creek Valley, the diamicton is found only in valley-margin terraces, where it overlies the oldest fluvial sediments. As discussed in the Rack-ELDA section (chapter 2), this diamicton contains several facies representing both proglacial and subglacial deposition related to a single ice advance.

Subsequent to deposition of the diamicton is a period of extensive erosion and downcutting, as shown in the western portion of section B-B' (wells 5 and 22). The lateral limits of downcutting are preserved in the southern portion of the study area (the location of section B-B'). In central portions of the study area (sections C-C' and D-D'), the incision has removed the Illinoian lacustrine sediments and diamicton. Although the maximum extent of downcutting is uncertain, adjacent logs from the Rack Quarry and the incised valley bottom (section B-B') indicate a minimum incision of about 30 m (100 ft) in the southern part of the study area, based on non-correlatable stratigraphy between the logs. There is no evidence of this deep incision in the Norwood Trough from available subsurface data, nor is there any significant present-day fluvial activity in the trough. The downcutting may have been related to the melting of the Illinoian ice.

Several units, as described in detail in section A-A', make up a post-incision stratigraphic sequence. The oldest of these units is sand and gravel, reflecting post-Illinoian fluvial activity. As with the sand unit described above, isolated, non-correlatable lenses and zones of silt and clay are interpreted to be overbank and/or abandonded channel deposits.

The sands and gravels are overlain by silts and clays interpreted to be of lacustrine origin. These lacustrine sediments are readily traceable throughout the Mill Creek Valley, and are elevationally- correlatable to a thick silt/clay unit in the nearby Little Miami River Valley (Nash and Savage, in prep.). The widespread occurrence of this unit suggests regional water level variations related to the Ohio River system, located less than 10 km to the south. Although no radiometric age estimates of these sediments are available, it may be that these lacustrine sediments are related to late Wisconsin glaciation. Rogers (1990) reports on transported wood in Ohio River sediments directly on top of bedrock approximately 270 km upriver from Cincinnati. The age estimates, ranging from about 22,000 to 24,000 BP, suggest that major aggradation in the Ohio River system was occurring coincident with the onset of late Wisconsin maximum glaciation in southwestern Ohio. Deposition of silts and clay (some described as "varved") in the Mill Creek Valley may be the local geologic record of this aggradation. Dates from the lacustrine sequence at the Rack Quarry (chapter 2) are slighlty younger than the dates reported by Rogers (1990). The lacustrine sequence at the Rack Quarry is correlated with this lacustrine sequence in the valley center.

In the portion of the valley adjacent to and north of the Hartwell Moraine, the lacustrine sequence is overlain by diamicton. South of the Hartwell Moraine, sands and gravels overlie the lacustrine sediments. The diamicton, because of its distributional relationship with the Hartwell Moraine, and its stratigraphically younger age than the underlying lacustrine sediments, is interpreted to be drift deposited by the late Wisconsin glacier. The sands and gravels south of the Hartwell Moraine are interpreted to be late Wisconsin outwash deposits.

North of the Hartwell Moraine, the diamicton is overlain by silts/clays. The silts/clays may represent 1) lacustrine sediments deposited in either subglacially or proglacially, or 2) diamicton (such as that below the silts/clays) improperly identified in the logs. If the sediments are proglacial lacustrine, it requires some marginal recession, and the lake likely formed between the ice margin and a moraine. If the sediments are misidentified diamicton, then the late Wisconsin diamicton sequence simply extends upwards to the valley floor. In either case, these sediments are interpreted to be late Wisconsin in age.

Near the Hartwell Moraine, the silts/clays are capped by a second diamicton, and an overlying silt/clay. Both of these sediments are interpreted to be late Wisconsin in age, with the upper silt/clay representing proglacial lake dammed on the downvalley side by the Hartwell Moraine.

South of the Hartwell Moraine, sediments identified as non-fill silts and clays are interpreted to be post-late Wisconsin overbank deposits.

CORRELATION OF SUBSURFACE DATA AND OUTCROP EXPOSURES

Stratigraphic sequences identified at nearly all exposures were projected to either to a nearby well, or to a nearby cross-section, whichever was closer (Plate 2). The observed outcrop stratigraphy was then correlated with the subsurface data wherever possible.

The composite diamicton sequence at Rack-ELDA is correlatable to subsurface units exposed in the Norwood Trough. The clay sequence at Rack-ELDA is correlatable to sequence of sediments forming the core of the valley. Sediments from both Caldwell Park, interpreted to be Illinoian in age, are not correlatable to adjacent subsurface data. The Cross-County Highway site, located largely in the core of the valley, is correlatable to the adjacent subsurface data. Units exposed at the Day Care Center site in Evendale are not correlatable to nearby subsurface data; the interpretation of those units as Illinoian in age (based on radiocarbon age estimates; see Chapter 3) precludes correlation. Correlation of exposed units at both the Glendale Waste Water Treatment Facility and Sharonville sites is not directly possible because of intervening bedrock "highs" between the sites and section A-A'. Correlations are based upon radiocarbon ages estimates at the sites, and interpreted age of the subsurface units as discussed above. Pre-late Wisconsin sediments at these sites are not correlatable with any units penetrated by the wells. The Dimmick Road site discussed in Chapter 5 is not included here; the site lies approximately 4 km northeast of the north end of section A-A'.

SIGNIFICANCE OF SUBSURFACE DATA

Subsurface stratigraphy, combined with correlatable outcrop exposures permits identification of stratigraphic sequences associated with at least two episodes of glaciation, and the identification of a major episode of fluvial erosion and downcutting between these two glacial episodes. Chronostratigraphic control of younger portions of the sequence allow placement of those portions of sequence into more regional

Plate 2 (in back pocket). Correlation of observed outcrop stratigraphies with the adjacent subsurface data.

frameworks related to fluvial activity of the Ohio River system. Outcrop-subsurface correlations of Illinoian-age sediments are only possible because of preservation of the Illinoian sediments in the Norwood Trough; as noted above, removal of Illinoian sediments from the core of Mill Creek Valley prevents correlation of the Caldwell Park and Day Care Center sites, and the lowest portions of the Glendale Waste Water Treatment Facility and Sharonville sites. Discontinuities in adjacent subsurface stratigraphies (e.g., west end of section B-B') indicate that studies of groundwater and pollutant flow at sites near terraces along the margin of the valley need to obtain detailed subsurface data. Discontinuous sand (aquifer) and clay (aquitard and/or aquiclude) zones provide the potential for both vertical and lateral migration of contaminants into unpredicted areas.

CHAPTER 5. SITES SUBGLACIAL TO LAURENTIDE ICE

INTRODUCTION

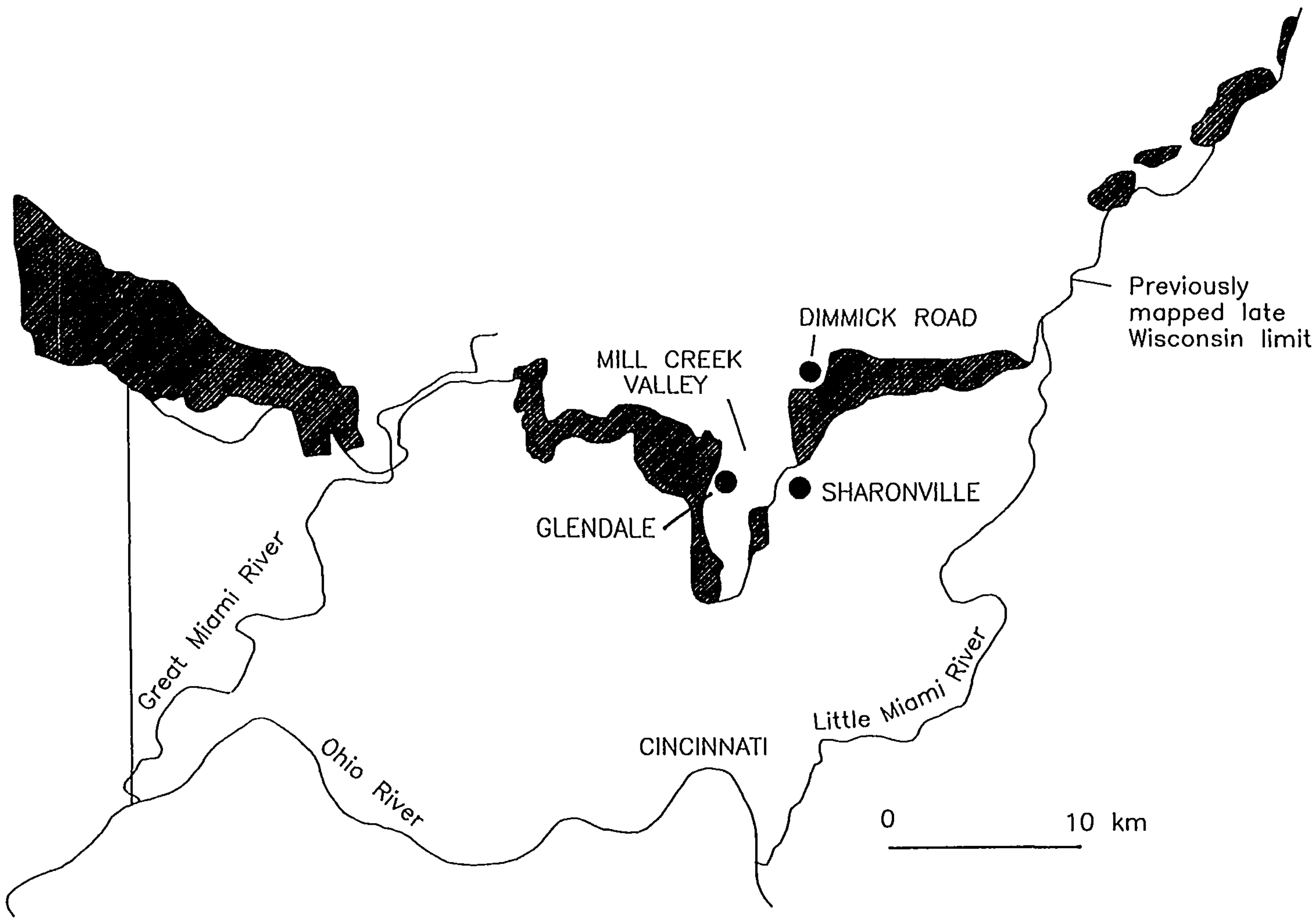
Southwestern Ohio provides a unique opportunity to study glacigenic sediment sequences at the margin of the southernmost advance of the Laurentide ice sheet (Miami Sublobe). The objective here is to make an interpretation of glacier conditions near this ice margin beginning about 19,700 yrs BP based on sedimentologic, stratigraphic, and structural data. To accomplish this, descriptions are presented here of late Wisconsin sediments at three localities: a construction excavation in Glendale, stream exposures near Sharonville, and a construction excavation in southern Butler County, just north of Sharonville (Fig. 5- 1). Stratigraphic relationships of these sediments, together with the physical conditions necessary for their formation are discussed. On the basis of these relationships and characteristics, a sequence of changes in glacier activity and thermal regime of the ice-sediment system of the Laurentide ice sheet near its southern margin in Ohio is proposed.

Studies of glacigenic sediments have traditionally been three-part: 1) description of physical characteristics, 2) interpretation of genesis, and 3) interpretation of glacier conditions. Within any single "set" of conditions, however, a variety of deposition processes can occur. Detailed analyses of the structural and textural features within a sedimentologic unit may narrow the number of likely origins for that unit, permitting an interpretation of the genesis. Equally likely, however, is that different genetic processes may produce sediments with common characteristics, making genetic interpretations, in some cases, suspect (Boulton, 1968, 1970; Dardis and McCabe, 1987).

Shaw (1987) has recently used a two-part approach of 1) description of physical characteristics, and 2) interpretation of glacier conditions. He demonstrates how physical characteristics within glacigenic sediments provide specific clues about the glacier and environmental conditions (i.e., frozen vs. freezing vs. melting thermal regimes, active vs. stagnant ice, subglacial vs. supra- or proglacial) necessary, or responsible, for their formation. This two-part approach emphasizes identification of glacier conditions, and lessens the necessity for interpretation of a specific genesis for each unit. The two-part approach of Shaw (1987) is applied here, with interpretation of genesis where possible, to develop a history of changes in marginal thermal regimes and ice activity near Cincinnati, Ohio.

The Glendale site, located in the Mill Creek Valley and within the mapped late Wisconsin limit of Gray *et al.* (1972), is discussed first (Fig 5-1). The Butler County

Fig. 5-1. Location map showing the Glendale, Dimmick Road, and Sharonville study localities near the margin of the Miami sublobe of the Laurentide ice sheet. The Glendale site is located in the Mill Creek Valley (MCV), the Dimmick Road site is located on the up-ice side of a bedrock upland east of the MCV, and the Sharonville site is on the dissected upland east of the MCV. A portion of the Hartwell moraine (the previously-mapped late Wisconsin limit) crosses the valley. Late Wisconsin ice limits after Dyke and Prest (1987), and Gray *et al.* (1972).


Previously
mapped late
Wisconsin limit
DIMMICK ROAD
MILL CREEK
VALLEY
SHARONVILLE
GLENDALE
Great Miami River
Little Miami River
Ohio River
CINCINNATI
0
10 km

Dimmick Road site, located outside of the Mill Creek Valley, but within the mapped late Wisconsin limit of Gray *et al.* (1972), is presented second. The Sharonville stream exposures, located along the margin of Mill Creek Valley and outside of the mapped late Wisconsin limit of Gray *et al.* (1972) are presented last.

GLENDALE WASTE WATER TREATMENT FACILITY

Location. This site is a construction excavation in the Mill Creek Valley in northern Hamilton County, and is approximately 7.5 km north of the Caldwell Park study area, and 3.5 km northwest of the Day Care Center site. The excavation measures approximately 40 m (NS) by 20 m (EW), and has a maximum depth of about 10 m. Units within the pit are best exposed along the north and east walls (Figs. 5-2, 5-3), with limited exposures along the south and west walls. The exposure was backfilled in the spring of 1988.

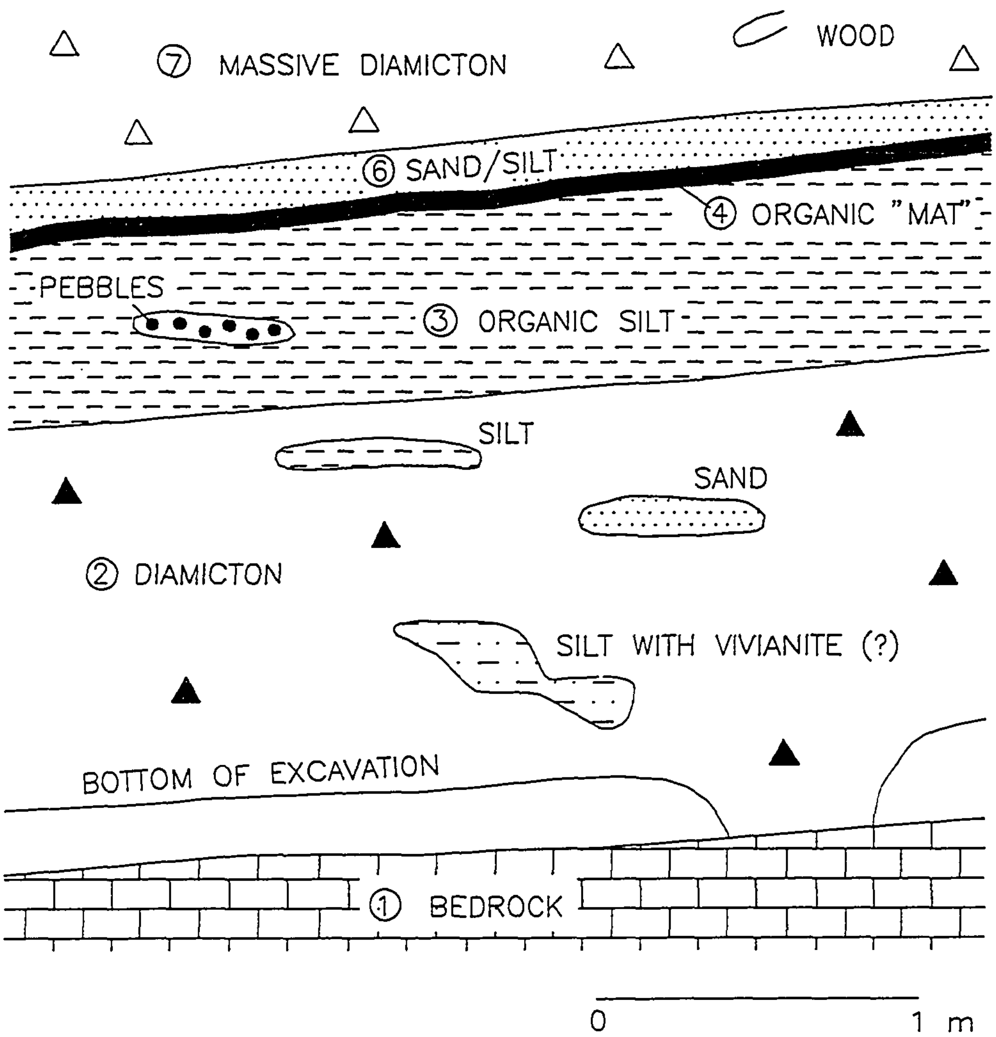
Unit Descriptions. The following units (from the base up) are exposed at the site: 1) Ordovician limestone bedrock, 2) diamicton, 3) organic-poor silt that graded upwards into organic-rich silt, 4) organic "mat" zone, 5) discontinuous clayey silt, 6) fine sand/silt, and 7) brown diamicton.

Unit 1, bedrock. Ordovician bedrock is exposed only in a trench in the south part of the pit. Although limited in exposure, the bedrock was observed to be striated; the orientation of the striations is 096- 276^{o}.

Unit 2, diamicton. Diamicton overlies bedrock, and has a maximum thickness of approximately 2 meters. Textural analysis of the matrix of the diamicton immediately overlying bedrock yielded a SSC ratio of 27:44:29. The basal 0.45 to 0.50 m of this unit is calcareous and massive, with no apparent structure. The upper 1.50 to 1.55 m of this diamicton is leached at the top, with carbonate content and pebble content both increasing downward; this zone is characterized by a pervasive, platy structure. These "plates" increase in size from about 1 cm near the top of the unit to about 2 cm near the base; the platy zone grades downward into the massive zone. Small lenses of medium to fine sand and silt are observed in the platy zone, but are rare. Rare "blebs" of a bluish-violet material, probably vivianite, are observed near the base of the platy zone. The basal contact of this diamicton unit with the underlying bedrock is sharp, and the striations on the bedrock indicate erosion immediately prior to, or contemporaneous with deposition of unit 2. This unit grades upwards into the organic-poor silts of the base of unit 3.

Unit 3, silt. This unit is composed dominantly of silt which is organic-poor at the

Fig. 5-2. Facemap of the east wall exposure of the excavation at the Glendale Waste Water Treatment Facility showing the lower portion of the observed stratigraphy. (Figure based on field sketches and photographs by C.S. Brockman, Ohio Department of Natural Resources, Division of Geological Survey, Columbus, OH.)


WOOD
⑦ MASSIVE DIAMICTON
⑥ SAND/SILT
④ ORGANIC "MAT"
PEBBLES
③ ORGANIC SILT
SILT
SAND
② DIAMICTON
SILT WITH VIVIANITE (?)
BOTTOM OF EXCAVATION
① BEDROCK
0
1 m

base (0.8 weight-percent loss on combustion at 600°C; SSC=20:59:21), and which becomes organic-rich (9.4 weight-percent loss on combustion; SSC=0:81:19) at the top. The unit is non- calcareous, and is generally pebble-free, although small concentrations of pebbles are occassionally observed. Faint, wavy, and generally horizontal laminations are present. The overall unit is massive, and is about 1 m thick. Gastropods are found in the upper portion, and the unit is capped by unit 4. The contact between units 3 and 4 is sharp and readily traceable across the exposure.

Unit 4, organic "mat". This unit is a thin horizon composed primarily of mosses and associated vascular plant material (N.G. Miller, 1989, pers. comm.), and has a maximum thickness of less than 1 cm. This organic horizon is traceable throughout the entire excavation, and reflects a paleosurface dipping to the north. Gentle undulations in this paleosurface are noted. Also included within this zone are gastropods, as well as needles, probably of spruce or tamarack. This organic horizon is capped by the silts of unit 5.

Unit 5, clayey silt. A calcareous clayey silt caps the organic horizon. This silt (SSC=0:82:18; dominantly fine silt) occurs as discontinuous bodies with abrupt lateral truncations, over the organic horizon. The unit has a maximum thickness of 2.5 cm, and the bodies are massive with no apparent internal laminations or deformation. The unit contains abundant needles like those noted in unit 4. The upper contact of this unit with the overlying coarse silt of unit 6 is sharp, and may be erosional.

Unit 6, silt. Calcareous coarse silts overlie the fine silts of unit 5. These coarse silts (SSC=4:84:12) generally coarsen upwards, and are horizontally- to rippled-laminated. These laminations have a spacing of 1 to 2 mm, and are locally deformed. The laminations form larger "packages" that range in thickness from 2 to 4 cm. The upper contact of the silts with the overlying diamicton of unit 7 is sharp and erosional.

Unit 7, diamicton. Calcareous diamicton (SSC=25:50:25) overlies the coarse silts of unit 6, and is the youngest unit exposed at the site. This diamicton has an exposed thickness of approximately 3.5 to 4 m, is oxidized throughout, is massive and contains abundant wood, clay, sand, and gravel lenses, and "balls" of peat up to 25 cm in length. Inclusions of shale bedrock are present, and occassionally contain internal slickensides. Vivianite is common in this diamicton and occurs on or adjacent to the wood, as well as lining fractures within the diamicton. The upper limit this unit has been extensively disturbed by construction, and the original thickness of the unit is unclear.

Chronologic control. Radiocarbon analyses, by both conventional and AMS methods provide the chronologic control for the stratigraphy; these are summarized in

Fig. 5-3. Facemap of north wall exposure of the excavation at the Glendale Waste Water Facility showing the middle and upper portions of the observed stratigraphy. Locations of samples are indicated, as are the locations of samples age estimated by conventional and AMS radiocarbon techniques (see also Table 5-1).

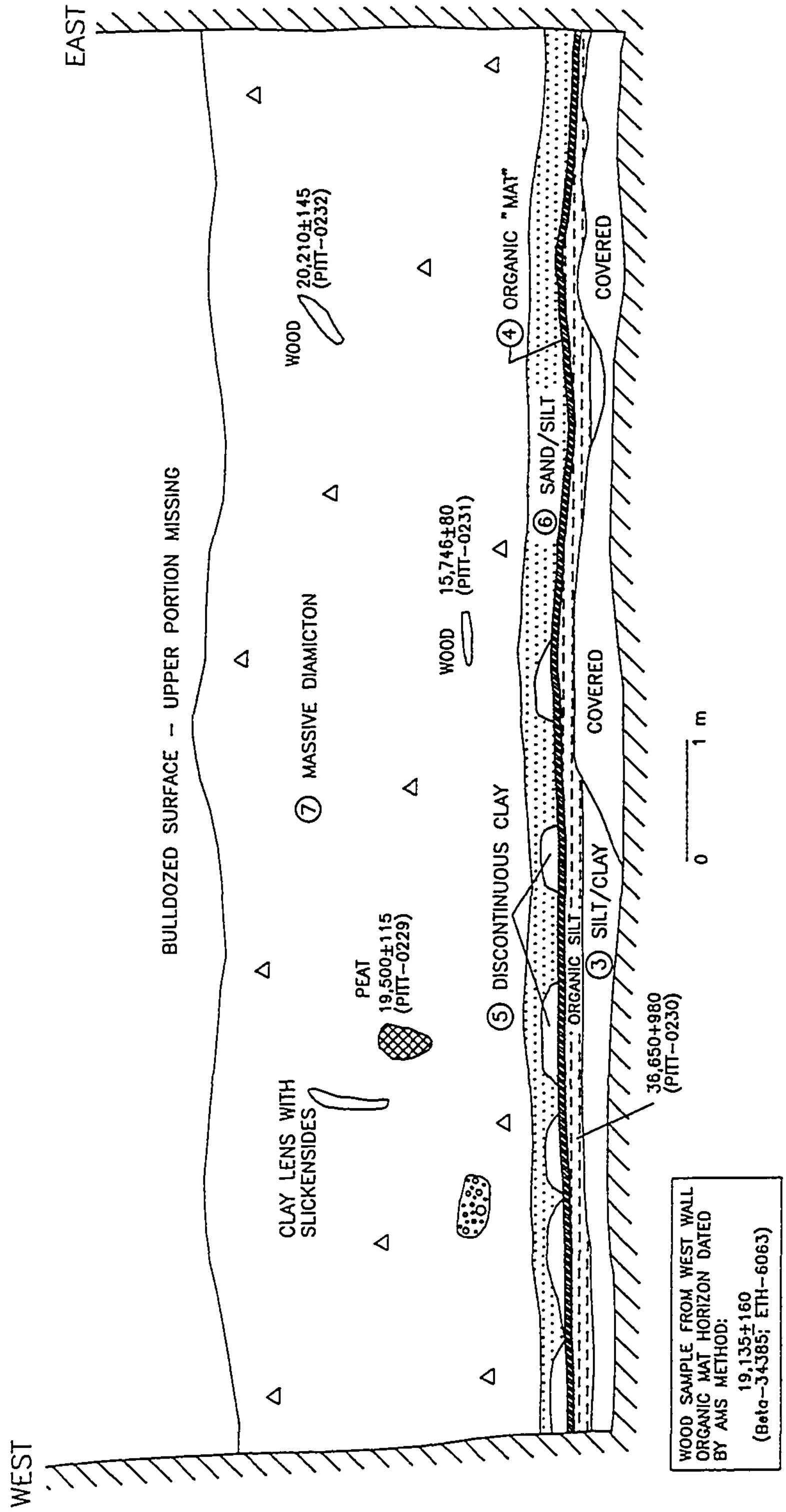

EAST
WEST
BULLDOZED SURFACE - UPPER PORTION MISSING
⑦ MASSIVE DIAMICTON
WOOD
20,210±145
(PITT-0232)
WOOD
15,746±80
(PITT-0231)
PEAT
19,500±115
(PITT-0229)
CLAY LENS WITH
SLICKENSIDES
④ ORGANIC "MAT"
⑥ SAND/SILT
⑤ DISCONTINUOUS CLAY
ORGANIC SILT
③ SILT/CLAY
COVERED
COVERED
36,650+980
(PITT-0230)
0
1 m
WOOD SAMPLE FROM WEST WALL
ORGANIC MAT HORIZON DATED
BY AMS METHOD:
19,135±160
(Beta-34385; ETH-6063)

Table 5-1. The age estimate of wood in the organic layer (unit 4) indicates the overlying units 4-7 are late Wisconsin in age.

TABLE 5-1. RADIOCARBON ANALYSES, GLENDALE WASTE WATER TREATMENT SITE. Age estimates expressed as mean ± one standard deviation.

Unit	Material Dated	Age Estimate	Lab Number	Method
7	wood	15,740 ± 80	PITT-0231	conventional
7	wood - Picea sp.	20,210 ± 145	PITT-0232	conventional
7	peat inclusion	19,500 ± 115	PITT-0229	conventional
4	wood - Salix sp.	19,135 ± 160	Beta-34385 ETH-6063	AMS[a]
3	organic silt	36,650 ± 980	PITT-0230	conventional

[a] - analysis provided by N.G. Miller, New York State Museum, Albany, NY.

Interpretation. Unit 2 is interpreted to represent a pre-late Wisconsin glacial advance, as evidenced by presence of striated bedrock. Subsequent to this advance were loess deposition and subsequent accumulation of organic material (unit 3), with development of a "moss mat" (unit 4). Clayey silt of unit 5, and the laminated silts and clays of unit 6 represents deposition in a proglacial aquatic environment immediately prior to late Wisconsin ice over-running the site. The sharp, truncational contact between the unit 6 and the overlying diamicton indicates erosion associated with the advance of late Wisconsin ice over the site. The presence of undeformed lenses and bodies of of sorted sediments indicates that their transport and deposition probably occurred while these bodies were frozen (Aber, 1985; Shaw, 1985) and under conditions of little or no shear stress. This is consistent with deposition from inactive, or stagnant ice; this unit is therefore interpreted to represent a subglacial meltout till.

DIMMICK ROAD RESERVOIR

Location. This site is a construction exposure for an underground water reservoir to be operated by the Butler County Water and Sewer Department. The site is located in the southern portion of Butler County, approximately 6 km north of the Sharonville study area, and 6.5 km northeast of the Glendale Waste Water Treatment Facility (Fig. 5-4), and lies within the mapped late Wisconsin limit of Gray *et al.* (1972). The excavation measures approximately 70 m (NS) by 50 m (EW); depth of the excavation ranges from about 7 m at the north end to about 13 m at the south end. The studied exposures are along the west and south walls of the pit. Backfilling closed the pit in the spring of 1990.

Unit Descriptions. The following units (from the base up) are exposed along the south and west walls of the excavation: 1) Ordovician limestone and shale bedrock, 2) weathered diamicton, 3) non-organic silt, 4) organic silt, 5) clay, and 6) diamicton. In general, the units along the south wall occur in an apparently undeformed state (Fig. 5-4a); along the west wall, however, there is pervasive deformation throughout units 1 through 5.

Unit 1, bedrock. Ordovician limestone and shale bedrock is exposed along much of the south and west walls of the pit; the upper surface of the bedrock is sloping, and rises to the south. The strike and dip of the paleosurface (not the bedrock units themselves) as determined from preconstruction drillers logs are N79^{o}E and 6^{o}NW, respectively. On the southern wall exposure, the bedrock has a maximum exposed thickness of about 2.5 m, is overlain by weathered diamicton (Fig. 5-4a), and appears to be undeformed. Along the western wall, the bedrock is overlain by deformed sediments of highly variably thickness (Fig. 5-4b). In the central portion of the west wall exposure, the sediments overlying the bedrock are highly deformed, and this deformation penetrates approximately 0.5 m into the bedrock (Fig. 5-5). The nature of this deformation appears to be faulting/shearing. Because the exposure is two-dimensional, it is not possible to determine the exact orientation of the faulting; the general sense of the offset in limestone beds, however, indicates that beds to the "north" of individual faults overlie the same beds on the "south" side of the fault. The magnitude of the offset is 5 to 10 cm along the apparent fault plane. Slickensides in shale portions of the bedrock are generally to the N-NW (Fig. 5-6). Along the south wall, bedrock is overlain by the weathered diamicton of unit 2. On the west wall, the upper limit of bedrock is generally marked by the deformed green shale layer (Fig. 5-5); in the deformed region, the shale is overlain by, or mixed with, units 2, 3, and 4. The lateral extent of the deformed bedrock is at least 16 m; at the southern-most end of observed deformation, bedrock is buried by slumping of the excavation wall.

Unit 2, weathered diamicton. This weathered diamicton is massive, with no apparent internal features along the south wall. The basal 1 to 1.2 m of the diamicton is

Fig. 5-4. Facemaps of the exposures at the Dimmick Road Reservoir excavation: a) south wall exposure, b) west wall exposure. There is no vertical exaggeration, and the scales are the same for both figures. Stipple in (b) indicates location of the detailed section of Figure 5-5. The symbols F_1 through F_5 on (b) indicate the locations of clast fabrics 1-5 in unit 6 diamicton; circles represent clast orientation projected onto the lower hemisphere of an equal area net; numbers on the lower side of each circle represent the fabric strength (S_1; 0 = random, 1 = uniform), azimuth and plunge of the mean vector (V_1), and number of clasts (n). Contour interval is 2 standard deviations, with black areas representing the maximum deviation from random. Measures after Lawson (1979).

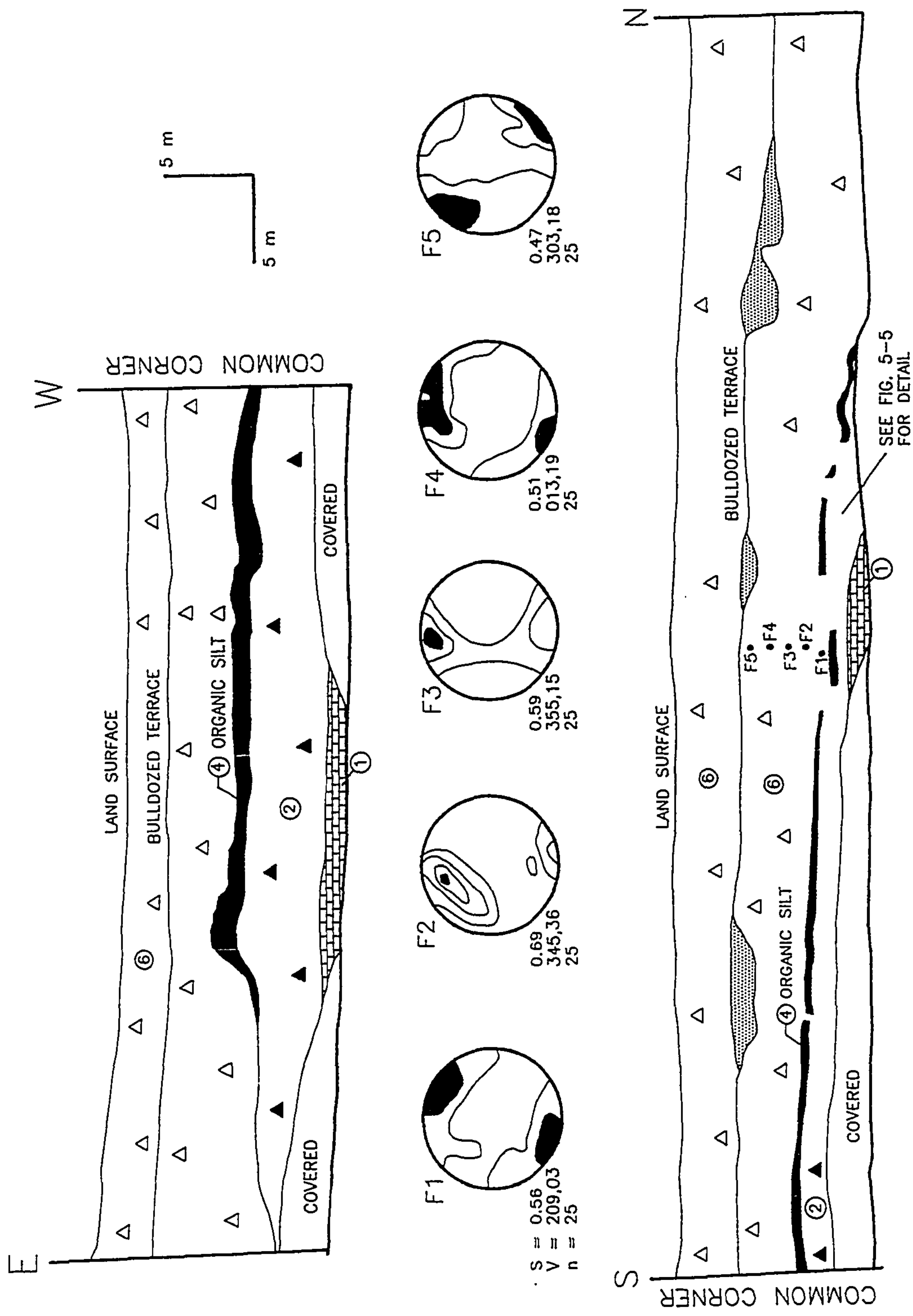
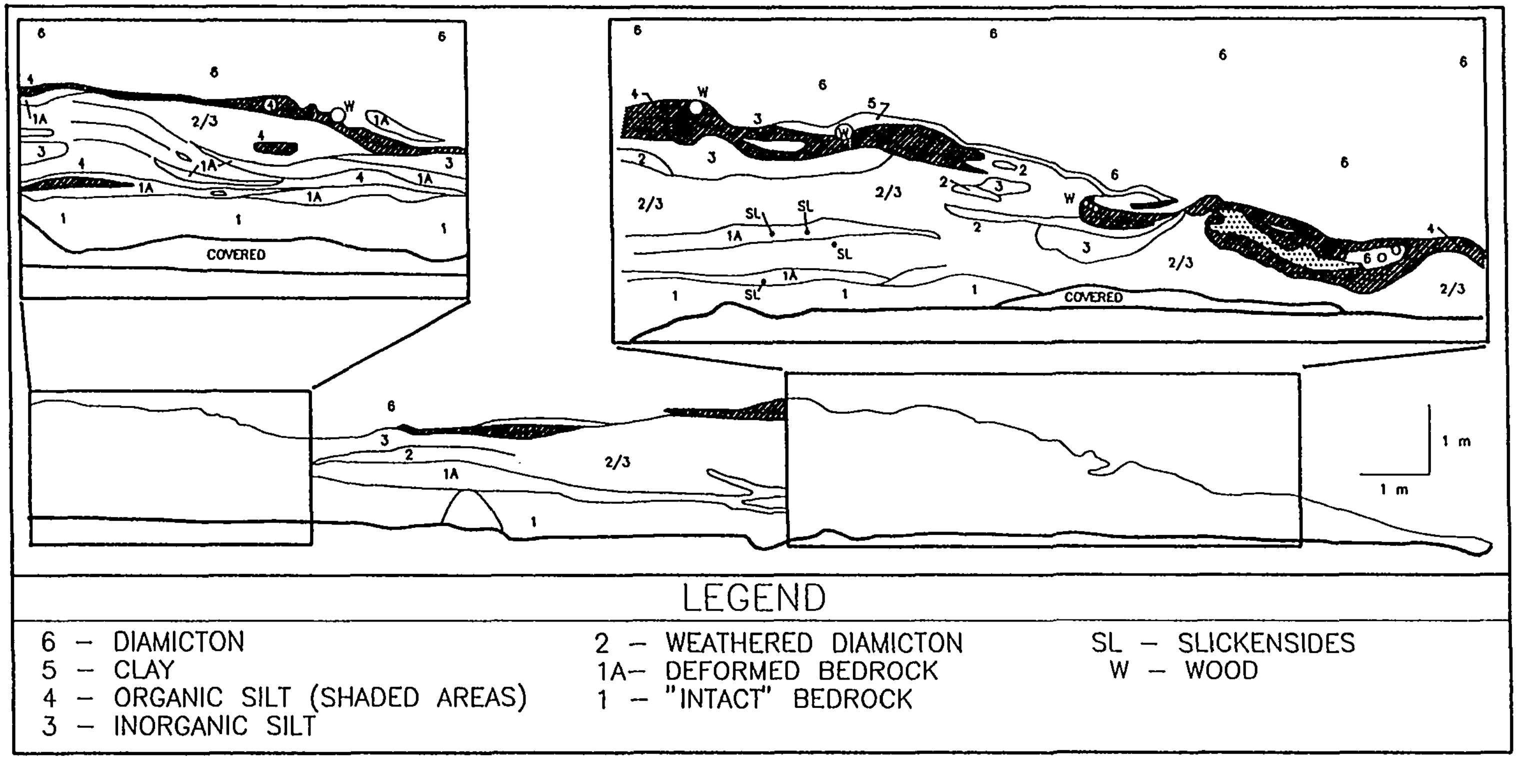

E
W
COMMON CORNER
LAND SURFACE
BULLDOZED TERRACE
ORGANIC SILT
COVERED
5 m
5 m
F1
F2
F3
F4
F5
S = 0.56
V = 209,03
n = 25
0.69
345,36
25
0.59
355,15
25
0.51
013,19
25
0.47
303,18
25
S
N
SEE FIG. 5-5
FOR DETAIL

Fig. 5-5. Detailed facemap of area indicated in Fig. 5-4, showing deformed nature of units 1 through 5, and the complex style of deformation.


6
5
4
3
2/3
2
1A
1
W
SL
COVERED
1 m
1 m
LEGEND
6 – DIAMICTON
5 – CLAY
4 – ORGANIC SILT (SHADED AREAS)
3 – INORGANIC SILT
2 – WEATHERED DIAMICTON
1A– DEFORMED BEDROCK
1 – "INTACT" BEDROCK
SL – SLICKENSIDES
W – WOOD

calcareous, and contains clasts of both calcareous and non-calcareous lithologies. The upper 4 to 5 m of the diamicton are generally non-calcareous, and limestone and dolomite clasts become virtually non-existant in the upper 2 m. Ghosts of non-calcareous clasts become more abundant in this upper 2 m. Along the south wall, the diamicton has thickness of 5 to 6 m, and is overlain by the inorganic silt of unit 3. This contact is irregular and indistinct. Along the west wall, the diamicton is folded and deformed (Fig. 5-5), and generally mixed with the inorganic silts of unit 3. Material clearly identifiable as unit 2 only occurs as small lenses. There are no clasts of calcareous lithologies observed in this unit along the west wall, and granule-sized (2-4 mm) ghosts are abundant. Where this unit is mixed with the silts of unit 3, the contact between the units is very gradational. The lateral extent of exposure of this unit along the west wall coincides with that of bedrock. In several locations, especially where this unit is mixed with overlying unit 3, features that appear to be shear planes are observed.

Unit 3, inorganic silt. Unit 3 is comprised of non-calcareous, inorganic silt. Along the south wall, and southern 15 m of the west wall of the excavation, this unit varies in thickness from 30 to about 60 cm, and is overlain by the organic-rich silts of unit 4. This contact is transitional, but generally regular across the walls. Along the central portion of the west wall, like unit 2, material clearly identifiable as unit 2 occurs only as small lenses (Fig. 5-5). More commonly, it is mixed with unit 2, as described above. Total thickness of the mixed units 2/3 varies from less than 0.10 to about 1.5 m. In the interval shown in Figure 5-5, this unit is only rarely overlain by unit 4.

Unit 4, organic silt. This unit is a massive, featureless, non- calcareous silt (SSC=12:78:10) with an organic content of 9.7 weight- percent (weight-loss on combustion at 600^{o}C). Locally, the silt contains abundant gastropods; the gastropods present are a mixed assemblage of terrestrial and aquatic species (Dell, 1991). The unit is observed on both the south and west walls (Fig. 5-4). On the south wall and the southern-most 15 m of the west wall, the unit has a uniform thickness of 0.7 m, and is overlain by unit 6 diamicton. This upper contact is sharp and easily traceable. Over much of the length of the west wall, occurrence of the unit is as deformed lenses and irregularly shaped bodies (Fig. 5-5). Maximum thickness of the silt in the deformed zone is about 0.5 m. This unit commonly overlies the mixed units 2/3 assemblage, but also occurs as lenses within units 1, 2, and 3. In the deformed zone, this unit is generally overlain by either clay (unit 5) or diamicton (unit 7). Near the southern part of the west wall, the silt generally becomes more continuous, but breaks in this continuity occur about every 10 to 15 m. Associated with these discontinuities are apparent vertical offsets that range from 0.3 to 0.7 m. Wood associated with unit 4 in the deformed zone is oriented to the NW (Fig. 5-6).

Unit 5, clay. This unit is thin, calcareous clay. It is observed only in the deformed zone on the west wall, and occurs as thin lenses and bodies generally capping the sequence of units 1 through 4. The unit contains laminations which may be extensively deformed. Slickensides are observed in this unit and trend to the N-NW (Fig. 5-6). This unit has a maximum observed thickness of about 0.2 m, and individual lenses range in length from 0.5 to about 5 m. Small inclusions of this clay are found in the basal 0.2 m of the overlying unit 6 diamicton. Wood within this unit in the deformed zone is oriented to the NW (Fig. 5-6).

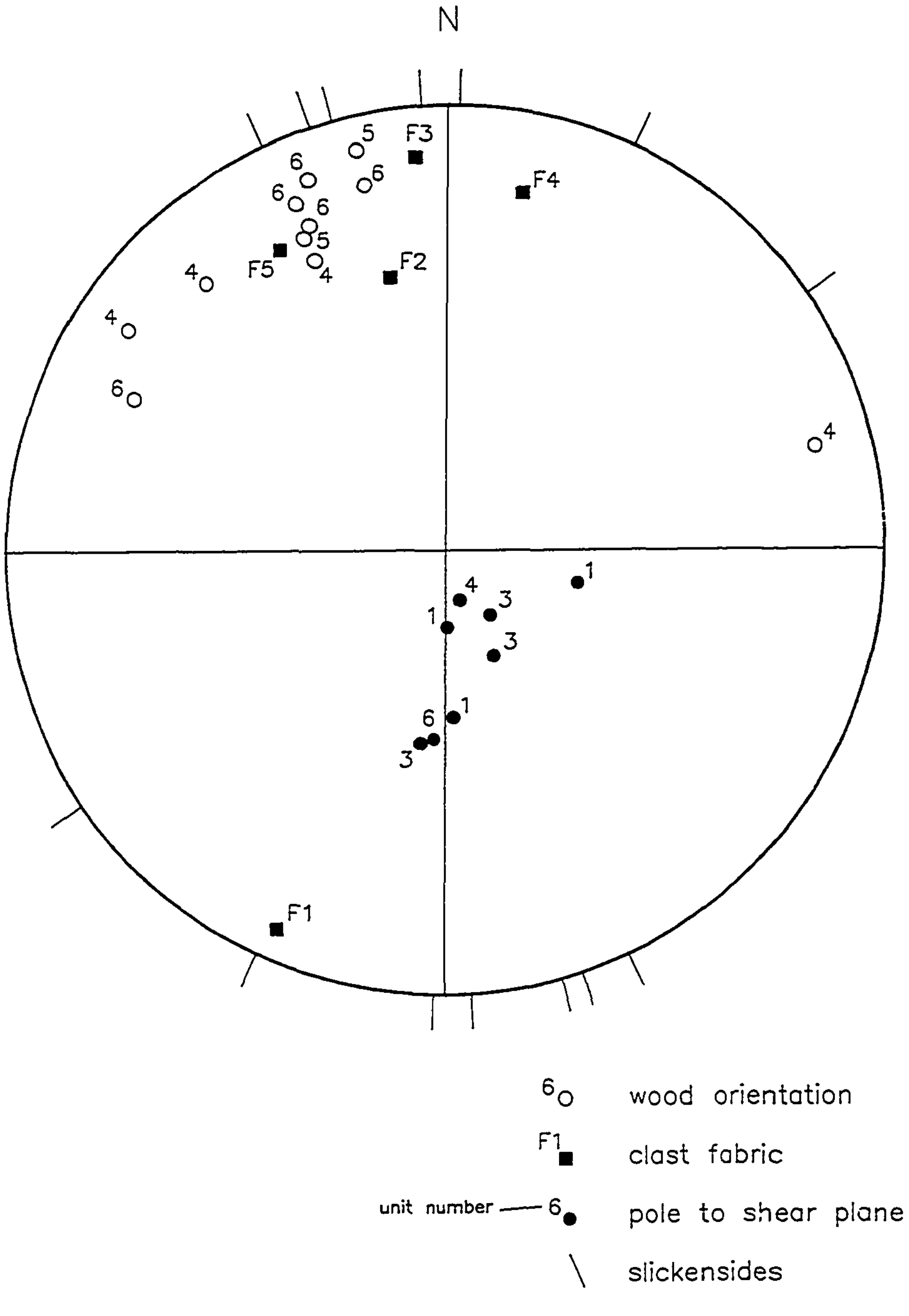
Unit 6, diamicton. Diamicton forms the uppermost stratigraphic unit at this site. Several facies of diamicton are observed along the west wall. These facies are largely inaccessible, and have not been studied in detail. All are calcareous, and are similar in texture (Table 5-2). The lowermost facies, which overlies units 1 through 5, contains shear planes that begin in the underlying sediments, cross unit boundaries, and terminate in basal 0.5 m of this facies. The upper facies exhibit channel-form structures, some of which are filled with diamicton, and some of which are filled with sand and gravel. The discontinuties noted in unit 4 organic silts do not appear to affect any diamicton facies except the lowermost. Abundant wood is observed in the basal 1.5 m of this unit; orientations of the logs are to the N-NW. Four of five clast fabrics (Fig. 5-4b) are to the N or NW.

TABLE 5-2. SUMMARY OF DIAMICTON TEXTURAL ANALYSES, DIMMICK ROAD RESERVOIR. Values are for single-sample analyses; samples of matrix collected from location of indicated clast fabric; fabric locations shown on Fig. 5-4.

Sample	Fabric	Sand (%)	Silt (%)	Clay (%)	Carbonate Content (%)
DIMW-S	5	36	48	16	18.7
DIMW-T	4	25	47	28	18.5
DIMW-P	3	29	45	28	22.4
DIMW-0	2	56	32	12	23.6
DIMW-K	1	48	40	12	21.8

Interpretation. Units 1-5 reflect a stratigraphy nearly identical to that observed at the Glendale site (bedrock-diamicton-silt-organic silt-diamicton). At this site, however, the origin of unit 2 diamicton is uncertain. Units 3 and 4 reflect loess deposition and subsequent accumulation of organic material. Unit 5 clays again represent a proglacial

Fig. 5-6. Structural data from the deformed zone along the west wall, Dimmick Road site; numbers next to each symbol indicate with unit the datum was collected from.


N
F1
F2
F3
F4
F5
wood orientation
clast fabric
unit number
pole to shear plane
slickensides

aquatic environment with sediment deposition prior to the overrunning by ice. Diamicton facies of unit 6, while not studied in detail, are interpreted to reflect at least one episode of active, basally-melting ice overrunning the site, followed by ablation and deposition of one or more facies of sediment flows and fluvial deposits. Clast fabrics in the diamicton suggest an ice flow direction from the N-NW. This interpretation is supported by the orientation remainder of the structural data: slickensides, wood alignment, and poles to shear planes. All reflect a probable ice flow direction from between 320° and 355° azimuth.

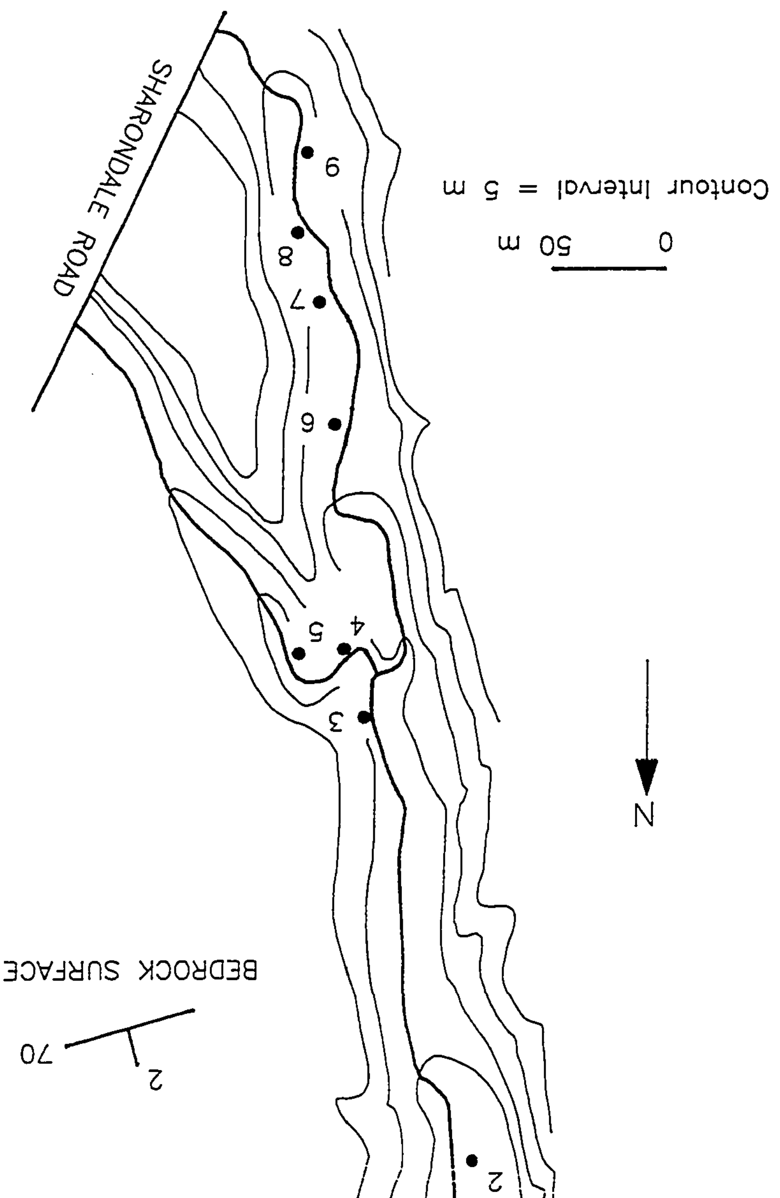
The deformation observed the sub-diamicton sediments is interpreted to be the result of early overrunning by the ice. Because the lowermost diamicton has also been deformed (by shearing), this indicates that the deformation was subsequent to deposition of this lowermost diamicton facies. The lack of evidence for extensive deformation in the majority of the diamicton sequence suggests that the deformation was was restricted temporally to the time immediately following deposition of the lowermost facies.

SHARONVILLE SITE

Location. This site is located in Sharonville, Ohio, approximately 6 km south of the Dimmick Road site and 4.2 km east of the Glendale site (Fig. 5-1). Unlike the Glendale and Dimmick Road sites, this site lies outside of the Hartwell Moraine, traditionally mapped as the southern limit of late Wisconsin glaciation (Gray *et al.*, 1972). Recently-developed radiocarbon age-control on in situ stumps rooted in organic silt (Lowell *et al.*, 1990a) indicates that the site was overrun by late Wisconsin ice. The site consists of outcrops in a north-trending stream valley incised into a drift-filled embayment in the bedrock uplands east of Mill Creek Valley. Extensive stream erosion has provided numerous fresh exposures of unconsolidated sediment and bedrock. The units closest to stream level are the best exposed; the upper units remain slumped and covered. Nine of these outcrops have been studied in detail (Fig. 5-7). These outcrops range from 2 to 5 m in height, and from 5 to 15 m in length, and extend laterally over 700 m.

Stratigraphy. The generalized stratigraphic sequence exposed in the valley includes Ordovician shale and limestone bedrock overlain by both pre-late Wisconsin and late Wisconsin sediments. The pre- Wisconsin sequence, in upward succession, includes: 1) a clay-rich diamicton, and 2) an organic silt bed. The lowermost late Wisconsin unit is a dense clay which overlies the silt (with the dated stumps), and which contains slickensides, and is sheared in the central part of the study area. The clay is overlain by

Fig. 5-7. Map of stream valley showing locations of studied sections, Sharonville site; section numbers correspond to those indicated on Figs. 5-10 and 5-14 and in Table 5-4; elevation contours in meters.


SHARONDALE ROAD
Contour Interval = 5 m
0 50 m
N
BEDROCK SURFACE
70
2
1
2
3
4
5
6
7
8
9

several facies of late Wisconsin sediments. Ice associated with deposition of these facies may have flowed from the west or northwest (local ice flow into the embayment from the main valley to the west), or from the north (flow from the adjacent uplands to the north into the embayment). In either case, as the ice passed over the study area, it was advancing up a sloping paleosurface, enhancing the compressional forces along the ice margin.

Unit Descriptions.

Unit 1, bedrock. Ordovician limestone and shale bedrock is observed at scattered locations throughout the stream valley. The bedrock surface within the embayment slopes to the northwest (Fig. 5-7); strike and dip of the bedrock surface within the embayment, calculated from subsurface and outcrop data, are N70^{o}E, and 2^{o}NW, respectively.

Unit 2, diamicton. Weathered sandy silty diamicton (SSC = 40:41:19) overlies bedrock, and is found in situ at section 5. The upper 40 cm of this diamicton are intensely weathered and non- calcareous. This diamicton becomes organic-rich in the upper 10-12 cm at section 5. The contact between this unit and the overlying organic-rich silts of unit 3 is very indistinct and transitional at section 5, where the units were exposed in a trench below present stream level. At sections 7 and 8, where both units are exposed above present stream level, the contact is still transitional, but much more distinct.

Unit 3, organic silt. Organic-rich silt overlies the diamicton of unit 2. This unit is observed at sections 5, 7, and 8, and is characterized by an increase in organic content upsection (3.9 weight- percent at base of unit, 9.3 weight percent at the top). These silts have been radiocarbon age estimated, with an interpreted age of >27,000 yr BP (Lowell *et al.*, 1990a). This unit is capped by the "organic zone" of unit 4. These silts also contain stumps rooted in the upper 5-15 cm at section 5. These roots yielded radiocarbon age estimates between about 19,700 yr BP and 22,000 yr BP (Lowell et al., 1990a). Stumps rooted in this silt are in growth position, and extend upward 10-25 cm above the organic zone of unit 4, and are covered and encased by the diamicton of unit 6.

Unit 4, "organic zone". Directly overlying the organic silt is a discontinuous layer composed dominantly of bryophytes and plant macrofossils, which appear to be "needles" from fir-type trees. This layer is noted at sections 5, 7, and 8; at section 5, the needles are concentrated in the area adjacent to the rooted stumps noted in unit 3 above. Directly overlying this layer is the massive clay of unit 5; needles and bryophyte fragments found in the basal 1 cm of the clay suggests that the contact between the silt-organic zone and overlying clay is sharp, but conformable.

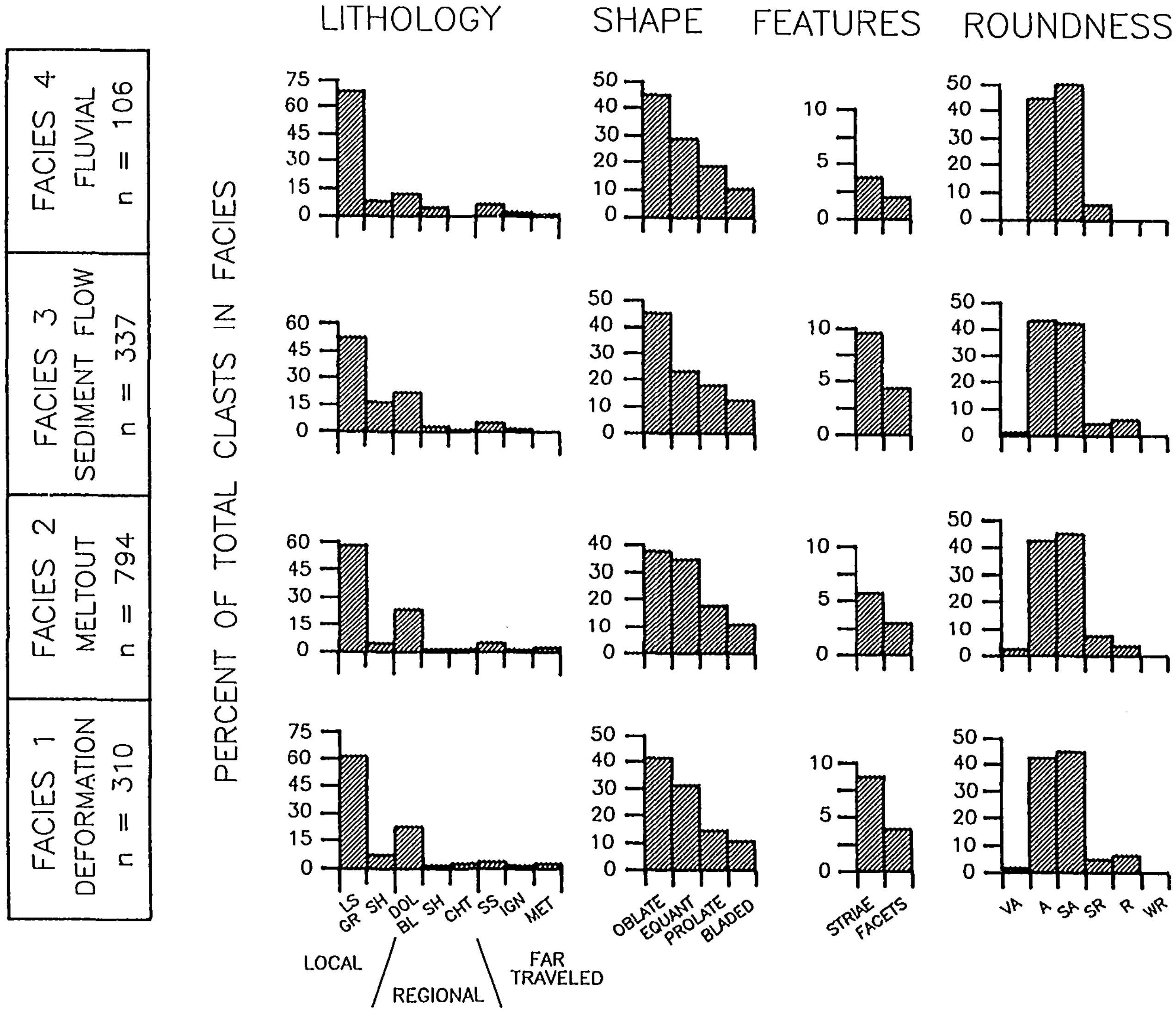
Unit 5, clay. Massive, calcareous clay caps the organic zone and organic silt. Like units 1-4, this unit is observed at sections 5, 7, and 8. The clay is generally less than 10-12 cm, but has a maximum thickness of 40 cm; at section 5 the clay contains shear planes and slickensides oriented at about 165-345°. This clay is generally continuous, but is noted to thin across topographic "highs" in the underlying organic silt. The upper contact of this unit with sequence of diamicton facies is sharp and distinct, and appears to be unconformable.

Unit 6, late Wisconsin facies assemblage. Four facies of late Wisconsin-age sediment are present at the Sharonville site; three of the facies are diamictons, and the fourth facies is sand and gravel. The three diamicton facies have nearly identical textural and compositional characteristics: 1) all are calcareous, sandy, and matrix-supported (Table 5-3), 2) mean values of clast lithology, shape, and roundness are nearly identical (Fig. 5-8), and 3) clay mineralogy (illite, chlorite, and kaolinite) of 15 samples is nearly identical.

Each diamicton facies does, however, have unique characteristics that permit assessment of the physical conditions present at the time of deposition. Unique characteristics of each facies are described below.

Facies 1. Low-angle, sand-filled planes distinguish this facies from the others. Spacing between individual planes is five to ten centimeters, and individual planes are 0.5 to 1 centimeter thick (Fig. 5-9). These planes generally strike NE-SW (40° to 60° azimuth) and have shallow (7 to 15°) dips to the NW. The sandy planes are undulatory, but they bend to become nearly horizontal in the upper 15-20 cm of the facies, terminating in a well-defined, nearly horizontal plane. Slickensides are observed along these planes, and are oriented at azimuths between 275° and 300°. Wood occurs along the sandy planes, but only as fragments without bark. This wood is oriented NE-SW, and dips in either direction. Two clast fabrics in this unit are to the northwest, and one is to the southwest (Fig. 5-10a); fabric strength (S_1) values range from 0.60 to 0.70. This facies contains "smudges" (Kruger, 1979) of underlying shale bedrock and organic silts, as well as small (two to four cm high by eight to ten cm long), highly deformed inclusions of the organic silts. Some of these inclusions are augen- shaped. The basal contact of this facies 1 with the underlying clays of unit 5 is sharp and unconformable. The upper contact of this facies with facies 2 is abrupt, and is denoted by the nearly horizontal termination of the sandy planes.

Fig. 5-8. Clast characteristics, including lithologic composition, shape, features, and roundness for facies 1, 2, 3, and 4 at the Sharonville site; lithologies include limestone (LS), green shale (GRSH), dolomite (DOL), black shale (BLSH), chert (CHT), sandstone (SS), undifferentiated igneous (IGN), and undifferentiated metamorphics (MET); fossiliferous limestone and green shale comprise the locally-derived lithologies; dolomite, chert, and black shale are regionally-derived lithologies, and represent a minimum clast transport distance of 45 to 50 km; all other lithologies are distally-derived, and represent a minimum transport distance of 240 km. Roundness categories are very angular (VA), angular (A), subangular (SA), subrounded (SR), rounded (R), and well-rounded (WR).



FACIES 4
FLUVIAL
n = 106
FACIES 3
SEDIMENT FLOW
n = 337
FACIES 2
MELTOUT
n = 794
FACIES 1
DEFORMATION
n = 310
PERCENT OF TOTAL CLASTS IN FACIES
LITHOLOGY
SHAPE
FEATURES
ROUNDNESS
LS GR SH DOL BL SH CHT SS IGN MET
LOCAL
REGIONAL
FAR TRAVELED
OBLATE EQUANT PROLATE BLADED
STRIAE FACETS
VA A SA SR R WR

Fig. 5-9. Facies 1, with shear planes (arrows); note unsheared nature of overlying facies 2.

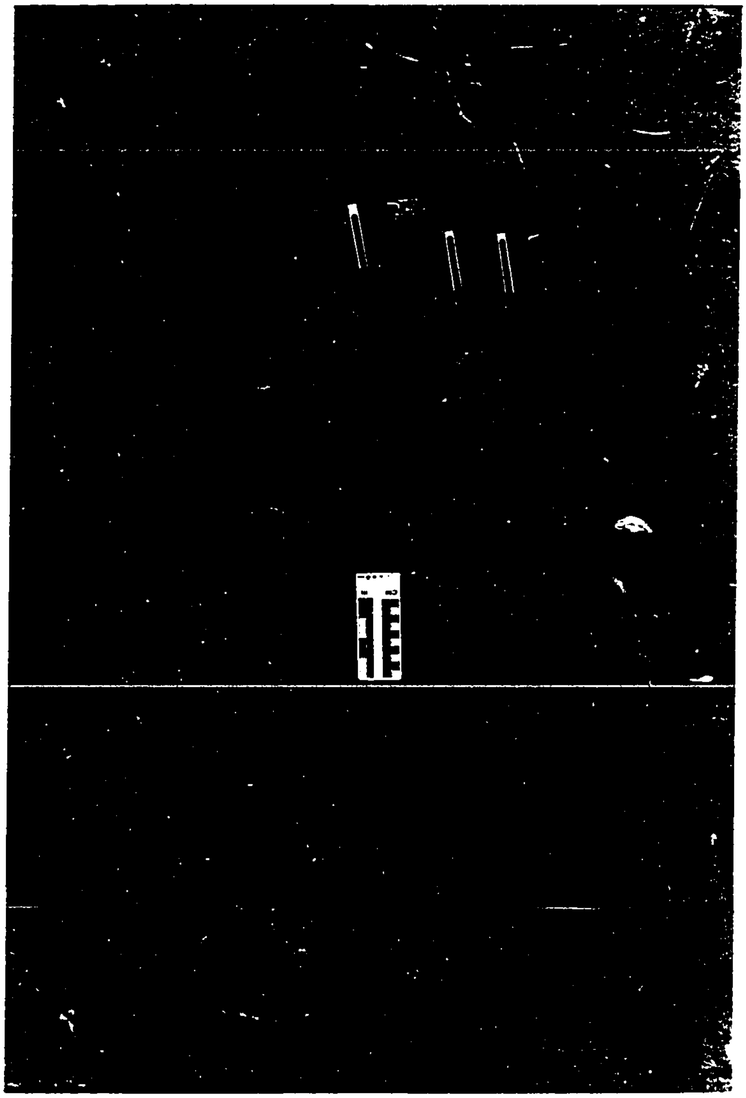


Fig. 5-10. Clast fabrics for each facies; a) Facies 1; b) Facies 2; c) Facies 3; circles represent clast orientation projected onto the lower hemisphere of an equal area net; numbers on the upper portion of each circle refer to fabric numbers shown on Figure 10 ("F" next to fabric number denotes fabric taken from a stacked section; numbers on the lower side of each circle represent the fabric strength (S_1; 0 = random, 1 = uniform), azimuth and plunge of the mean vector (V_1), and number of clasts (n). Contour interval is 2 standard deviations, with black areas representing the maximum deviation from random. Measures after Lawson (1979).

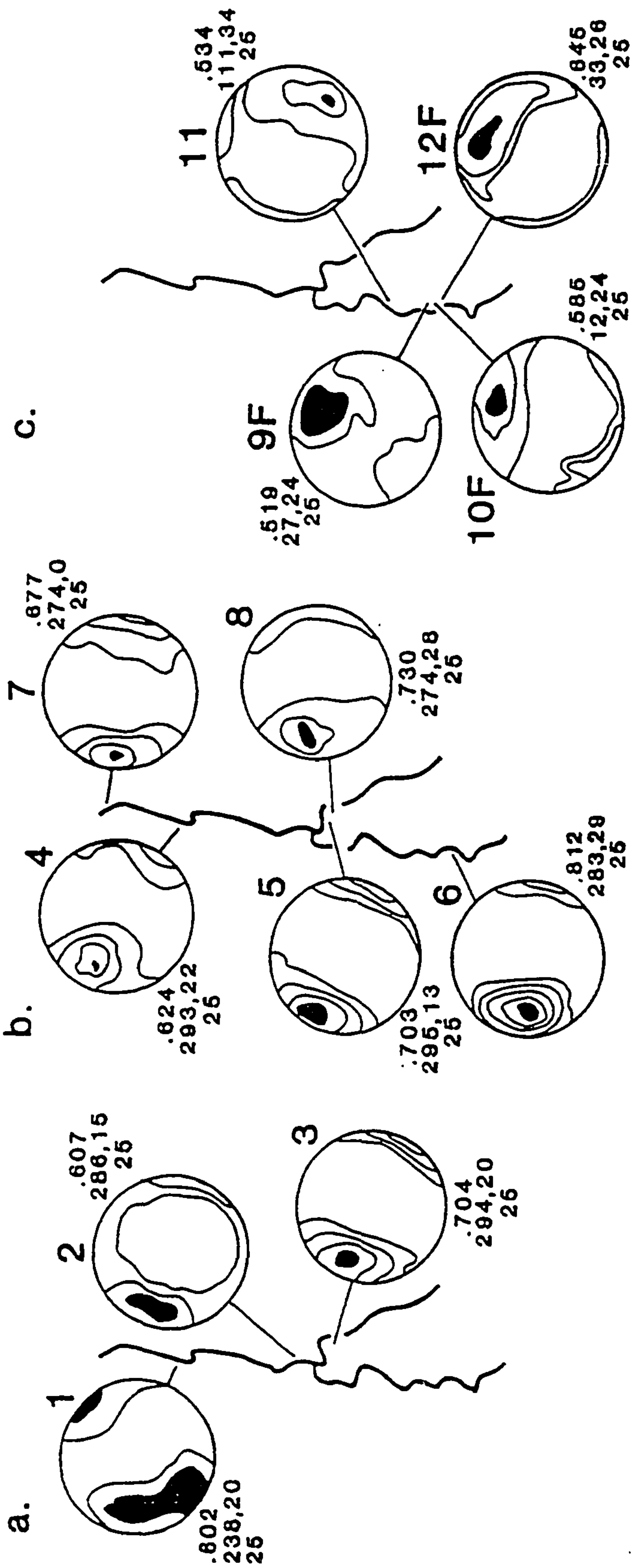

a.
b.
c.
1
.802
238,20
25
2
.607
286,15
25
3
.704
294,20
25
4
.624
293,22
25
5
.703
295,13
25
6
.812
283,29
25
7
.677
274,0
25
8
.730
274,28
25
9F
.519
27,24
25
10F
.585
12,24
25
11
.534
111,34
25
12F
.645
33,26
25

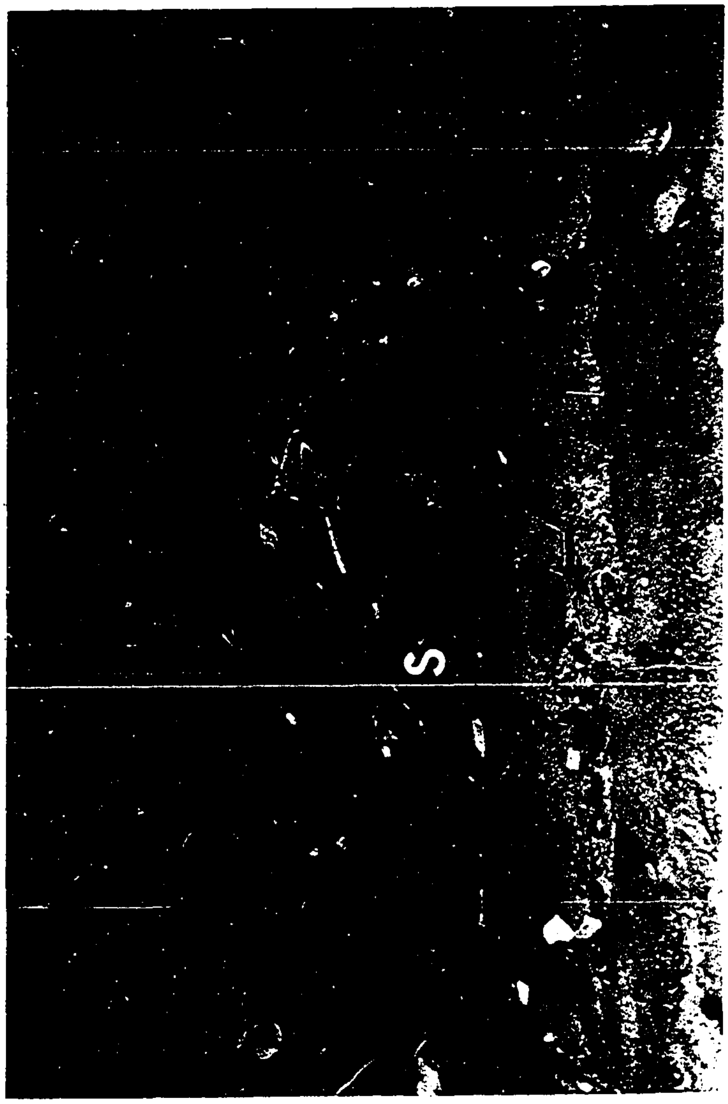
TABLE 5-3. SUMMARY OF TEXTURAL ANALYSES, SHARONVILLE SITE.
Values expressed as mean and ± one standard deviation)

Facies	n	Sand (%)	Silt (%)	Clay (%)	Carbonate Content (%)
4b	1	97	2	1	–
4a	1	94	5	1	–
3	3	26.6 + 0.5	49.0 + 0.9	24.4 + 0.4	28.7 + 3.1
2	8	33.1 + 5.4	53.9 + 6.5	13.0 + 8.5	32.8 + 3.4
1	4	23.3 + 8.6	49.8 + 9.1	26.9 + 1.1	32.5 + 2.6

Facies 2. Numerous angular, lenticular, and convoluted bodies of sand, silt, clay, and gravel within the diamicton characterize this unit. Their orientation may be vertical, horizontal, or dipping. Within many of these bodies, relict bedding and/or laminations are visible (Fig. 5-11). Like the bodies themselves, this relict bedding exhibits no preferred orientation, but in the silt and clay bodies it may be deformed and contorted, and in many cases parallel to the boundaries of the body itself. Other lenses exhibit both concave- downward morphology and internal laminations, along with vertical grading. This facies contains abundant wood, including logs up to two meters in length. Nearly all of the wood is circular in cross-section, and some logs retain bark along their lengths. Larger logs (diameter greater than 15 cm) may have sand and gravel drapes over them. Smaller pieces of wood, also circular in cross-section and commonly with bark, are found in sand bodies within the diamicton. Orientations of wood in the diamicton are dominantly NW-SE. Clast fabrics in this facies dip to the northwest, and have the highest fabric strengths of the three facies, ranging from 0.62 to 0.81 (Fig 5-10b). The lower contact of facies 2 is generally sharp and distinct; the basal ten cm of facies 2 exhibits a five to eight percent increase in clay content. The upper contact of facies 2 with facies 3 is transitional and less distinct.

Facies 3. Unlike the previous two, this facies is massive, with neither the shear planes characteristic of facies 1, nor the bodies of sorted material characteristic of facies 2. Small concentrations of clasts (eight to ten clasts) are present, but rare; these clusters are comprised of randomly oriented clasts which are generally not striated. Rare, small, irregular bodies of the underlying organic silt are present. Wood is present in this unit, and may have some bark still attached. Some of the wood is bent, and frayed ends of the wood generally have diamicton matrix injected into them. Clast fabrics in this facies are variable (Fig. 5-10c). The lower contact of this facies with underlying facies 2 is transitional; the upper contact of this unit was not observed.

Fig. 5-11. Sand and gravel lens in facies 2; note bedding preserved within this lens.


S

Facies 4. This facies consists almost entirely of sand and gravel, with very small amounts of silt and clay. Facies 4 occurs as large lensoid bodies in facies 3 (up to two meters high and four meters long; Fig. 5-12), and occurs as two different sediment types. The first type (facies 4a) is medium to coarse gravel, with lesser amounts of sand, and trace amounts of silt and clay. In general, these lenses have concave-downward upper contacts, and are overlain, at least in part, by facies 3.

The second type (facies 4b) consists of sands overlain by a carbonate-cemented gravel conglomerate. The sands are cross-bedded, and the cross-bedding is truncated at the upper contact with the conglomerate. The sand lenses are less than one meter thick, and range from two to three meters in lateral extent. The conglomerate is 0.35 to 0.45 m thick, and its lateral extent is the same as the underlying sand at all locations.

Transported blocks. In sections 7 and 8 at the southern end of the study area (Fig. 5-7), the entire assemblage of pre-late Wisconsin sediments (units 1-5), as well as facies 2 and/or 3, occur as transported blocks, or floes. A key characteristic of this package of sediments is that they have been transported, rotated, and deposited as a series of imbricate blocks.

At section 7, two blocks are observed; at the contact between the two blocks weathered shale bedrock (the oldest exposed unit in the valley) overlies the massive diamicton of facies 3 (the youngest observed diamicton in the valley). At section 8 (Fig. 5-13), the older sediments repeat three times: once as a "partial" sequence (only the weathered shale and organic-rich silt are present), and twice as "complete" sequences (weathered bedrock through facies 2 or 3 diamictons). At each contact between blocks, older sediments are observed to overlie younger sediments. The contacts between these sequences have strikes between 0^{o} and 35^{o} azimuth. Clast fabrics from facies 3 diamicton within the stacked sequences (Fig. 5-10; fabrics 9, 10, 12) are all to the northeast.

Composite Stratigraphy. Stratigraphic relationships observed at four sections in the central and southern portions of the valley (Fig. 5-14; Table 5-4, sections 5 - 8) were used to construct a composite stratigraphy for the site (Fig. 5-15). These sites were used because they contain the best exposures of multiple unit sequences. Pre-late Wisconsin sediments observed in a trench at section 5 were in situ, and are the oldest units. Also at section 5, massive clays, and facies 1 and 2 form the base of the late Wisconsin sequence. At section 6, approximately 80 m south of section 5, facies 2, 3, and 4a were found; these sediments represent the next portion of the sequence. At sections 7 and 8, the incorporation of facies 3 in the blocks of transported sediments indicates that this

Fig. 5-12. Facies 4 sand and gravel inset in facies 3 at section 6; at left end of facies 4 (central portion of photo), the sands are overlain by facies 3; in the middle and at the right end, the upper portion of facies 4 has been removed by erosion, and is overlain with Recent alluvium.

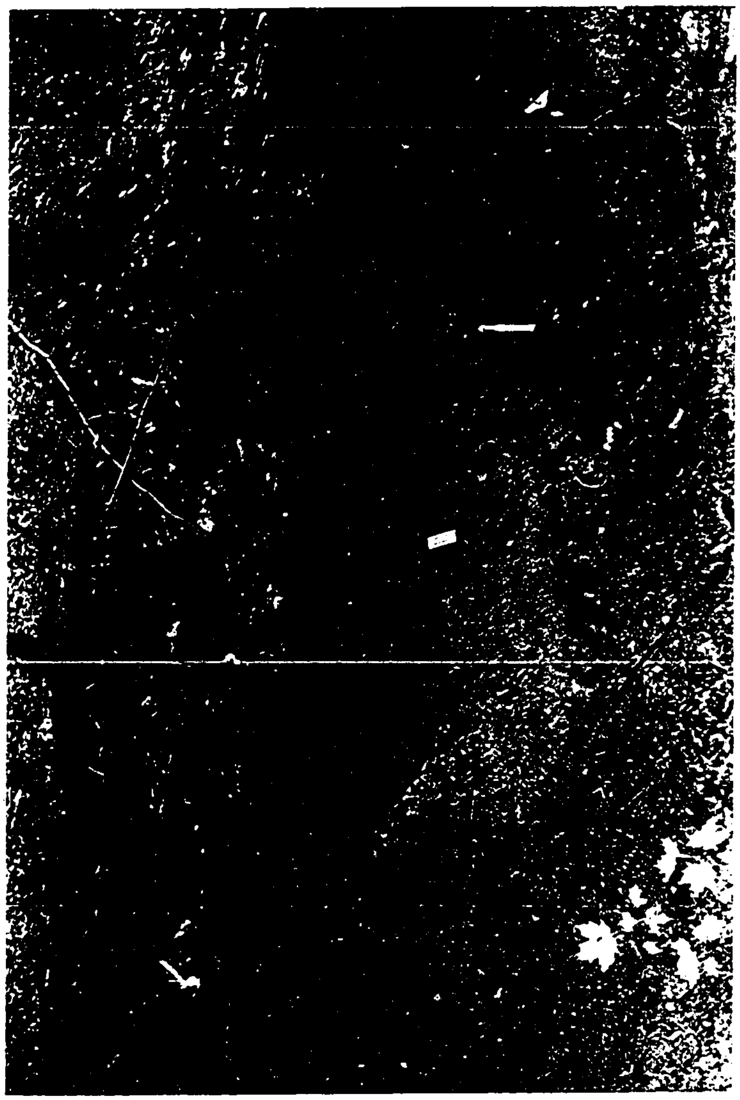
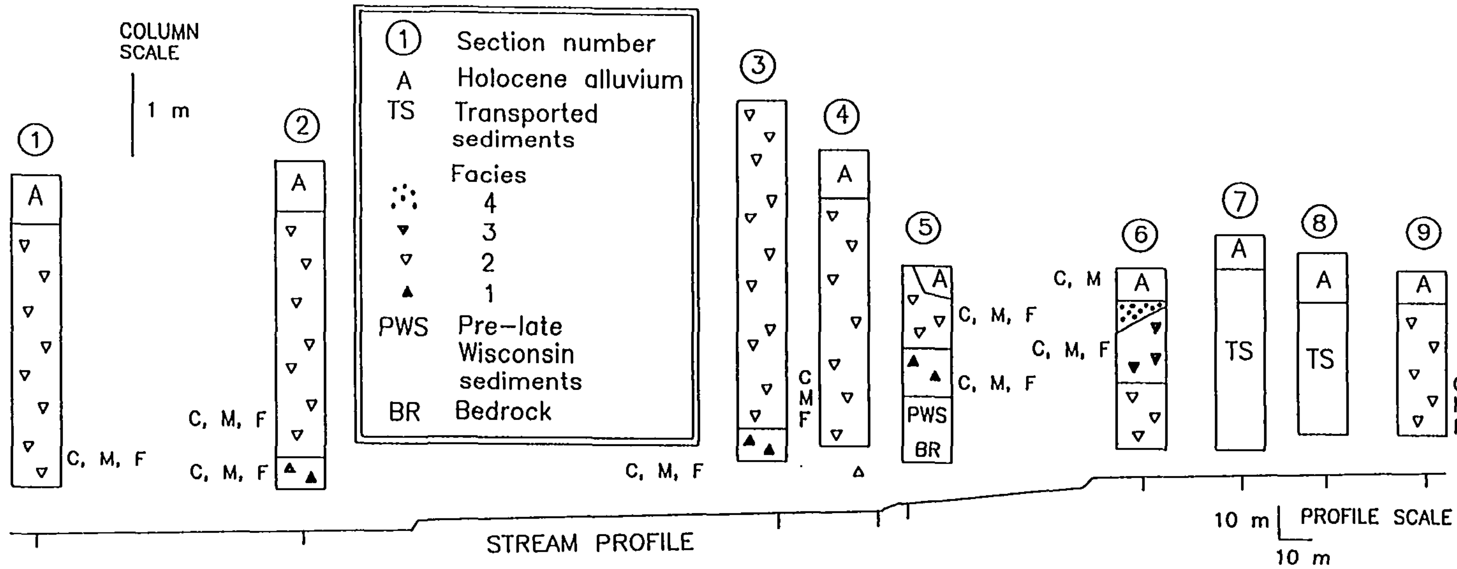


Fig. 5-13. Photographs and facemap of section 8, with stacked, transported sediment blocks; Facies 2 and 3 diamictons indicated; other materials labeled: wood (W), bedrock (b), weathered diamicton (wd), organic silt (or), clay (cy).

Fig. 5-14. Geographic distribution of the observed facies; numbers above each column corresponds to section numbers on Fig. 2; "C" denotes clast sample, "M" denotes matrix sample, and "F" denotes the location of a clast fabric.


COLUMN SCALE
1 m
Section number
A Holocene alluvium
TS Transported sediments
Facies
4
3
2
1
PWS Pre-late Wisconsin sediments
BR Bedrock
C, M, F
C, M
STREAM PROFILE
10 m
PROFILE SCALE
10 m

transport/deformation occurred after facies 3 deposition. Eight of the nine sections are capped by Recent alluvium.

TABLE 5-4. Facies occurrences and distribution, Sharonville site.

Age	Facies	1	2	3	4	S 5	6	7	8	9	Maximum Thickness (m)
Recent	Alluvium	*	*		*	*	*	*	*	*	—
Late Wisconsin	4b					*					—
	4a						*				—
	3						*	S	S		2.0
	2	*	*	*	*	*	*			*	3.5
	1		*	*		*					0.5
	Clay					*		S	S		0.4
Pre-late Wisconsin	Org. Silt					*		S	S		1.3
	Wthd. Diam.					*		S	S		0.9
	Bedrock					*		S	S		—

* - indicates presence of facies at indicated section
S - indicates a "stacked" section

Interpretation of Pre-late Wisconsin Units, Late Wisconsin Glacier Conditions, and Diamicton Genesis.

Genesis of Pre-late Wisconsin sediments. Units 1-5 reflect a stratigraphy nearly identical to both the Glendale and Dimmick Road sites. Unit 2 at Sharonville is too weathered to provided useful information for genetic interpretation. The silt of unit 3 is interpreted to represent loess deposition prior to, or contemporaneous with organic accumulation at about 27,000 yr BP (Lowell *et al.*, 1990a), and the formation of a pre-late Wisconsin soil horizon. That the upper portion of unit 2 diamicton is enriched in organics suggests that soil formation was at least locally extensive. The organic zone, and stumps rooted in this zone, reflect stabilization of the land surface prior to about, with some tree growth on that land surface between 22,000 and 19,700 yr BP. The massive clay of unit 5, like the clays at Glendale and Dimmick Road, is interpreted to represent a proglacial lacustrine sediment deposited immediately prior to overrunning by late Wisconsin ice. The timing of the advance at this site has previously been interpreted to have occurred at 19,670$\pm$68 (Lowell *et al.*, 1990a).

Incorporation of pre-late Wisconsin sediments. Angular blocks of these sediments within the diamicton facies provide information about the first late Wisconsin advance over the site. The organic silt blocks in the overlying facies indicate that the substratum was probably initially unfrozen, and was subjected to erosion by net basal freezing associated with the overriding of active ice (Weertman, 1961; Shaw, 1971, 1987; Boulton, 1979; Wickham and Johnson, 1981). This occurred prior to, or contemporaneous with the deposition of the parent material for facies 1. The paucity of blocks of the pre-late Wisconsin diamicton or bedrock in the overlying diamictons suggests that the depth of incorporation was restricted to the organic silt horizon. The angular nature of these blocks suggests transport as frozen blocks, and may be the result of brittle fracture.

Formation of Facies 1. The sandy planes are interpreted to be shear planes; these shears, together with the highly deformed inclusions of the underlying organic silt reflect the deformed nature of this unit. Deposition of this facies, and its subsequent deformation may have been contemporaneous with a change from frozen/freezing to melting basal conditions associated with still-active ice. Deformation of the underlying clays supports the idea of a frozen (freezing) to basal melting transition (Boulton, 1972b; Hansel *et al.*, 1987; A. Dreimanis, pers. comm.), and a thawing of the underlying sediments. Shearing, such as that noted in this facies, has been interpreted by Boulton *et al.* (1974) to be an ice-marginal process. Orientations of the shear planes, interpreted to be dipping upglacier (Hicock and Dreimanis, 1985), and the slicksides along the planes, indicate a possible ice flow direction from the northwest. Two of the fabrics support this flow direction.

Characteristics of this diamicton, as described above, are consistent with those reported by previous workers for subglacially deposited tills (e.g., Boulton, 1970; Kruger and Marcussen, 1976; Kruger, 1979; Broster *et al.*, 1979; Dreimanis, 1982, 1988). Because of the highly deformed nature of the diamicton, we interpret this facies to be a deformation till. This facies may correspond to the "deforming bed till" of Alley *et al.* (1987).

Deposition of Facies 2. The undeformed, or slightly deformed nature of blocks of organic silt, sand and gravel, and clay in this facies indicates that their transport and deposition probably occurred while the blocks were still frozen (Aber, 1985; Shaw 1985), and under conditions of very little shear stress. These characteristics are consistent with deposition associated with inactive ice, and represent a transition from active, melting ice to inactive (or stagnant) melting ice. Subsequent release of the blocks could have been by a) supraglacial deposition in a sediment flow deposit; b) supraglacial meltout; or c) subglacial meltout. Clast fabrics in this unit, generally to the northwest, support the notion of ice flow from the northwest, as discussed above in facies 1.

Undeformed laminations in drapes over logs, and consistent clast fabrics over several hundred meters of lateral exposures (J. Shaw, pers. comm.; Haldorsen and Shaw, 1982; Bouchard *et al.*, 1984; Van der Meer *et al.*, 1985) suggest a meltout, rather than flow, origin; channel-form sand and gravel lenses are likely englacial or subglacial in origin and favor subglacial meltout for deposition of this facies (Boulton, 1972b). I therefore interpret this facies to be a subglacial meltout till.

Paul and Eyles (1990) have discussed some theoretical conditions governing the the formation and preservation potential of meltout till, and conclude that these tills require any basal shear stress to be below the yield strength of the sediment, and pore water pressures within the sediment to be below the level necessary to induce fluidization. Because these are rare conditions, they also conclude that meltout tills must likely form a very small part of the preserved glacial record, and are likely to be very restricted in thickness. Although Paul and Eyles (1990) conclude that basal and englacial debris concentrations are far too low to permit accumulation of thick sequences of meltout till, other workers (e.g., Boulton, 1970; 1972a) have reported debris concentrations with the potential to produce meltout tills at least five meters thick.

We propose that the embayment setting of the Sharonville site is an area with high potential for both the formation and preservation of meltout till for the following reasons: 1) presence of extensive sand and gravel aquifers in the major valley (Mill Creek) located upglacier from the study site; these aquifers, over 1500 m wide, and in some places in excess of 15 m thick (Bernhagen and Schaefer, 1946), were probably capable of draining substantial quantities of subglacial meltwater, thereby keeping overall regional pore water pressures reduced, and relative sediment shear strength high, and 2) very gentle slope of the substrate, providing little gradient to initate flow. Our interpretation of stagnant ice at the time of deposition, if correct, serves to reduce or eliminate shear stress from active ice. Likewise, deposition in a subglacial setting would reduce the likelihood of flow.

Formation of Facies 3. This facies is massive, with no unique identifying characteristics. Melting conditions are required for deposition by supraglacial and subglacial sediment flow, as well meltout and lodgement; the fundamental difference is whether the ice is active or inactive at the time of deposition. The characteristics within this facies, as described above, allow us to interpret this unit as being deposited under melting conditions, probably in an ice-marginal setting.

Formation of Facies 4. The morphology of these bodies, especially facies 4a, indicates little or no truncation of their upper contacts with facies 3, and suggests deposition in a subglacial fluvial setting, reflecting continued melting conditions. The stratigraphic position of the sands and gravels indicates that they were deposited contemporaneously with facies 3.

Transport of megablocks. Imbricate, stacked megablocks of sediments have been reported by numerous authors (e.g., Kupsch, 1962; Moran *et al.*, 1980; Aber, 1985; Aber and Lundqvist, 1988; and references therein). These studies have identified common characteristics likely to favor such stacking. These features include 1) ice flow upslope 2) compressional ice flow, 3) active ice flowing over a freezing- or frozen-bed marginal zone, 4) pre-existing planes of weakness in the bed, and 5) decreased shear strength in the sediments due to elevated pore water pressure. The first two factors are readily applicable to the this site because of the geomorphic setting and interpreted ice flow direction. The third is consistent because we are near the terminus of the late Wisconsin advance, and ice flow may have been over a freezing or frozen bed. Weathered, highly fissile shale bedrock is the basal unit affected by the stacking; the fissility of the shale is consistent with the fourth factor. Moreover, the unweathered bedrock is likely less permeable than the overlying weathered bedrock and unlithified sediments, and may act to promote highly localized zones of high pore water pressures, consistent with factor 5. The mechanism discussed above has been termed "glacial-thrust" (Moran *et al.*, 1980), or "ice- thrust".

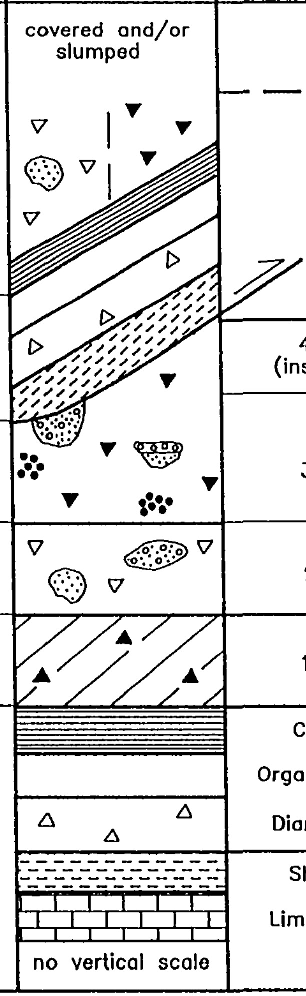
The youngest unit obviously affected by the stacking is facies 3; therefore the interpreted reactivation of ice flow over the site had to have occurred after deposition of facies 3 from stagnant ice. We interpret the stacking at Sharonville to be the result ice-marginal deformation processes associated with reactivation of ice in the embayment.

SUMMARY OF GEOLOGY AT THE THREE SITES

The observed stratigraphy at each of the three sites is nearly identical: bedrock overlain by a sequence of pre-late Wisconsin sediments, which are in turn overlain by diamictons of late Wisconsin age. The key marker horizons in the stratigraphy are the organic silt and the capping organic "mat". Radiocarbon age estimates from these horizons at two of the three sites establish the overlying diamicton sequence as late Wisconsin in age. The extreme similarity between the Dimmick Road stratigraphy and the dated stratigraphies at Glendale and Sharonville lead to an interpretation of the Dimmick Road site as also being late Wisconsin in age. Additionally, the same stratigraphy is reported at nearby locations studied by other workers (C.S. Brockman, Ohio Geological Survey, pers. comm., Chamberlain Park; Crawford, 1977, location 35).

Differences in the sequence of observed diamicton facies (e.g., multiple, but different, facies at Sharonville and Dimmick Road; a single facies at Glendale Waste

Fig. 5-15. Composite stratigraphic sequence, including interpretation of sediment genesis and processes.



FABRICS	LITHOLOGY	FACIES	SEDIMENT INTERPRETATION	PROCESS INTERPRETATION
			?	?
9, 10, 12			Transported sediments	second advance over freezing or frozen ice–marginal sediments with subsequent entrainment and stacking
		4 (inset)	Fluvial sediments	cessation of ice movement, with localized in situ melting, slumping, and development of fluvial drainage
11		3	Sediment flow deposits	
4, 5, 6, 7, 8		2	Melt–out till	
1, 2, 3		1	Deformation till	release of sediment, and deformation by moving, basally–melting ice
		Clay	Proglacial lacustrine	initial advance of ice over freezing bed, and entrainment of sediment
		Organic silt	Loess	
		Diamicton		(pre–late Wisconsin sediment)
		Shale	Bedrock	
		Limestone		

Water Facility) at each of the three sites (Table 5-5) are attributed to local fluctuations in basal conditions and processes (i.e., deposition and erosion) active at the time the sites were beneath the glacier.

TABLE 5-5. Observed stratigraphy at sites covered by Laurentide ice.

Interpreted Age	Facies	Glendale	Dimmick Road	Sharonville
Recent				*
Late Wisconsin	Cemented fluvial sand & gravel			* (6-F4b)
	Uncemented fluvial sand & gravel		* (in 6)	* (6-F4a)
	Sediment flow deposits		* (6)	* (6-F3)
	Meltout till	* (7)		* (6-F2)
	Deformation till		?	* (6-F1)
	Proglacial lacustrine sediments	* (5, 6) silt	* (5) clay	* (5) clay
Pre-Late Wisconsin	Loess	* (3) O.S.[a] * (3) I.S.[b]	* (4) O.S.[a] * (3) I.S.[b]	* (3) O.S.[a]
	Diamicton of uncertain origin	* (2) subglacial?	* (2)	* (2)
Ordovician	Bedrock	* (1)	* (1)	* (1)

[a] - Organic silt
[b] - Inorganic silt
* (2) - facies present, and unit number

DISCUSSION OF MARGINAL DYNAMICS

On the basis of sedimentologic, structural, and stratigraphic data, a sequence of changes in the activity and basal thermal regime of the ice at these sites, beginning at about 19,700 yr BP (Lowell *et al.*, 1990a) is reconstructed. The interpreted sequence of glacier conditions, from oldest to youngest, is given below. After each step, stratigraphic units representing that step are listed (G = Glendale, D = Dimmick, S = Sharonville).

1) active ice flow over a freezing bed (entrainment of pre-late Wisconsin sediments (all sites),
2) basally-melting, active ice (D6 deposition, D1 through lowermost D6 deformation; S-facies 1 deposition and deformation),
3) melting, inactive ice (G7, uppermost D6, and S-facies 2, 3 and 4 deposition),

4) active ice flow over a freezing bed ("thrusting" and stacking of megablocks of ice-marginal sediment; Sharonville only), and

5) melting, inactive ice (deposition of megablocks; Sharonville).

It is important to note that the thermal "zones" described in previous sections are generally margin parallel, and may be quite narrow (e.g., Kupsch, 1962; Moran *et al.*, 1980; Wickham and Johnson, 1981).

The proposed sequence lends itself to the formulation of two hypotheses to account for the origin of the lithofacies and associated deformation. The primary difference between the two hypotheses lies in the cause for ice stagnation responsible for facies 2 and 3 deposition at the Sharonville site. In the first hypothesis, the observed stratigraphic sequence reflects only changes in the character of the ice lying within the bedrock embayment. In this hypothesis, ice within the embayment became detached from the main, still-active ice mass in the Mill Creek Valley, and stagnated, resulting in deposition of facies 2 meltout till and facies 3 sediment flow sediments. After some time, ice within the embayment again became active, mobilizing older sediments. This hypothesis is testable by description of the presence or absence of similar sequence of changes in the activity and basal thermal regime at sites outside of the embayment. If this sequence is not observed elsewhere, the changes in the nature of the ice may be restricted to a small area, and likely represent only a reactivation of locally stagnant ice. It must be emphasized that it is the sequence of changes in ice behaviour, not the specific sedimentary sequence, that must be identified to test the hypothesis.

In the second hypothesis, facies 2 and 3 represent regional cessation of ice movement and subsequent melting. Entrainment and transport of older sediments represents regional reactivation of ice, and implies regional changes in boundary conditions of the glacier. This hypothesis is testable by additional study across the Miami Sublobe.

Ekberg (1991) studied several sites in the western portion of the Miami sublobe near Oxford, Ohio, and concluded that two advances occurred after 20,000 yr. B.P. This study supports the hypothesis that there may have been a regional cessation and reactivation of Laurentide ice in the Miami sublobe. Documentation of this reactivation at additional sites would lend further support to this hypothesis.

CONCLUSIONS

The following conclusions are drawn from study of the sites covered by Laurentide ice:

1. pre-late Wisconsin stratigraphy at sites located within the late Wisconsin glacial limit

is generally uniform and readily correlatable between study localities.

2. sedimentologic, structure, and stratigraphic data from glacigenic sequences at the southern margin of the Miami sublobe of the Laurentide ice sheet reflect a sequence of ice advance - stagnation/recession - readvance, beginning about 19,700 yr BP;

3. timing of the advance - stagnation/recession - readvance sequence observed at Sharonville appears to be temporally consistent with other sites located along the western margin of the same sublobe.

4. preservation of a significant thicknesses of meltout till may be attributed to a specific set of local geologic and geomorphic conditions.

SIGNIFICANCE TO STUDY OBJECTIVES

The significance of these sites to the overall objectives of this study is that a changes in the thermal regime and activity of the late Wisconsin glacier can be interpreted from sedimentologic and structural analysis of the glacigenic sediments. Changes in both thermal regime and activity may be related merely to local topographic and geomorphic effects, or they may reflect regional changes in paleoclimate. The similarity to other sites of the same age which record nearly the same changes supports some sort of regional change in the glacier system, but this study cannot be considered conclusive.

Additionally, the composite stratigraphic sequence of glacigenic sediments provides a geologic record suitable as a check for paleoclimate modeling. The fundamental question to guide such modelling would be "Is the paleoclimate interpreted from independent proxy records (like those at the Rack Quarry site) consistent with the paleoclimate necessary to generate the observed sequence of glacigenic sediments within the ice margin?". This question is further addressed in chapter 6 of this dissertation.

CHAPTER 6. ASSESSMENT OF LATE WISCONSIN GLACIER CONDITIONS AND PALEOCLIMATE INTERPRETATION

INTRODUCTION

The hypothesis of this study is that glaciology theory combined with geologic observations provides a framework for characterizing the thermal conditions near the margin of the glacier, and for ultimately estimating ice surface temperature conditions, a paleoclimate proxy indicator. To test this hypothesis, the following methodology is applied (Fig. 6-1): 1) apply glaciology theory to identify which parameters are needed to characterize the thermal conditions of the glacier, 2) interpret thermal and ice-movement conditions necessary to produce the observed geology, 3) derive and/or estimate additional glaciologic parameters, and 4) numerically combine the glaciology theory with the observed geology to estimate ice surface temperatures for each time interval. Sensitivity analysis of the calculations identifies which glaciologic parameters are most important for paleoclimate estimation (5); comparison with independent local and regional paleoclimate estimates during the same time interval provides a check on the validity of the analysis (6).

Application of this methodology with the late Wisconsin glacigenic sequence discussed in Chapter 5 yields ice surface temperature estimates ranging from 0 to -19°C for the five intervals of interest. Sensitivity analysis suggests that heat generated by basal sliding (a function of basal sliding velocity and basal shear stress) is the primary thermal "input"; it is shown that even significant variations in sliding velocity and basal shear stress produce only minor variations in the final calculated ice surface temperature. The range of temperatures estimated by this analysis is consistent with the temporally-equivalent estimates predicted independently from local biota, as well as regional biota and geology.

GLACIOLOGY THEORY - HEAT SOURCES

The first step in determining ice surface temperatures is to identify those parameters which will characterize the thermal conditions of the glacier. Glaciology principles provide a methodology for evaluating these thermal conditions. Characterization of thermal conditions within the glacier requires identification of the potential sources of heat within the glacier system. Primary sources of heat at or near the base of a glacier are geothermal heat, frictional heat produced by ice sliding over its bed, and frictional heat produced by the internal deformation of the ice (Fig 6-2).

Fig. 6-1. Flowchart showing approach utilized in paleoclimate reconstruction; this flowchart also corresponds to the organization of this chapter.

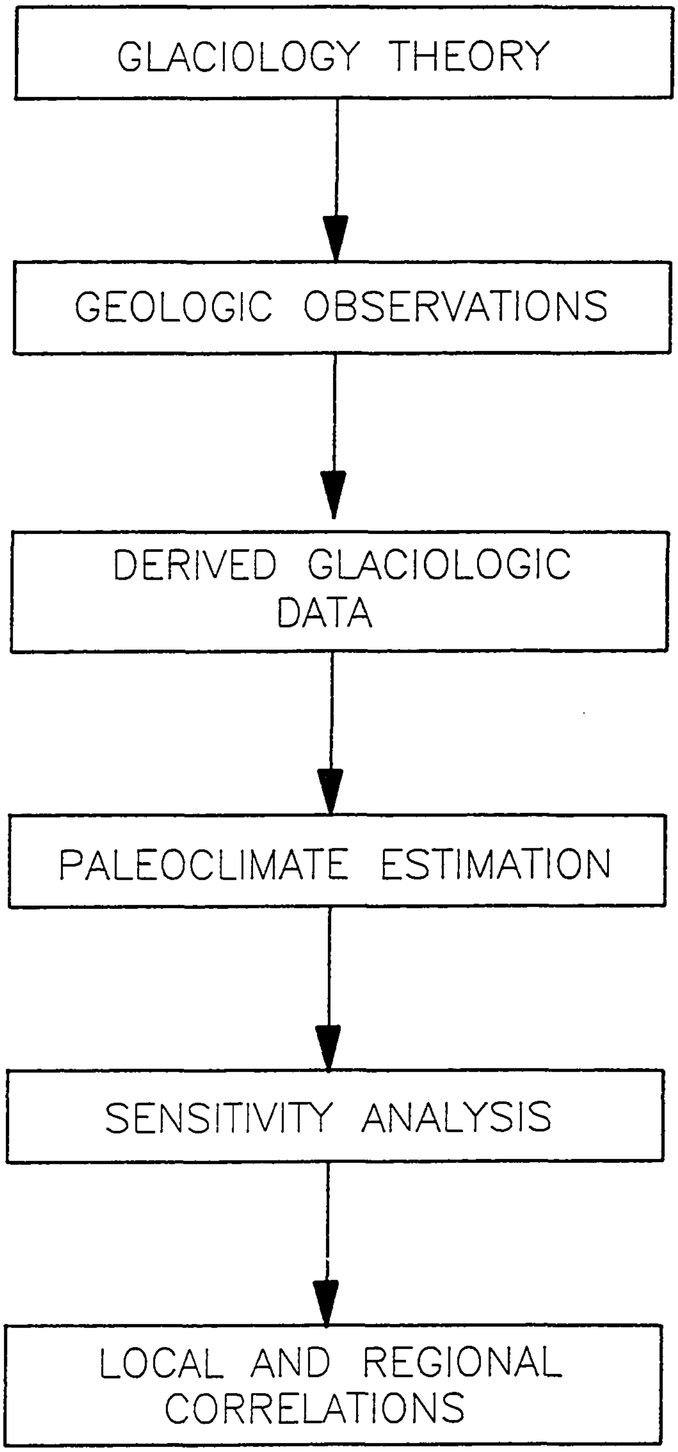
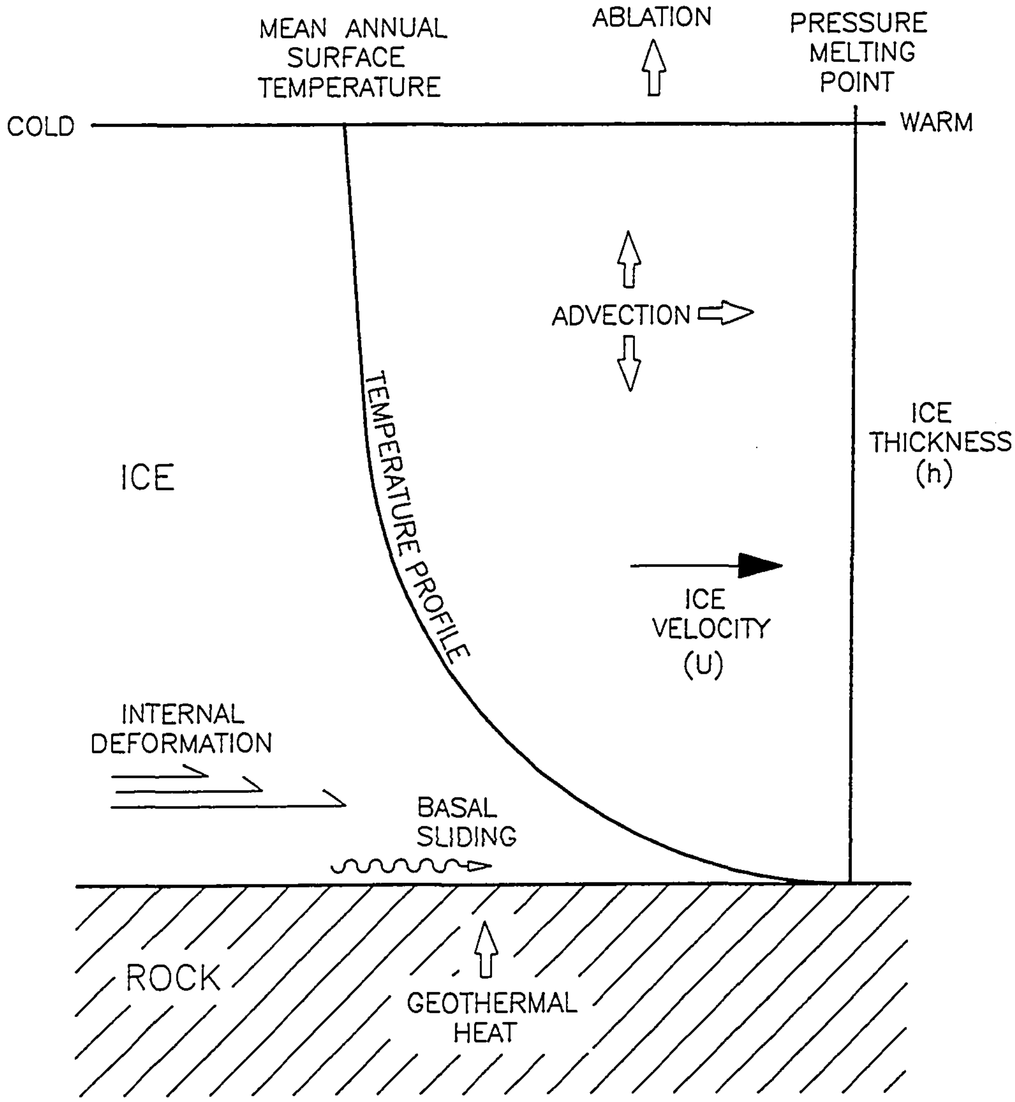

GLACIOLOGY THEORY
GEOLOGIC OBSERVATIONS
DERIVED GLACIOLOGIC DATA
PALEOCLIMATE ESTIMATION
SENSITIVITY ANALYSIS
LOCAL AND REGIONAL CORRELATIONS

Fig. 6-2. Schematic profile through a glacier showing potential heat sources, and a general temperature profile. Modified from Drewry (1986).


MEAN ANNUAL
SURFACE
TEMPERATURE
ABLATION
PRESSURE
MELTING
POINT
COLD
WARM
ADVECTION
TEMPERATURE PROFILE
ICE
ICE
THICKNESS
(h)
ICE
VELOCITY
(U)
INTERNAL
DEFORMATION
BASAL
SLIDING
ROCK
GEOTHERMAL
HEAT

Additionally, advective heat transport by meltwater provides another heat flux which must be considered. Glaciology theory of each of these sources, considered as a heat flux, is discussed below; estimation of the each heat flux for each interval is discussed in Appendix A, and is summarized in Table 6-2.

GEOTHERMAL HEAT FLUX. Heat supplied to the base of the glacier is the first of the sources to be considered. Waddington (1987) has discussed both spatial and temporal variability in geothermal flux, the sources of this variability, and the general effects on the glacier system as whole. Because this study is concerned with a small geographic area, and with a geologically-short interval of time, geothermal heat flux will be considered to be a constant. Measured geothermal heat fluxes in North America were reported by Judge (1973a, 1973b), and synthesized by Sugden (1977). The estimated geothermal flux for southwestern Ohio is 1.85×10^6 J m^{-2} yr^{-1}.

FRICTIONAL HEAT. Frictional heat within the glacier system is derived from two sources: heat generated at the ice-bed interface as a result of contact between actively-moving ice and its bed ("basal sliding"), and heat resulting from internal deformation of the ice.

Basal Sliding. Heat generated by basal sliding is a function of basal shear stress at the base of the glacier, and the sliding velocity of the glacier. This heat due to basal sliding (Λ_s) may be expressed by

$$\Lambda_s = \tau_b \, U_s / J \, c_i \, \rho_i \qquad (1)$$

where τ_b is basal shear stress, U_s is sliding velocity, **J** is the mechanical equivalent of heat, c_i is the specific heat capacity of ice, and ρ_i is the density of ice.

If we consider this the heat contributed by basal sliding as a flux (Ψ_s), rather than as an "amount" of heat, the c_i and ρ_i terms are removed, and this relationship is expressed by (Ritz, 1987):

$$\Psi_s = U_s \, \tau_b \qquad (2)$$

The mechanical equivalent of heat, **J**, is omitted in this step, because it has a value of unity in S.I. (Paterson, 1981).

Alley (1991, and references summarized therein) reports estimated basal shear stress values for southern portions of the Laurentide ice sheet ranging from 5 to 50 kilopascals (kPa; = 0.05 to 0.50 bar). Hughes (1981) estimated basal shear stress values ranging from 70 to 125 kPa (0.70 to 1.25 bar) for southern marginal areas of the Laurentide ice sheet. Values reported by other authors (e.g., Nye, 1952; Mathews, 1974; Andrews, 1987) generally lie within this range. One notable exception is Clarke *et al.* (1988); they report that the driving basal stresses for several lobes of the southern Laurentide ice sheet may have been as low as 2 kPa (0.02 bar) or even less. Schilling and Hollin (1981) speculate that exceptionally low basal shear stresses (5-10 kPa or less) may reflect high basal melting and surging. Thus, this study will consider basal shear stress values of 5, 50, and 100 kPa.

TABLE 6-1. SUMMARY OF BASAL SHEAR STRESS AND BASAL SLIDING VELOCITY VALUES FOR EACH INTERVAL. See text for references, and see Appendix A for example calculation for interval 1.

	BASAL SHEAR STRESS		SLIDING VELOCITY	
	Range	Value Used	Range	Value Used
INTERVAL	(kPa)	(kPa)	(m yr-1)	(m yr-1)
5	5-125	0	100-1000	0
4	5-125	100	100-1000	100
3	5-125	0	100-1000	0
2	5-125	5	100-1000	500, 1000
1	5-125	50	100-1000	500

Ice velocities of 100 to 1000 m yr^{-1} for southern portion of the Laurentide ice sheet were suggested by Alley (1991; summarized from references therein). For analyses in this study, ice velocity values of 100, 500, and 1000 m yr^{-1} will be considered. For an advancing glacier, or a glacier with a stable ice margin, the ice velocity must be greater than marginal advance rate. As a comparison between the range of ice velocities suggested by Alley (1991) and ice margin advance rate, Goldthwait (1958) estimated a marginal advance rate of the late Wisconsin ice margin in southwestern Ohio of about 25-30 m yr^{-1} (based on radiocarbon chronology). Refinement of the radiocarbon chronology by Lowell and his students at the University of Cincinnati (Lowell *et al.*, 1990; Ekberg, 1991; Ekberg and Lowell, in prep.) suggests a marginal advance rate of approximately 70 m yr^{-1}. The range of ice velocities suggested by Alley (1991) therefore meets the requirement of ice velocity greater than marginal advance rate.

Internal Deformation. Heat generated by internal deformation is a function of both the shear strain and shear stress within the ice, and may be expressed by:

$$\Lambda_d = \varepsilon_{xy} \tau_{xy} / J c_i \rho_i \tag{3}$$

where $\boldsymbol{\varepsilon}$ is the shear strain within the ice, $\boldsymbol{\tau}$ is the shear stress within the ice, and **J**, $\mathbf{c_i}$, and $\boldsymbol{\rho_i}$ are constants as defined above.

Robin (1955) concluded that the internal heat of deformation may be treated as a flux at the base of the glacier (in addition to the geothermal flux). This conclusion has the implicit assumption that heat generated everywhere within the ice (except at its base) is zero; this would seem reasonable because most shearing within the glacier occurs near its base. Robin (1955) estimated that for sliding velocities of approximately 20 m yr^{-1}, the heat due to internal deformation is roughly equivalent to the geothermal heat flow. Although the range of postulated sliding velocities for the southern margin of the Laurentide ice sheet (Alley, 1991) is greater than the 20 m yr^{-1} noted by Robin (1955), the approximation of deformational heat flux nearly the same as geothermal heat flux will be used for this study. The use of this relationship is justified because 1) during intervals where ice is flowing over a freezing or frozen bed, the sliding velocity is likely to be in the range of 20 m yr^{-1}, and 2) during intervals of elevated sliding velocity, basal friction may be reduced by a deforming glacier bed (e.g., Alley *et al.*, 1987; Alley, 1991), and or elevated basal water pressures, thereby reducing internal deformation of the basal ice.

As an additional approximation of heat due to internal deformation, Paterson (1971) estimated that, for temperate glaciers, heat due to internal deformation is sufficient to melt approximately 1 percent of the total ice thickness per 100 years. The heat required to complete this melting may be calculated by:

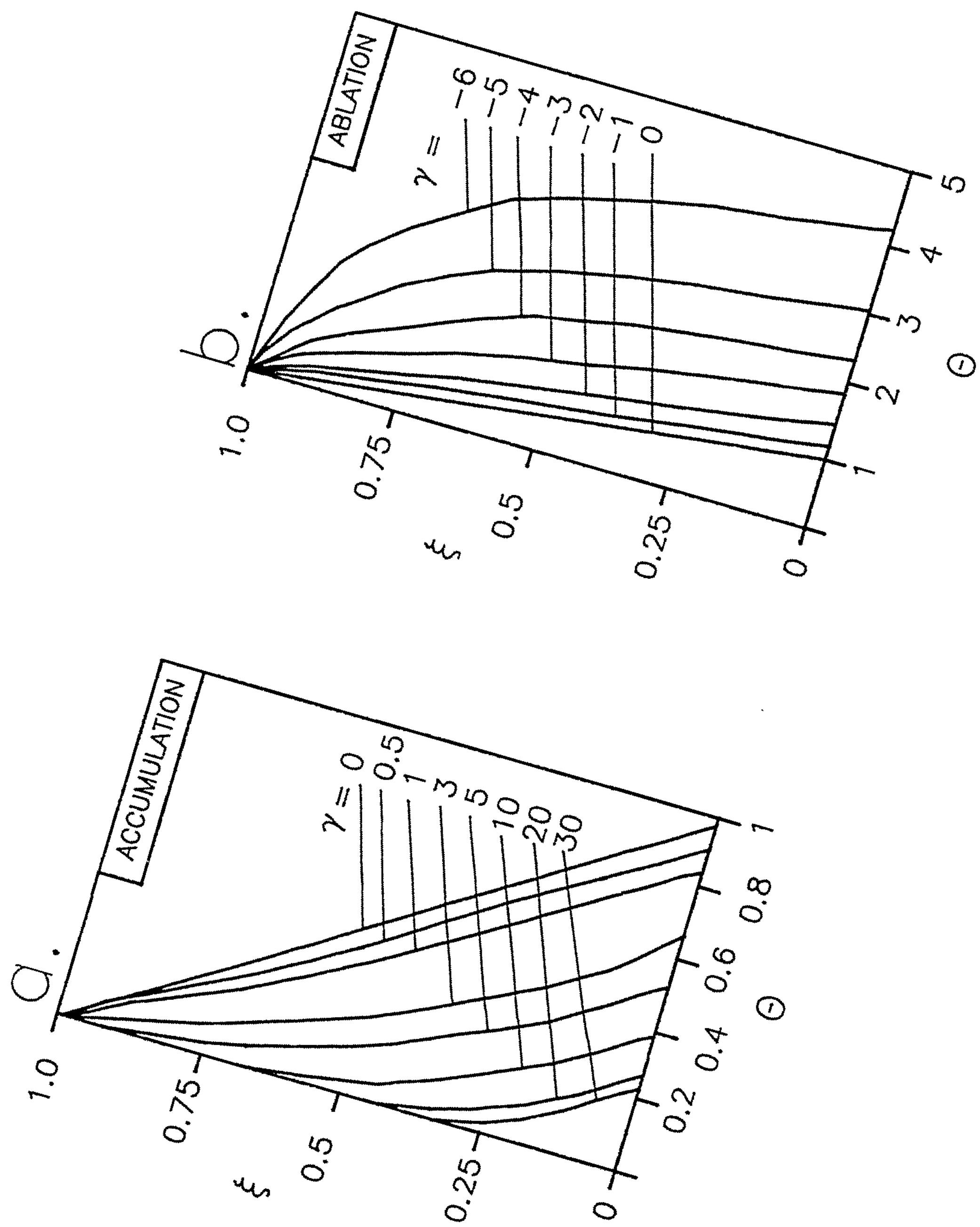
$$\Lambda_d \cong T_{mlt} \rho_i L \tag{4}$$

where $\mathbf{T_{mlt}}$ is the thickness of ice melted, $\boldsymbol{\rho_i}$ is the density of ice, and **L** is the latent heat of fusion (334 kJ kg^{-1} @ 0°C). As a check on the validity of this approximation, for a given total ice thickness of 150 m, it is observed that 0.015 m yr^{-1} of ice is melted, and an approximate heat flux of 4.5×10^6 J m^{-2} yr^{-1} is generated. This value is of the same order as the geothermal heat flux approximation of Robin (1955), as well as the fluxes due to basal sliding, as estimated above. For a more detailed theoretical treatment of heat produced by internal deformation, the reader is directed to Clarke *et al.* (1977). For this study, heat flux due to internal deformation is only relevant for periods of active ice flow. This flux is assumed to be the same for intervals 1, 2, and 4, and not present during intervals 3 and 5.

ADVECTIVE HEAT. Advection within the glacier results in the net transport of heat from one point within the glacier to another (fig. 6-2). Advection may occur in the ice itself (no melting present) as a result of both vertical and lateral ice-temperature gradients. This type of advection is a function of the vertical and horizontal velocities of the ice itself. Advection may also occur by the formation and migration of meltwater within the glacier, and in the sediments beneath the glacier. A common treatment of the results of ice advection is to estimate the relative, rather than absolute, temperature difference between the base and surface of the glacier (e.g., Clarke *et al.*, 1977). The relative temperature treatment is used for this study. This treatment does not provide an "absolute" advective heat flux term, like basal sliding or internal deformation, but rather provides a check on the final estimated difference between basal and surface ice temperatures.

Ice Advection. Advection due to ice movement and spatial temperature gradients is generally separated into vertical and horizontal components, with each component treated individually. The vertical component is a function of the temperature difference between the base of the glacier and the ice surface, the direction and magnitude of vertical velocity of the ice itself, and the thickness of the ice (Hooke, 1977). In the accumulation zone, net vertical velocity is downwards. Because the ice surface temperature is generally colder than the basal ice temperature, the net effect of this downward velocity component is to produce an upward-decreasing temperature gradient profile through the ice (Fig. 6-3a). In the ablation zone, vertical velocity is upwards, with the net result of transporting heat away from the base of the glacier. The net effect of upward ice movement in the ablation zone is to produce an upward-increasing temperature gradient profile (Fig. 6-3b). The effects of vertical advection (for ice surface temperatures colder than basal ice temperatures) may be characterized as follows (Hooke, 1976, 1977):

Fig. 6-3. a) Dimensionless steady-state temperature profiles for various positive values of the advection parameter γ, corresponding to accumulation; b) dimensionless steady-state temperature profiles for various negative values of the advection parameter, corresponding to ablation. Dimensionless variables are: ξ = distance above the glacier bed, Θ = temperature. Both figures redrawn from Clarke *et al.* (1977).


b.
ABLATION
γ = −6
−5
−4
−3
−2
−1
0
1.0
0.75
0.5
0.25
0
ξ
1
2
3
4
5
Θ
a.
ACCUMULATION
γ = 0
0.5
1
3
5
10
20
30
1.0
0.75
0.5
0.25
0
ξ
0.2
0.4
0.6
0.8
1
Θ

1. for constant ice thickness and difference between basal and ice surface temperatures, increasing the vertical ice velocity results in an increase in basal ice temperature;

2. holding vertical ice velocity and difference between basal and ice surface temperature constant, decreasing ice thickness produces a decrease in basal ice temperature.

Estimation of the magnitude of vertical advection requires some estimation of the vertical velocity component. The vertical velocity (v_{vi}) can be expressed as (Hooke, 1977)

$$v_{vi} = - A / U \tan \alpha \qquad (4)$$

where **A** is the ablation rate, **U** is the horizontal velocity at the ice surface (positive downglacier), and α is the ice surface slope (negative downglacier)

If the range of vertical ice velocities for the study area can be estimated, it is possible to estimate the magnitude of vertical advection. If we consider the situation where vertical advection is occurring, but heating due to internal deformation is negligible, a dimensionless advection parameter may be defined (Clarke *et al*, 1977) . This parameter, λ,is expressed by:

$$\lambda = h v_{vi} / \kappa \qquad (5)$$

where **h** is ice thickness normal to the ice surface, v_{vi} is vertical ice velocity, and is thermal diffusivity. For small ice surface slopes, the difference between vertical ice thickness and ice thickness normal to the ice surface is negligible. To predict the magnitude of advection the calculated value of λ is compared with Fig.6-3b (Fig. 1 of Clarke *et al.*, (1977)), and the dimensionless temperature term (Θ) of Clarke *et al.* (1977) is estimated. Clarke *et al.* (1977) have suggested that the temperature difference between the base of the ice and the ice surface is approximately 10Θ.

Temperature gradients in the horizontal direction are generally small enough (on the order of 10^{-5} °C m^{-1}) that, despite horizontal velocities which may be several tens or hundreds of meters per year, very little warming or cooling of the ice takes place (Hooke, 1977; Paterson, 1981). Because this study deals with a spatially restricted area near the late Wisconsin ice margin, the affects of horizontal advection will be ignored in the later analyses.

Water Advection. Advection due to water within the glacial system is the result of water movement within the glacier, at the base of the glacier, and within the bed of the glacier (groundwater). Paterson (1981) indicates that percolation of water through the glacier in the accumulation zone, and the heat released when this water melts at some depth, is an important source of warming within the accumulation zone. Within the ablation zone, however, all snow and ice are lost in the summer, so the latent heat is lost, and does not warm the glacier. Additionally, most water in temperate glaciers is contained in moulins, crevasses, large stream channels, and isolated cavities; while these influence the temperature of the ice in their vicinity, Paterson (1981) concludes that there are not enough of them to affect more than a small part of the glacier. Heat flux due to meltwater advection within the glacier, except in isolated locations, is assumed to be negligible.

The effects of subglacial groundwater flow on temperature profiles through glaciers are summarized by Echelmeyer (1987). He found these effects most pronounced for thin glaciers, where basal temperatures would be $<0^{o}C$, with ice surface temperatures $\leq -10^{o}C$. For ice sheets, the thermal effects of groundwater can be neglected if the ice surface temperature is $\geq -10^{o}C$. Echelmeyer (1987) determined analytically that for ablation rates of 1-2 m yr^{-1}, a frozen bed thickness of 1-5 m, and an overlying ice thickness of 100 m, groundwater present below the frozen basal sediment layer may double the temperature 3gradient expected by considering geothermal gradient alone. An important consideration of Echelmeyer's (1987) analysis is that it requires the presence of a porous, permeable medium beneath the glacier for the groundwater to flow through. At the Sharonville and Dimmick Road study areas, less than 3 m of unconsolidated sediments overlie generally impermeable limestone and shale bedrock. Much of this unconsolidated material is very clay-rich, and likely was a very poor pathway for the migration of groundwater. Additionally, both sites lie adjacent to the Mill Creek Valley, which contains a major sand and gravel aquifer. It is likely that most of the subglacial meltwater was drained from beneath the glacier by this aquifer, and that the heating effects due to groundwater advection at the sites is negligible.

GEOLOGIC OBSERVATIONS & GLACIER BOUNDARY CONDITIONS

The second step towards estimating ice surface temperatures is to use geologic observations to interpret and estimate thermal conditions, ice-movement, and ice thickness necessary to produce the observed geology. These items are discussed below.

BASAL THERMAL REGIME. The principal boundary condition determined from a site with glacigenic sediments is the basal thermal regime present during time intervals of interest. The glacigenic sediments have the potential for providing rough temperature estimates at the base, and near the margin, of the glacier. The temperature estimates are based on style of deposition and/or deformation; interpretation of the mode of deposition and/or deformation is based on characteristics of the sediments observed in the field. Thermal effects on the sediments are generally the result of basal ice temperature crossing the threshold from freezing to melting conditions, or vice versa. As a result, temperatures estimated for each interval are considered "limiting" temperatures; that is, the limiting temperatures define one bracket of the range of temperatures which are necessary to explain the observed geology.

Late Wisconsin glacigenic sediments at the Sharonville and Dimmick Road sites provide a sequence of changes in the dynamics of the late Wisconsin glacier. Five intervals of unique glacier conditions are identified (Chapter 5):

1. active ice flow over a freezing bed (entrainment of substrate),

2. wet-based, active ice flow (deposition of deformation till, deformation of underlying substrate),

3. melting, inactive ice (meltout till deposition and sediment flow),

4. active ice flow over a frozen bed ("thrusting" and stacking of megablocks),

5. melting, inactive ice (deposition of megablocks).

Each interval is unique in the thermal requirements necessary to produce the observed geology; the thermal requirements are discussed for each interval. Interval 1 represents an interval when the temperature at the base of the glacier is at or slightly below the pressure melting point of ice. Active sliding of ice requires the presence of some water at the base of the glacier, but incorporation of the underlying substrate by "freezing-on" indicates that temperatures below the pressure melting point are also present. The limiting basal ice temperature for this interval is therefore interpreted to be $-0.1^{o}C$; this temperature defines the warmest the basal temperature could be to satisfy conditions of basal freezing.

The deposition of deformation till and subsequent deformation of the underlying substrate in interval 2 requires melting at the base of active ice (Boulton, 1972b). Deposition and deformation under basally melting conditions indicates an increase in basal ice temperature to above the pressure melting point of ice. Thus, the limiting basal temperature for this interval is interpreted to be $+0.1^{o}C$.

Interval 3 reflects a time of basally melting, inactive ice. For melting to occur under stagnant ice, the basal temperatures must be greater than the melting point of ice. The limiting basal temperature for this interval is also interpreted to be $+0.1^{o}C$ or warmer.

Interval 4, like interval 1, represents basal temperature conditions that are close to, but slightly below the pressure melting point of ice; this is evidenced by the "thrusting" and stacking of frozen megablocks of sediments. The thickness of the megablocks (3.5 to 4 m) suggests colder basal temperatures than during interval 1, but this cannot be directly quantified; the limiting basal temperature is interpreted to be -0.1^{o}. This limit defines the warmest that the basal temperature conditions could be.

Interval 5 reflects a second episode of stagnant ice and basal melting. Like interval 3, the limiting basal temperature for this interval is $+0.1^{o}C$; temperatures equal to or warmer than this temperature will produce basal melting.

ICE THICKNESS. The second boundary condition derived from observed geology is ice thickness. Recent studies have estimated ice sheet profiles with flow models (e.g., Hooke, 1976, 1977; Sugden, 1977; Schilling and Hollin, 1981; Mooers, 1990). These models, in general, require estimation or assumption of one or more variables, including ice discharge, ice velocity, accumulation and ablation rates, basal shear stress, geothermal heat flux, and advective heat flux. These models usually generate ice thickness, basal shear stress, and ice velocity profiles that extend for several hundred kilometers, such as from the center of an ice cap or sheet to the glacier margin. The area of interest in this study is a narrow zone within 10 km of the mapped late Wisconsin ice margin of Gray *et al.* (1972); because most of the modelling approaches fail near the ice margin, simpler empirical approaches for estimation of ice thickness have been utilized.

For intervals 1 and 4, the dominant process interpreted from the character of the sediments in these intervals is incorporation as frozen blocks. This, as discussed in chapter 5, is consistent with processes active along the margin of an advancing glacier (e.g., Kupsch, 1962; Moran *et al.*, 1980; Aber, 1985; Aber and Lundqvist, 1988), where ice thicknesses may be greatly reduced, and the use of an equilibrium ice profile is inappropriate. It is possible, however, to consider ice thickness in light of the basal thermal conditions reflected by the sediments. Incorporation of underlying substrate materials as frozen blocks in a subglacial position during these intervals requires propagation of the "freezing front" (the $0^{o}C$ isotherm) through the overlying ice, and into the sediments to the same depth as the thickness of the incorporated sediments (in the case of interval 4, the maximum thickness of an individual incorporated megablock is 3.5 to 4 m). This propagation is driven by fluctuations in ice surface temperature. The extent of propagation is greatly enhanced under thin ice conditions. Paterson (1981) has indicated that this type of propagation of the freezing front can be important on a seasonal basis, and indicates an ice thickness of no greater than 15 to 20 m. Other workers (e.g., Cameron and Bull, 1962; Muller, 1963) have found the limiting ice thickness of this seasonal propagation to be between 10 and 15 m. Assuming seasonal surface temperature fluctuations in the study area, an ice thickness of 15 m is estimated for intervals 1 and 4.

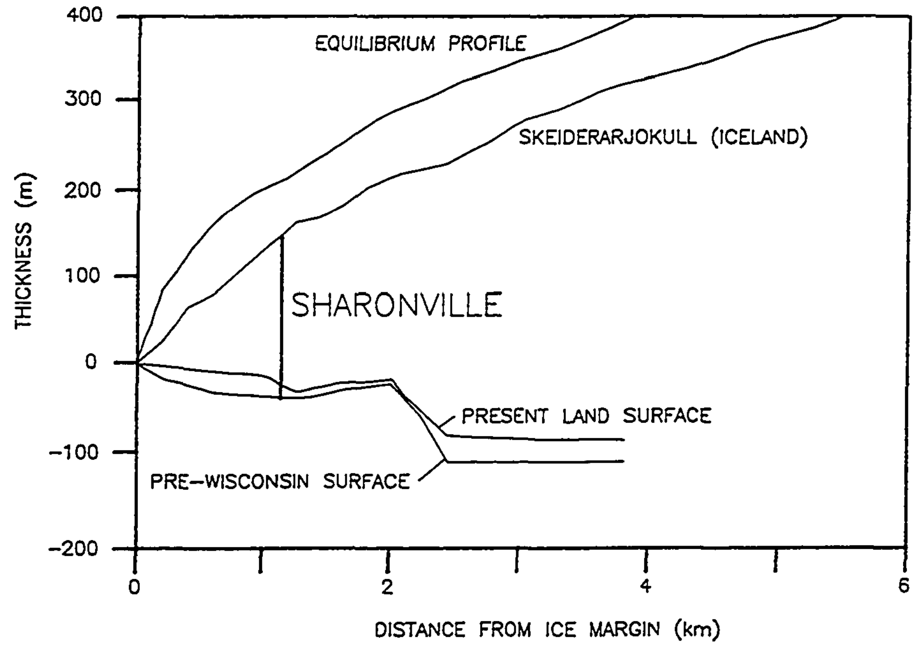
Interval 2 represents the time of increasing ice thickness, with the maximum ice thickness at the end of the interval immediately prior to cessation of ice movement. The extent of the Hartwell Moraine in the study area suggests that the ice margin during this interval was fairly stable; this suggests that the glacier was at equilibrium, or near-equilibrium conditions. A theoretical equilibrium ice profile and measured marginal ice surface profiles from retreating modern Icelandic glaciers (Skeidararjokull, Army Map Service (1949); Eyjabakkajokull, and Blautukvislarjokull, Bjornsson (1988)) were utilized to estimate a range of possible equilibrium ice thicknesses. The theoretical profile provides an estimate of maximum equilibrium ice thickness; the profiles of a retreating glaciers provide an estimate of minimum "equilibrium" ice thickness. The theoretical profile and the measured ice surface profile at Skeidararjokull were superimposed over the interpreted pre-late Wisconsin paleosurface along late Wisconsin flowlines (interpreted from clast fabrics, slickensides, wood orientation). The locations to tie the ice profiles to the paleosurfaces were based on mapped geomorphic features, and interpreted late Wisconsin ice marginal position. The position of each study site along flowline was noted, and the range of ice thicknesses was estimated by subtracting the relative bed elevation from the the theoretical and measured relative ice surface elevation. At both the Sharonville and Dimmick Road sites, the estimated equilibrium ice thicknesses for interval 2 ranged from 100 to 200 m (Fig. 6-4). An average value of 150 m is estimated for the thickness of interval 2.

During interval 3, inactive, basally melting ice suggests that ice thickness must be less than the equilibrium ice thickness determined for interval 2. Constraints on ice thickness for intervals 2 and 4 suggest that initial ice thickness during interval 3 was at or near the "equilibrium" thickness determined for interval 2, and that by the end of interval 3, ice had thinned to about 15 m.

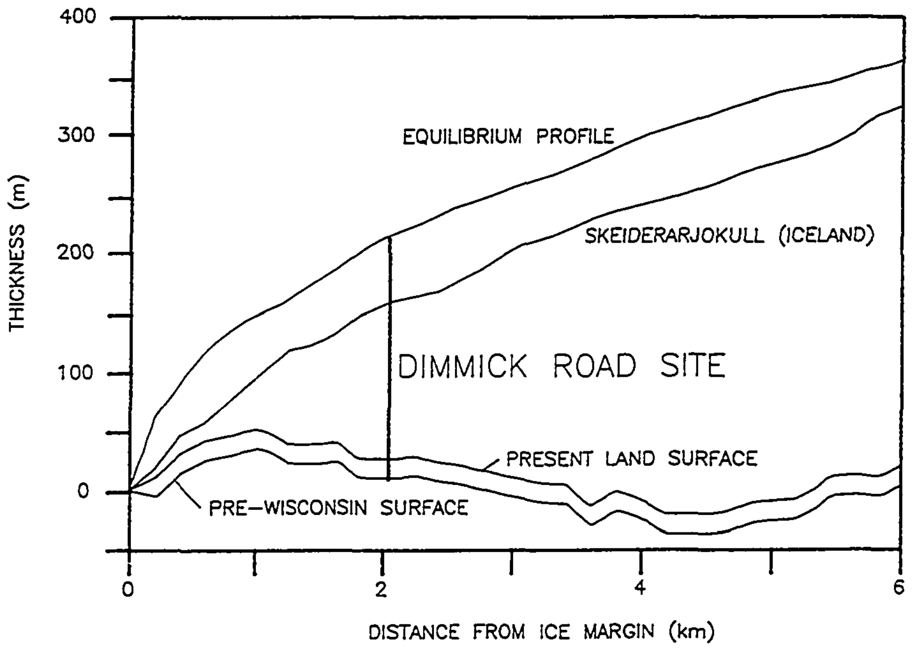
The thickness of ice during interval 5, like that of interval 3, is constrained by the thickness of ice overlying the site at the onset of melting, and by the total melting of ice

Fig. 6-4. Profiles used for ice thickness estimation; a) Sharonville site, b) Dimmick Road site. Theoretical equilibrium profile, modern glacier ice surface profile (Skeidararjokull), pre-late Wisconsin topographic surface, and present day land surface as labeled. Positions of Sharonville and Dimmick Road sites with respect to ice margin are indicated by vertical lines; the vertical line indicates the estimated ice thickness.

a.


400
300
200
100
0
-100
-200
THICKNESS (m)
EQUILIBRIUM PROFILE
SKEIDERARJOKULL (ICELAND)
SHARONVILLE
PRESENT LAND SURFACE
PRE-WISCONSIN SURFACE
0
2
4
6
DISTANCE FROM ICE MARGIN (km)

b.


400
300
200
100
0
THICKNESS (m)
EQUILIBRIUM PROFILE
SKEIDERARJOKULL (ICELAND)
DIMMICK ROAD SITE
PRESENT LAND SURFACE
PRE-WISCONSIN SURFACE
0
2
4
6
DISTANCE FROM ICE MARGIN (km)

at the end of the interval. Because no additional sediments related to the advance of interval 4 were observed, it it not possible to determine an ice thickness near the close of that interval. However, the maximum ice thickness during this interval must have been less than the equilibrium thickness of 150 m.

TABLE 6-2. SUMMARY OF GLACIER BOUNDARY CONDITIONS AND HEAT FLUXES. See Appendix A for example estimation of individual and total heat fluxes.

INTERVAL	BASAL TEMPERATURE (°C)	ICE THICKNESS (m)	FLUXES GEOTHERMAL (**)	BASAL SLIDING (**)	INTERNAL DEFORMATION (**)	TOTAL HEAT FLUX (**)
5	+0.1	< 150	1.85	0	0	1.85
4	-0.1	15	1.85	10	1.85	13.7
3	+0.1	150-15	1.85	0	0	1.85
2	+0.1	150	1.85	2.5 - 5.0	1.85	6.2 - 8.7
1	-0.1	15	1.85	25	1.85	28.7

** all values for heat fluxes are $\times 10^6$ J m^{-2} yr^{-1}

ADDITIONAL GLACIOLOGIC PARAMETERS & EVALUATION OF THE HEAT BUDGET

Theoretical Considerations of the Heat Budget. Weertman (1961) and Boulton (1972) have identified three fundamental boundary conditions relating heat produced to the ability of the heat to be removed:

$$1)\ \Psi_{tot} < K_i\,(dT/dh)_i \qquad (7)$$

$$2)\ \Psi_{tot} = K_i\,(dT/dh)_i \qquad (8)$$

$$3)\ \Psi_{tot} > K_i\,(dT/dh)_i \qquad (9)$$

where Ψ_{tot} is the total heat flux from all potential sources, K_i is the thermal conductivity of ice, and $(dT/dh)_i$ is the temperature gradient in the basal portion of the glacier. As discussed in Drewry (1986), for case 1, the temperature gradient is able to remove all heat produced, and and the glacier will be frozen to its bed. This is the condition which appropriate for interval 4. Case 2 is the situation where there is a balance between heat produced and heat removed, and a balance between freezing and melting at the ice bed interface; this case likely describes conditions during interval 1. In case 3, the gradient cannot remove all the heat, and melting at the ice-bed interface will occur. This is appropriate for the conditions of intervals 2, 3, and 5.

Application of Theory. Each interval may be evaluated with the appropriate relationship to determine the necessary limiting basal temperature gradient. Because total heat flux of the sources has been estimated above, and K_i is a constant, these determinations are straightforward. An example of this calculation for interval 1 is given in Appendix A; results of similar calculations for the remaining intervals are listed in Table 6-3.

Interval 1 is controlled by the relationship of (8), which defines the condition of balance between basal melting and freezing. Evaluating this relationship with Ψ_{tot} = 28.7×10^6 J m^{-2} yr^{-1}, and Ki = 2.1 W m^{-1} $^oC^{-1}$ (Paterson, 1981), a limiting basal temperature gradient of -0.433 ^oC m^{-1} is calculated. Because heat flow is away from the the bed, this gradient must be negative.

Intervals 2, 3, and 5 are satisified by (9), where total heat flux of the sources exceeds the heat removed by the glacier, and net basal melting occurs. Using the values for Ψ_{tot} listed in Table 6-2 above, and the constant value for K_i, the following limiting values for basal temperature gradient are calculated:

interval 2 $(dT/dh)_i$ = -0.094 to -0.131 ^oC m^{-1}

intervals 3, 5 $(dT/dh)_i$ = -0.028 ^oC m^{-1}

These gradients define the minimum (i.e., the "most negative") gradient to sustain basal melting; the actual gradients must be greater ("warmer") than this.

Frozen bed conditions of interval 4, where heat supplied is less than the heat able to be removed, are satisfied by (7). The calculated limiting basal temperature gradient, using the estimated Ψ_{tot} listed above, is -0.207 ^oC m^{-1}. In order to maintain frozen bed conditions, the actual gradient must be less than ("colder") than this.

CALCULATION OF ICE SURFACE TEMPERATURES

Having estimated basal ice temperature, ice thickness, and limiting basal temperature gradient for each interval, it is possible to estimate the ice surface temperature. An example of this calculation for interval 1 is given in Appendix A.

Summarizing the calculations for each interval, the following ice surface temperatures are noted:

Interval 5	-6.6°C
Interval 4	-19.5 to -14°C
Interval 3	-4.1 to 0°C
Interval 2	-3.2°C
Interval 1	>0°C

These estimations of ice surface temperature are based on best estimates of glaciological conditions present at the time of sediment deposition; these estimates take into account only variables within the glacial system. The "averaged" nature of the glaciologic parameters requires that these temperature estimates be considered "annual" at best. Oerlemans and Hoogendoorn (1989) concluded that glacier mass balance, as a function of meteorologic parameters, is controlled by equilibrium line altitude (ELA), mean annual precipitation, mean annual temperature, and mean summer temperature. Hanson (1987) concludes that of all meteorologic factors, the primary control on glacier mass balance is mean summer temperature.

Additional variables which could supply or remove heat from the glacier system include latent heat associated with condensation, evaporation, and sublimation at the ice surface, atmospheric circulation, and insolation. Refinement of the ice surface temperature estimates should take into account as many of these additional parameters as possible.

SENSITIVITY ANALYSIS

Having completed the ice surface temperature estimates for each interval, the calculations were examined to determine which glaciologic parameters are most important in the estimation. Again using interval 1 as an example, it is recalled that total heat flux is given by the expression

$$\Psi_{tot} = \Psi_s + \Psi_d + \Psi_g + \Psi_{ad}, \tag{10}$$

and that for interval 1, this may be expressed by

$$\Psi_{tot} = (25 + 1.85 + 1.85 + 0) \times 10^6 \text{ J m}^{-2} \text{ yr}^{-1}.$$

It is readily observed that the heat flux due to basal sliding has the greatest control on the total heat flux. It may also be recalled that heat flux due to basal sliding is expressed by

$$\Psi_s = \tau_b U_s, \qquad (11)$$

suggesting that basal shear stress and basal sliding velocity are two of the most important glaciologic parameters for paleotemperature estimation.

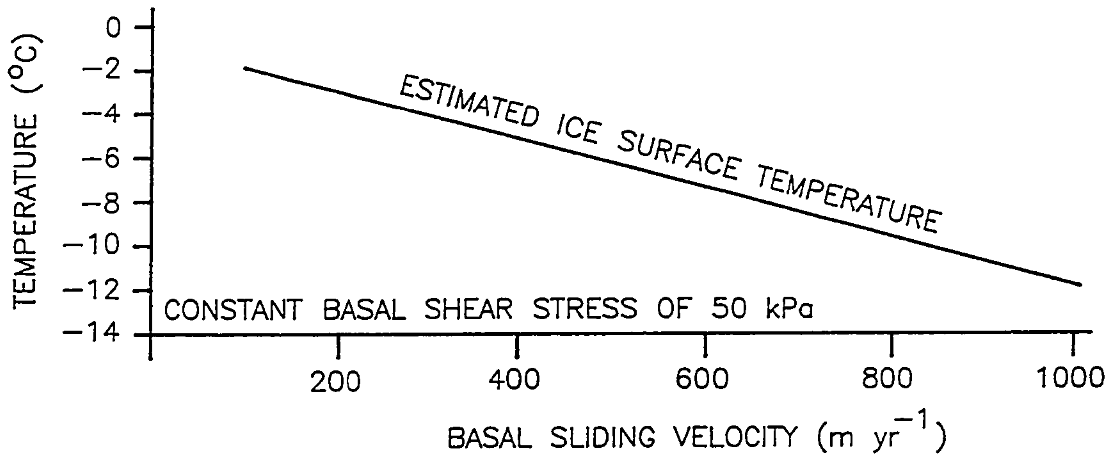
To test the effects of variations in both basal shear stress and basal sliding velocity on ice surface temperature estimation, one variable was held constant, while the other variable was allowed to change over the range of values presented earlier in this chapter. In the first test, basal sliding velocity was fixed at 500 m yr^{-1}, and basal shear stress was allowed to vary from 5 to 100 kPa. The ice surface temperature estimates ranged from about -1°C to -12°C (Fig. 6-5a); this difference is +/- 5.5°C from the temperature estimated from interval 1. For the second test, basal shear stress was fixed at 50 kPa, and basal sliding velocity varied from 100 to 1000 m yr^{-1}. Again, ice surface temperature estimates were found to range from about -2 to -12°C (Fig 6-5b).

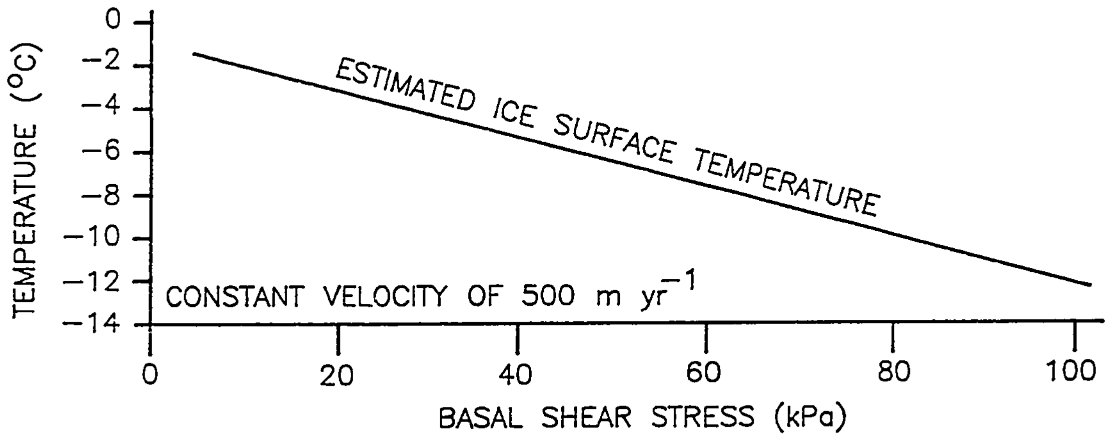
These analyses indicate that within a wide range of geologically-reasonable basal shear stress or basal sliding velocity values, consistent and reproducible ice surface temperature estimates are calculated. Glaciologically unreasonable conditions (e.g., very high basal shear stress coupled with very high basal sliding velocities) resulted in unrealistic ice surface temperature estimates (<-200°C!). While these analyses are not all inclusive, they indicate that for geologically and glaciologically reasonable inputs, plausible estimates of ice surface paleotemperature may be derived.

CHRONOLOGY AND REGIONAL PERSPECTIVE

The final stage in development of the paleoclimate reconstruction is to place the temperature estimates into a chronologic framework, and to place the local geologic observations and temperature estimates into a regional framework. With respect to the chronologic framework, the sites which form the basis for this paleoclimate reconstruction have *in situ* datable organic materials only at the base of the sequence.

Fig. 6-5. Sensitivity analysis results; (top) basal shear stress held constant at 50 kPa, basal sliding velocity varied between 100 and 1000 m yr^{-1}; (bottom) basal sliding velocity held constant at 500 m yr-1, basal shear stress varied between 5 and 100 kPa; note that for both cases, the total range of estimated ice surface temperature is only about 10^{o}C.


TEMPERATURE (°C)
0
-2
-4
-6
-8
-10
-12
-14
ESTIMATED ICE SURFACE TEMPERATURE
CONSTANT BASAL SHEAR STRESS OF 50 kPa
200
400
600
800
1000
BASAL SLIDING VELOCITY (m yr⁻¹)


TEMPERATURE (°C)
0
-2
-4
-6
-8
-10
-12
-14
ESTIMATED ICE SURFACE TEMPERATURE
CONSTANT VELOCITY OF 500 m yr⁻¹
0
20
40
60
80
100
BASAL SHEAR STRESS (kPa)

Timing of the onset of late Wisconsin glaciation has been discussed at length in Lowell *et al.* (1990), and is interpreted to have occurred at 19,970 $\pm$ 68. Duration of late Wisconsin glaciation is not yet determinable from the sediments and organic materials observed at the study localities.

The final step is to place the paleoclimate reconstruction into a regional perspective. Other regional Late Wisconsin paleoclimate interpretations have been based on both non-glacial geologic data, as well as biota. Also, comparison of the general interval stratigraphy with similar stratigraphies in other locations provides clues as to the regional behavior of the Laurentide glacier.

Geologic Paleoclimate Proxies. Periglacial geologic features, such as ice-wedge polygons, pingos, and frost mounds, have been extensively studied as paleoclimate indicators. Modern arctic settings have provided opportunities for detailed estimation of mean annual temperature and precipitation requirements for periglacial feature formation (see Karte and Liedtke (1981) for detailed summary).

Recent studies of marginal areas of the southern portion of the Laurentide ice sheet have noted the presence of periglacial features, and have based glaciologic and paleoclimatic reconstructions on estimates of temperature necessary for the features to develop. Periglacial features related to late Wisconsin glaciation have been identified in Minnesota (Chernicoff, 1983; Mooers, 1990), Wisconsin (Attig and Clayton, 1986; Attig *et al.*, 1989), Illinois (Johnson, 1990), Indiana (in Pewe, 1983), and Ohio (Totten, 1973). These features, dominantly ice-wedge casts, are associated with both the advance of the Laurentide glacier to its maximum position, and its retreat. Of the studies cited above, Johnson (1990) relates most directly temporally and spatially to southwestern Ohio.

Johnson (1990) reported ice-wedge polygons developed in Illinoian-age drift near the late Wisconsin maximum position, and interpreted the onset of permafrost development to have occurred during advance of the late Wisconsin glacier between 21,000 and 20,000 yr BP. Ice-wedge casts were also observed in late Wisconsin glacigenic deposits exposed by deglaciation between 19,000 and 17,000 yr BP, and Johnson (1990) emphasizes the importance of permafrost development in a narrow zone in front of a retreating ice margin. The absence of known patterned ground in areas exposed by deglaciation after about 16,000 yr BP suggests no permafrost formation after that time. Johnson (1990) estimates that mean annual air temperature near the ice margin was $-6^{o} \pm 2^{o}C$ (about $17^{o}C$ colder than at present). He concludes that the southernmost extent of permafrost development was about 38^{o} 30' N latitude; this is consistent with the speculative southern limit of Pewe (1983).

The data of Johnson (1990) are comparable to those from southwestern Ohio. Temporally, radiocarbon age estimates (see chapters 2 and 5) indicate that the southwestern Ohio study area is contemporaneous with the Illinois area of Johnson (1990). Spatially, the location of the southwestern Ohio study area (39^o 15'N latitude, and positions less than 7 km from the late Wisconsin margin) lies within the area of potential permafrost as indicated by both Johnson (1990) and Pewe (1983). Patterned ground in southwestern Ohio is apparent in air photos (Ohio Department of Natural Resources, Division of Geological Survey); to date, these features have not been extensively studied, so their origin is uncertain. However, the features are nearly identical in appearance to those shown in Johnson (1990), and interpreted to be of periglacial origin. The calculated -6^{o}C temperature of Johnson (1990) matches well with the temperatures estimated in this study.

Biota-based Paleoclimate Proxies. Central midcontinent environments prior to the late Wisconsin glacial maximum have been characterized (summarized in Garry *et al.*, 1990) as transitional from cool climates into late Wisconsin full glacial conditions. Garry *et al.* (1990) concluded that, in Illinois, the initial climatic shift toward full-glacial conditions occurred at around 25,000 yr BP; mean July temperatures were estimated to be 11 to 13^{o}C, with mean January temperatures of -30 to -20^{o}C. In central Indiana, Morgan (1987) estimated mean July temperatures of 16^{o}C, and mean annual temperatures of 0 to -1^{o}C. In northern Ohio, Morgan *et al.* (1983) and Morgan (1987) estimated a mean July temperature of less than 15^{o}C and a mean annual temperature of 0^{o}C during the period 28,000 to 24,000 yr BP. Recent work by Dell (1991) near Cincinnati suggested mean annual temperatures ranged from 4 to 6^{o}C during the period from 22,000 to 20,000 yr BP.

Sites reflecting full-glacial environmental conditions suggest the presence of tundra-like conditions in a narrow zone near the ice margin. These tundra conditions were interpreted to have persisted from 20,000 to 14,000 yr BP in Minnesota (Birks, 1976), from 18,000 to 17,000 yr BP in Iowa (Baker *et al.*, 1986), and in Illinois beginning at about 21,500 yr BP (Garry *et al.*, 1990). Near Cincinnati, work by Lowell *et al.* (1990b) indicates a cold, dry climate (mean annual precipitation less than 50 cm yr^{-1}, mean January temperature of -30 to -10^{o}C, mean July temperature of 5 to 12^{o}C) was established by about 20,200 yr BP, and persisted until at least 19,100 yr BP.

Sediment-based temperature estimates from this study are in good agreement with the regional biota temperature estimates.

Regional Stratigraphic Comparisons. The late Wisconsin glacial stratigraphic sequence observed near Cincinnati is very similar to other regional late Wisconsin glacial sequences. Ekberg (1991) identified an identical two-advance sequence approximately 25 km northwest of this study area, but within the same Miami sublobe. The timing of Ekberg's (1991) sequence is the same the Cincinnati sequence, and are interpreted to record contemporaneous events. In Illinois (Lake Michigan Lobe), nearly identical stratigraphic sequences have been reported from Wedron (Hansel *et al.*, 1987; Johnson and Hansel, 1990). Radiocarbon age estimates suggest that these Lake Michigan Lobe sequences are nearly contemporaneous with the Miami sublobe sequences. This supports Ekberg's conclusion of apparent synchroneity between these two lobes.

Younger sediments (about 16,000 yr BP) from northeastern Illinois also contain similar sequences (Wickham and Johnson, 1981; Hansel and Johnson, 1987; Johnson and Hansel, 1989). The occurrence of similar sequences in younger sediments suggests that the glacial conditions responsible for sediment deposition and deformation were time-transgressive; if the glacial conditions were time-transgressive, it seems reasonable to conclude that similar controlling climatic (or meteorologic) conditions were also time transgressive.

PALEOCLIMATE SUMMARY - CINCINNATI

Biota from sites within 5 km of the interpreted late Wisconsin ice margin (discussed in Chapter 2) provide paleoclimate estimates which complement the estimates derived from the sediments. Biota provide a "snapshot" of paleoclimate immediately prior to late Wisconsin glaciation near Cincinnati, and also provide a comparison on conditions present during glaciation. An integrated summary of late Wisconsin paleoclimate near Cincinnati is presented below.

1. The upper surface of the pre-late Wisconsin soil profile exposed at the Sharonville, Dimmick Road, and Glendale sites, has been radiocarbon age estimated to be between 20,000 and 22,000 radiocarbon years in age (see chapter 5), and contains abundant gastropods. These gastropods indicate that the mean annual temperature in the area shortly before late Wisconsin maximum glaciation was $+4^{o}$ to $+6^{o}$C (Dell, 1991). Comparing this to the present-day mean annual temperature for Cincinnati of 12.3^{o}C (National Oceanic and Atmospheric Administration, 1979), it seems apparent that climatic deterioration in southwestern Ohio was underway several hundred, if not thousand, years prior to the advance of late Wisconsin ice into the area.

2. Fauna at the Rack Quarry indicate that by about 20,200 yr BP (still prior to advance of late Wisconsin ice over the study sites), a cold, dry climate was established in

the area. This climate was characterized by a mean annual precipitation of 50 cm or less, with mean January temperatures -30 to -10°C, and mean July temperatures of 5 to 12°C. Radiocarbon age estimates in the peat (see chapter 2) support the idea that this cold, dry climate remained relatively constant through the time of ice advance over the study sites, and persisted until at least about 19,100 yr BP. Although the chronologic control precludes direct comparison of biota-based temperature estimates with interval-specific sediment-based estimates, it is apparent ranges of temperature estimates are very compatible.

3. Initial ice advance over the study sites (interval 1) at 19,670±68 (Lowell *et al.*, 1990a), was accompanied by temperatures colder than during the preglacial period listed in (1) above. The nature of the substrate deformation suggests that the deformation may have occurred on a seasonal time scale. This interval provides the youngest chronolgic control on the glacigenic sediments.

4. Interval 2 reflects continued cooling associated with establishment of near-equilibrium glacial conditions.

5. Interval 3 reflects a gradual trend of warming. This trend has not been recognized in the biota associated with the peat horizon; however, this may simply be the result of insufficient sample density in the biota-rich horizons.

6. Interval 4 reflects an episode of cooling. As with intervals 2 and 3, this cooling has not been observed in the peat-related biota.

7. Interval 5 represents an overall warming in the area; fauna associated with the clays overlying the peat at the quarry (younger than about 19,100 yr BP) reflect an overall warming as well.

FINAL ASSESSMENT OF METHODOLOGY

Ice surface temperature estimations, based on geologic observations and glaciologic reconstructions, are consistent with temperature ranges predicted from biota and periglacial records. Trends of climatic variability (e.g., cooling associated with glacial advance and establishment of near-equilibrium glacial conditions) are discernable with this analysis. Discrepancies between ice surface temperature and temperatures derived from other records are likely the result of uncertainties of the glaciologic parameters. Refinement of these parameters, especially basal sliding velocity and basal shear stress, should lead to more precise temperature estimates. It is concluded that this methodology can provide realistic temperature estimates if the necessary parameters are known, or can be estimated. In areas lacking biota for paleoclimate interpretation, this method may provide useful paleotemperature information. In areas where biota-based paleoclimate interpretations may be completed, this method provides an independent check on temperature estimates.

CHAPTER 7. SUMMARY OF QUATERNARY GEOLOGY, MILL CREEK VALLEY

The final objective of this study was the development of a "land surface" model; that is, the identification of stratigraphic sequences in different geomorphic settings, and the construction of a composite stratigraphy for the study area. In the sections below, individual stratigraphic sequences are summarized, and the composite stratigraphy which forms the land-surface model is presented.

SUMMARY

The Mill Creek Valley north of Cincinnati is rich in Quaternary sediments of both glacial and non-glacial origin. Extensive fluvial activity in the Mill Creek Valley from pre-Illinoian time through the present, combined with overriding of the area by two continental glaciers has resulted in a stratigraphically and geomorphically complex distribution of these sediments. This study has identified stratigraphic sequences in each of three distinct geomorphic settings: valley-marginal terrace, upland, and valley bottom. Each of these settings contains an unique stratigraphy, as discussed below.

Valley-marginal terrace. The stratigraphic sequence found in the terrace setting is comprised of the oldest sediments in the study area. This sequence includes pre-Illinoian fluvial sands and gravels, Illinoian lacustrine silts and clays, and is capped by one or more facies of Illinoian glacial deposits. Terrace sites identified in this study (Rack/ELDA and Caldwell Park) are south of the mapped late Wisconsin glacial limit, and are free of late Wisconsin drift. The Norwood Trough contains the terrace stratigraphy because of the lack of significant post-Illinoian fluvial activity in the trough. Structural and clast fabric data from the Illinoian tills indicates ice flow from the east, consistent the deposition by the "Clermont lobe" as identified by Tucker (1962).

Upland. The upland sites, including Glendale Waste Water Treatment Facility, Sharonville, and Dimmick Road Reservoir, contain the most complete glacigenic sequences, with drift interpreted to be of both Illinoian and late Wisconsin age. Also preserved within this sequence at each locality is an organic-rich loess horizon interpreted to represent a pre-late Wisconsin soil horizon. Extensive radiocarbon analysis from these sites has been the basis for the chronology of this interpreted sequence. The upland position of these sites, above the level of incision and erosion by Mill Creek, has resulted in the preservation of this pre-Illinoian through late Wisconsin stratigraphy. The upland positions are also well above the the elevations at which the pre-Illinoian fluvial sediments of the terrace settings, and the post- Illinoian fluvial, Wisconsin lacustrine, and post-Wisconsin fluvial sediments of the valley bottom settings were deposited. Consequently, the upland sites are free from these sediments. Striated bedrock underlying Illinoian diamicton at the Glendale site suggests east-west ice flow, consistent with the flow direction infered at the terrace sites. Clast fabrics and structural data from late Wisconsin tills at the Sharonville and Dimmick Road sites reflect local ice flow directions controlled by topography. Identification of multiple till facies at the Sharonville and Dimmick Road sites indicates fluctuations in the dynamics of the late Wisconsin glacier. Late Wisconsin glacigenic sediments at the Sharonville site indicates late Wisconsin ice extended outside the limit defined by the Hartwell Moraine in the northeastern part of the valley.

Valley bottom. The valley bottom stratigraphy is identified primarily through subsurface data, correlated with surface exposure data from the Cross-County Highway construction sites. This stratigraphy includes post-Illinoian fluvial, late Wisconsin lacustrine and glacial (both diamicton and outwash), and post-late Wisconsin fluvial sediments. This sequence reflects the importance of fluvial activity in removing the oldest portions of the stratigraphic history in the valley. Identification of the extent of late Wisconsin drift in the subsurface, while in general agreement with the mapped position of the Hartwell Moraine, indicates that glacigenic deposition was occurring at locations outside of the Hartwell Moraine along its southernmost position.

At the Rack site, a rare peat horizon found within the late Wisconsin lacustrine sediments of the valley bottom sequence provides a unique opportunity to sample various biota records that are temporally equivalent to the late Wisconsin glacial maximum a few kilometers up the valley. Interpretation of the records (by other workers) provides a picture of a generally cold, dry paleoclimate associated with the glacial maximum.

Composite Quaternary Stratigraphy. On the basis of outcrop and subsurface data, a composite Quaternary stratigraphy may be constructed for the study area. This composite stratigraphy is shown detailed in Fig. 7-1. The basal unconsolidated unit of this composite stratigraphy is pre-Illinoian fluvial sands and gravels directly overlying bedrock. Overlying these fluvial sediments are a number of units related to the advance and retreat two glaciers. Radiocarbon age estimates indicate that the younger of the two advances is late Wisconsin in age; the older advance is interpreted to be the so-called Illinoian advance, but no chronologic data from these sediments is presently available. The youngest sediments in the study area are fluvial sands and rare gravels interpreted to represent post-late Wisconsin fluvial deposition. An interesting observation is that there are no extensive deposits of late Wisconsin-age outwash. No explanation for the lack of these deposits is offered here.

Fig. 7-1. Summary composite stratigraphy of northern Mill Creek Valley, Hamilton County, Ohio. In the column labeled "Geomorphic Occurrence", VTE = valley-marginal terrace exposure, VBE = valley bottom exposure, UE = upland exposure, SS = noted in subsurface logs.

GENERALIZED LITHOLOGY	INTERPRETATION	EVENT	GEOMORPHIC OCCURRENCE	SEDIMENT TYPES	STUDIED UNITS
	Post-late Wisconsin fluvial and late Wisconsin outwash	Deglaciation	VBE & SS	sands and gravels	CP-5
	Late Wisconsin: outwash / drift	Incision Late Wisconsin Glaciation	VBE & SS / UE, VBE & SS	HARTWELL MORAINE: sands & gravels / multiple diamicton facies	CCH-3 G-7 DR-6 S-6
	Late Wisconsin lacustrine	Onset of late Wisconsin glaciation	VBE & SS	silts & clays peat @ Rack Quarry	RC-4 G-6 DR-5 RC-3 G-5 S-5 RC-2 CCH-2
	Post-Illinoian fluvial & Illinoian outwash / Loess	"Sangamon" Interstadial	VBE & SS / UE	sand & gravels / organic silt / inorganic silt	G-3 DR-4 CCH-1 S-3 DR-3
	Illinoian drift	Incision Illinoian glaciation	VTE, UE, SS	multiple diamicton facies	CP-2 CP-3 DC-3 G-2 RD-5 CP-4 DC-4 DR-2 RD-4 DC-1 DC-5 S-2 RD-3 DC-2 DC-6
	Pre-Illinoian lacustrine	Onset of Illinoian glaciation	SS	silts and clays	RD-2
	Pre-Illinoian fluvial	"Deep Stage" fluvial	SS	sands and gravels	RD-1 RC-1
	Ordovician bedrock		VBE, VTE, UE, SS	limestone - shale	CP-1 DR-1 G-1 S-1

RC - Rack/ELDA Clay sequence
RD - Rack/ELDA Diamicton sequence
CCH - Cross-County Highway @ I-75
CP - Caldwell Park

G - Glendale Water Treatment Facility
S - Sharonville
DR - Dimmick Road Reservoir
DC - Day Care Center

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APPENDIX A.
EXAMPLE ICE SURFACE TEMPERATURE
CALCULATIONS FOR INTERVAL 1.

APPENDIX A.
EXAMPLE PALEOTEMPERATURE CALCULATION SET

These calculations are for **interval 1 only**; calculations for all other intervals may be completed by substituting the appropriate values of all parameters for that interval. See Chapter 6 for detailed discussion of each variable.

STEP 1.

Identify individual heat fluxes, and estimate the total heat flux for the interval.

geothermal

Ψ_g = constant = 1.85×10^6 J m^{-2} yr^{-1}

internal deformation

Ψ_d = constant = 1.85×10^6 J m^{-2} yr^{-1}

basal sliding

$\Psi_s = U_s \tau_b$

U_s = basal sliding velocity = 500 m yr^{-1}

τ_b = basal shear stress = 50 kPa

Ψ_s = (500 m yr^{-1}) * (50 kPa)

$\Psi_s = 25 \times 10^6$ J m^{-2} yr^{-1}

total heat flux

$\Psi_{tot} = \Psi_g + \Psi_d + \Psi_s$

$\Psi_{tot} = (1.85 + 1.85 + 25) \times 10^6$ J m^{-2} yr^{-1}

$\boldsymbol{\Psi_{tot} = 28.7 \times 10^6}$ **J m^{-2} yr^{-1}**

STEP 2.

Identify the relationship which is appropriate for the basal thermal conditions (eqns. 7, 8, and 9 in Chapter 6), and calculate the limiting temperature gradient.

For interval 1 (net balance between freezing and melting), the appropriate relationship is:

$$\Psi_{tot} = K_i\,(dT/dh)_i$$

where K_i is the thermal conductivity of ice, and $(dT/dh)_i$ is the temperature gradient through the ice. Re-arranging this to solve for the temperature gradient gives

$$(dT/dh)_i = \Psi_{tot} / K_i$$

For interval 1,

$\Psi_{tot} = 28.7 \times 10^6 \text{ J m}^{-2} \text{ yr}^{-1}$

$K_i = 2.1 \text{ W m}^{-1} {}^oC^{-1}$, and

$(dT/dh)_i = (28.7 \times 10^6 \text{ J m}^{-2} \text{ yr}^{-1}) / (2.1 \text{ W m}^{-1} {}^oC^{-1})$

$\mathbf{(dT/dh)_i = -0.433\ {}^oC\ m^{-1}}$

Because heat flow is away from the glacier bed, this temperature gradient must be negative.

STEP 3.

Using the calculated temperature gradient through the ice, and estimates of ice thickness (h_{ice}) and basal temperature (T_{base}) derived from the observed geology, estimate the ice surface temperature.

For interval 1,

$(dT/dh)i = -0.433\ {}^oC\ m^{-1}$

$h_{ice} = 15$ m

$T_{base} = -0.1^oC$;

the estimated ice surface temperature is given by

$T_{surf} = T_{base} + ((dT/dh)_i * h_{ice})$

$T_{surf} = (-0.1^oC) + ((-0.433^oC\ m^{-1}) * 15\ m)$

$\mathbf{T_{surf} = -6.6^oC}$

The estimated ice surface temperature during interval 1 is therefore interpreted to be -6.6^{o}C.

APPENDIX B.
LOCATION OF STUDIED OUTCROPS

APPENDIX B. OUTCROP LOCATIONS

SECTION #	MAP (7.5')	UTM N	UTM E	UTM ZONE	EXPOSURE TYPE	COMMENTS
KS-87-04	Cinti. East	4345800	722300	16	Stream	North bank of unnamed stream, approx 700 m E of Reading Rd
KS-87-09	Glendale	4348690	724150	16	Stream	West bank, east tributary of unnamed stream, 200 m from Sharondale Rd.
KS-87-10	Cinti. East	4342510	719100	16	Excavation	Cross-County Highway @ I-75, exposure east of interstate
KS-87-11	Cinti. East	4342510	719100	16	Excavation	Cross-County Highway @ I-75, exposure east of interstate
KS-87-12	Glendale	4349820	720130	16	Excavation	Construction exposure @ Glendale Water Treatment facility, Sharon Rd.
TL-87-210	Glendale	4348520	724140	16	Stream	West bank, west tributary of unnamed stream, 100 m from Sharondale Rd.
Rack Quar.	Cinti. West	4339740	715460	16	Quarry	Office building of the Rack Sand Co., Este Ave.
KS-88-03	Glendale	4349050	724030	16	Stream	East bank of unnamed stream, 600 m from Sharondale Rd.
KS-88-04	Glendale	4348950	724030	16	Stream	West bank of unnamed stream, 500 m from Sharondale Rd.
KS-88-05	Cinti. East	4342780	719410	16	Excavation	Construction excavation adjacent to new Cross-County Highway
KS-88-06	Glendale	4348670	724120	16	Stream	West bank, east tributary of unnamed stream, 230 m from Sharondale Rd.
KS-88-07	Cinti. West	4340340	715680	16	Landfill	ELDA Landfill, excavation for new "cell"
KS-88-08	Cinti. West	4340340	715680	16	Landfill	ELDA Landfill, excavation for new "cell", 50 m N of KS-88-07
KS-88-12	Cinti. East	4342910	717010	16	Construction	South side of construction access road, Cross-County Hwy borrow pit
KS-88-13	Cinti. East	4341910	718630	16	Construction	Trench along east side, N-bound I-75, 100 m south of Mill Creek
KS-88-14	Glendale	4348540	724140	16	Stream	East bank, west tributary of unnamed stream, 125 m from Sharondale Rd.
KS-89-01	Glendale	4348550	724130	16	Stream	East bank, west tributary of unnamed stream, 160 m from Sharondale Rd.
KS-89-02	Glendale	4348600	724140	16	Stream	East bank, west tributary of unnamed stream, 190 m from Sharondale Rd.
KS-89-03	Glendale	4348700	724130	16	Stream	East bank, junction of unnamed streams, 225 m from Sharondale Rd.
KS-89-06	Glendale	4354480	724690	16	Excavation	Excavation for underground reservoir, Dimmick Rd., Butler County
KS-90-02	Cinti. West	4340290	715820	16	Bluffs	Bluffs outside ELDA landfill, exposure behind CWS Bldg, Este Ave.
KS-90-04	Cinti. East	4342142	716696	16	Stream	Caldwell Pk., SW stream, west bank approx. 220 m from Mill Creek
KS-90-05	Cinti. East	4342165	716655	16	Stream	Caldwell Pk., SW stream, west bank approx. 275 m from Mill Creek
KS-90-06	Cinti. East	4342263	716992	16	Stream	Caldwell Pk., NE stream, west bank approx. 5 m from Mill Creek
KS-90-07	Cinti. East	4342162	716627	16	Stream	Caldwell Pk., SW stream, west bank approx. 300 m from Mill Creek
KS-90-08	Cinti. East	4342086	716837	16	Stream	Caldwell Pk., SW stream, west bank approx. 90 m from Mill Creek
KS-90-09	Cinti. East	4342114	716813	16	Stream	Caldwell Pk., SW stream, east bank approx. 120 m from Mill Creek
KS-90-10	Cinti. East	4342278	716963	16	Stream	Caldwell Pk., NE stream, west bank approx. 35 m from Mill Creek
KS-90-11	Cinti. East	4342408	716922	16	Stream	Caldwell Pk., tributary to NE stream approx. 150 m from Mill Creek
KS-90-12	Cinti. East	4342307	716715	16	Stream	Caldwell Pk., central stream, west bank approx. 275 m from Mill Creek
KS-90-13	Cinti. East	4342318	716707	16	Stream	Caldwell Pk., central stream, west bank approx. 290 m from Mill Creek
KS-90-14	Cinti. East			16	Stream	Caldwell Pk., central stream, west bank approx. 180 m from Mill Creek

APPENDIX C.
GRAIN SIZE ANALYSES

APPENDIX C. GRAIN SIZE ANALYSES (VALUES EXPRESSED AS WEIGHT-PERCENTS FOR THE INDICATED FRACTION)

EVENDALE DAY CARE CENTER (KS-87-04)

	SAND									SILT						CLAY	
	1000-2000	707-1000	500-707	354-500	250-354	177-250	125-177	88-125	63-88	44-63	31-44	22-31	16-22	8-16	4-8	2-4	<2
DIAMICTON SAMPLES																	
DAY CARE-E	8.04	3.70	4.14	4.08	4.84	4.16	5.01	4.88	4.39	9.02	5.41	7.73	4.12	8.76	6.18	3.86	11.71
DAY CARE-F	6.51	3.55	3.90	4.05	4.65	4.15	5.31	4.93	4.68	9.25	5.73	6.61	6.17	9.25	6.17	3.08	12.02
DAY CARE-G	6.85	3.31	3.75	3.63	4.77	4.09	5.45	5.37	5.20	10.06	5.35	6.64	7.49	10.27	5.14	3.42	9.20
DAY CARE-H	7.25	3.28	3.68	3.61	4.49	4.13	5.24	5.44	5.25	11.62	5.14	6.48	6.70	10.72	5.14	2.90	8.92
DAY CARE-I	6.59	3.63	3.80	3.65	4.50	4.19	5.47	5.57	5.46	8.81	6.29	6.80	8.06	10.07	5.54	3.27	8.31
DAY CARE-J	6.98	3.34	3.76	3.57	4.69	4.23	5.69	5.74	5.49	8.97	4.73	6.97	11.95	6.23	3.74	3.49	10.42
DAY CARE-K	7.69	3.72	4.12	3.85	4.89	4.48	5.68	5.68	5.36	9.96	5.93	6.17	4.98	12.33	3.56	3.32	8.26
DAY CARE-L	7.20	3.93	3.64	3.36	4.28	3.92	5.23	5.23	5.05	10.6	4.93	5.19	7.53	10.38	4.93	3.11	11.43
DAY CARE-M	8.35	3.97	3.98	3.88	4.90	4.57	6.49	6.50	5.65	9.79	6.18	5.93	4.38	8.25	4.12	3.87	15.69

GLENDALE WATER TREATMENT FACILITY (KS-87-12)

	1000-2000	707-1000	500-707	354-500	250-354	177-250	125-177	88-125	63-88	44-63	31-44	22-31	16-22	8-16	4-8	2-4	<2
DIAMICTON SAMPLES																	
KS-87-12-16B	3.21	2.07	2.13	2.24	2.80	2.67	3.35	3.14	2.94	8.36	6.14	6.39	8.36	13.27	7.86	6.14	18.92
KS-87-12-17	4.26	2.03	2.37	2.34	3.23	2.81	3.59	3.13	2.74	7.35	3.89	4.54	6.27	11.89	10.38	6.92	22.25
NON-DIAMICTON SAMPLES																	
KS-87-12-12	0.59	0.88	1.80	2.47	3.01	2.79	3.22	2.79	2.45	7.69	6.84	9.40	11.39	13.96	9.40	5.41	15.94
KS-87-12-13	0.00	0.00	0.00	0.09	0.08	0.07	0.07	0.05	0.01	4.60	21.37	24.33	6.91	8.55	14.80	9.21	9.86
KS-87-12-14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	4.19	3.91	8.94	20.11	31.28	13.97	5.59	12.01
KS-87-12-15	0.00	0.00	0.00	0.00	0.00	0.04	0.10	0.68	3.13	16.18	15.93	14.38	14.38	18.49	4.88	3.08	8.72

APPENDIX C. GRAIN SIZE ANALYSES (VALUES EXPRESSED AS WEIGHT-PERCENTS FOR THE INDICATED FRACTION)

SHARONVILLE SITES

	SAND									SILT						CLAY	
	1000-2000	707-1000	500-707	354-500	250-354	177-250	125-177	88-125	63-88	44-63	31-44	22-31	16-22	8-16	4-8	2-4	<2
DIAMICTON SAMPLES																	
KS-87-09-A	4.19	2.64	4.60	5.29	6.66	4.93	5.06	3.86	2.44	6.07	4.74	6.26	5.99	10.39	7.47	2.45	16.96
KS-87-09-E	3.58	1.61	2.21	2.21	3.38	3.46	5.23	5.39	3.58	8.00	8.52	9.00	8.92	13.01	6.78	3.87	11.28
KS-87-09-PP	1.61	0.91	1.08	1.18	1.69	1.50	2.12	2.22	1.56	8.00	6.75	8.16	8.95	15.69	11.77	6.12	20.69
TL-87-210-C	4.78	1.66	2.62	2.66	3.74	3.61	4.90	5.11	3.57	11.35	1.09	9.99	9.56	13.96	7.91	5.10	8.39
KS-88-03-C	5.05	2.77	3.38	3.44	4.18	3.90	4.74	4.26	2.91	9.01	6.45	7.88	8.69	14.15	12.85	3.80	2.55
KS-88-04-C	4.33	3.36	5.03	5.15	6.28	5.11	5.85	5.07	3.04	7.16	8.62	5.45	10.08	11.82	7.71	2.65	3.28
KS-88-04-H	2.09	1.38	1.93	2.52	3.99	4.24	5.89	5.43	3.38	11.34	3.90	4.32	4.69	9.53	7.37	5.74	22.27
KS-88-04-I	3.90	1.89	2.28	2.96	4.07	3.81	5.17	4.88	3.25	13.95	5.63	5.69	7.05	9.31	6.88	4.94	14.34
KS-88-06-D	5.59	2.06	2.70	2.75	3.85	3.58	4.63	4.22	2.75	12.06	7.06	6.29	8.45	22.72	8.48	1.29	1.42
KS-88-14-B	5.50	2.34	2.84	3.09	4.04	3.58	4.45	4.06	3.30	8.33	5.61	5.98	11.05	6.52	7.79	3.26	18.27
KS-89-01-A	4.59	1.65	2.11	2.40	2.99	2.78	3.59	3.47	3.28	9.03	5.05	5.05	6.91	12.76	9.57	5.05	19.61
KS-89-02-B	3.75	1.79	2.18	2.39	3.16	2.83	3.64	3.49	3.05	8.88	5.36	6.70	9.05	12.57	7.04	5.53	18.59
KS-89-03-B	3.26	1.60	2.01	2.15	2.77	2.72	3.55	3.63	3.39	8.05	4.91	8.24	5.69	12.36	9.81	5.89	19.98
KS-89-03-D	3.18	1.41	1.86	1.94	2.79	2.79	4.05	4.47	2.75	7.32	4.88	6.31	8.04	17.22	5.45	5.31	20.21
NON-DIAMICTON SAMPLES																	
KS-87-09-D	0.00	0.00	0.04	0.21	0.29	0.21	0.25	0.21	0.08	1.50	0.87	0.13	1.83	8.94	15.82	6.42	63.22
KS-87-09-II-1	••	••	••	••	••	••	••	••	6.16	6.26	10.91	18.48	18.34	16.45	8.53	3.12	3.75
KS-87-09-JJ-1	••	••	••	••	••	••	••	••	7.06	6.54	8.06	15.73	17.60	24.18	10.21	4.16	6.46
KS-87-09-KK-1	••	••	••	••	••	••	••	••	8.43	5.17	6.80	14.03	15.40	23.18	12.03	3.35	11.61
KS-87-09-LL-1	••	••	••	••	••	••	••	••	17.90	6.13	4.79	8.71	11.72	17.50	12.59	7.43	13.23
KS-87-09-JJ-2	••	••	••	••	••	••	••	••	6.47	3.84	8.18	12.74	14.87	22.35	9.58	4.96	17.01
KS-87-09-KK-2	••	••	••	••	••	••	••	••	7.70	3.07	8.56	13.95	13.19	22.26	10.41	5.45	15.41
KS-87-09-LL-2	••	••	••	••	••	••	••	••	14.41	4.78	4.14	6.87	13.63	16.58	11.40	7.56	20.63
TL-87-210-D	••	••	••	••	••	••	••	••	21.80	21.58	14.82	12.19	10.10	9.44	1.09	3.61	5.37
KS-88-04-F	9.82	5.31	7.67	8.88	13.69	13.12	11.84	6.83	3.67	5.35	4.13	3.18	2.42	2.17	0.79	0.42	0.71
KS-88-04-G	0.86	0.37	0.33	0.37	0.37	0.33	0.41	0.41	0.37	1.17	0.81	1.84	3.69	13.41	18.03	13.74	43.51

APPENDIX C. GRAIN SIZE ANALYSES (VALUES EXPRESSED AS WEIGHT-PERCENTS FOR THE INDICATED FRACTION)

I-75 @ CROSS-COUNTY HIGHWAY

	SAND									SILT						CLAY	
	1000-2000	707-1000	500-707	354-500	250-354	177-250	125-177	88-125	63-88	44-63	31-44	22-31	16-22	8-16	4-8	2-4	<2
DIAMICTON SAMPLES																	
KS-87-11-D	3.80	2.00	2.20	2.41	2.81	2.97	5.47	5.39	4.68	8.77	4.98	5.58	6.78	10.96	8.77	4.58	17.86
KS-87-11-G	1.54	1.15	1.47	2.23	3.53	3.03	3.63	3.19	2.83	6.37	4.46	5.35	6.87	11.97	10.18	6.49	25.71
KS-88-13-C	2.36	1.68	3.80	11.03	14.85	13.01	9.44	3.04	1.71	3.59	1.79	2.56	3.46	6.54	5.64	3.84	11.64
KS-88-13-F	0.61	0.28	0.33	0.31	0.34	0.37	0.44	0.32	0.21	3.25	1.08	2.03	5.42	15.84	18.28	12.05	38.81
NON-DIAMICTON SAMPLES																	
KS-87-11-A	0.04	0.00	0.02	0.04	0.09	0.19	3.00	17.50	20.96	26.48	13.74	7.54	4.02	3.85	1.51	0.84	0.16
KS-87-11-B	0.00	0.00	0.00	0.00	0.00	0.06	0.13	0.18	0.19	4.14	8.28	17.77	22.89	22.89	9.98	4.14	9.36
KS-87-11-C	0.33	0.14	0.15	0.15	0.15	0.15	0.25	0.33	0.42	4.38	2.19	4.82	11.83	15.78	16.66	10.30	31.96
KS-87-11-E	0.06	0.10	0.12	0.16	0.55	3.16	19.40	26.17	17.29	13.56	6.60	3.75	3.03	3.03	1.07	1.43	0.50
KS-88-05-A	0.00	0.00	0.00	0.01	0.00	0.01	0.04	0.06	0.07	1.49	0.15	0.45	1.34	5.80	13.68	14.58	62.30
KS-88-13-A	0.00	0.00	0.12	1.75	4.67	42.62	42.83	7.44	0.66	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00
KS-88-13-E	0.29	0.25	0.42	1.83	5.88	46.96	28.89	5.41	1.29	1.25	1.00	0.50	0.75	1.88	1.38	1.00	1.00

DIMMICK ROAD RESERVOIR (KS-89-06)

	1000-2000	707-1000	500-707	354-500	250-354	177-250	125-177	88-125	63-88	44-63	31-44	22-31	16-22	8-16	4-8	2-4	<2
DIAMICTON SAMPLES																	
DIMW-K	8.72	3.83	4.55	4.29	5.99	5.14	6.29	5.36	4.22	9.59	4.51	5.08	5.36	8.18	6.77	2.82	9.30
DIMW-O	10.48	4.82	5.36	4.91	6.62	5.91	7.23	6.43	5.19	7.51	4.51	5.76	2.50	6.51	4.76	4.26	7.26
DIMW-P	4.45	1.88	2.20	2.42	3.14	2.78	3.46	3.45	3.20	8.43	5.34	4.78	7.58	10.67	8.15	5.34	22.75
DIMW-S	5.76	2.71	3.42	3.33	4.37	3.77	4.66	4.49	3.99	8.19	6.49	6.21	5.65	13.83	7.34	5.93	9.88
DIMW-T	4.15	2.16	2.16	2.19	2.90	2.60	3.34	3.24	2.98	6.16	4.40	3.96	10.56	11.88	9.68	6.82	20.81

APPENDIX C. GRAIN SIZE ANALYSES (VALUES EXPRESSED AS WEIGHT-PERCENTS FOR THE INDICATED FRACTION)

RACK SAND QUARRY (KS-88-01)

	******************** SAND										*************** SILT						* CLAY *	
	>2000	1000-2000	707-1000	500-707	354-500	250-354	177-250	125-177	88-125	63-88	44-63	31-44	22-31	16-22	8-16	4-8	2-4	<2
NON-DIAMICTON SAMPLES																		
RACK-A	0.00	0.04	0.03	2.51	29.85	38.35	17.62	6.95	2.39	0.74	1.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RACK-C	0.44	1.48	0.86	1.65	2.69	3.68	2.93	1.71	0.81	0.39	2.47	0.00	0.55	1.10	7.41	13.17	12.89	45.79
RACK-E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.95	0.19	0.57	2.66	3.23	16.17	16.17	59.71
RACK-F	0.25	1.89	2.49	4.21	17.13	44.18	21.39	5.83	1.80	0.32	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RACK-G	0.00	0.00	0.00	0.00	0.01	0.01	0.04	0.08	0.13	0.11	7.19	5.32	9.38	19.39	26.27	14.07	8.44	9.54
RACK-H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.05	11.51	8.48	12.42	17.26	23.01	12.11	3.94	10.23
RACK-I	0.87	0.15	0.22	0.29	0.23	0.31	0.25	0.35	0.52	1.16	20.54	13.80	14.41	11.96	17.48	7.97	3.68	5.81
RACK-J	0.17	0.04	0.01	0.04	0.18	0.26	0.18	0.33	0.65	1.94	24.50	19.33	15.96	10.56	10.79	5.39	2.25	7.40
RACK-K	0.05	0.07	0.12	5.51	41.95	35.99	8.88	2.56	1.62	0.67	2.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RACK-L	0.00	0.06	0.00	0.06	0.06	0.17	0.17	0.22	0.28	0.45	7.40	10.00	12.20	14.20	21.99	13.60	5.60	13.58
RACK-P	0.00	0.01	0.01	0.27	0.33	0.54	0.32	0.71	0.78	0.27	5.79	6.03	9.41	10.37	19.30	14.72	9.17	21.97
RACK-Q	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.01	0.01	0.02	1.80	0.33	0.98	4.59	30.80	10.81	12.78	37.80
RACK-S	4.86	0.74	0.56	0.59	1.98	24.86	40.87	15.40	5.41	1.67	2.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RACK-T	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.06	0.07	0.04	1.59	0.99	1.39	5.75	17.04	17.24	13.28	42.46
RACK-U	0.00	0.00	0.04	0.03	0.02	0.02	0.01	0.02	0.02	0.02	1.88	0.23	0.47	4.93	4.23	12.92	17.15	57.98
RACK-V	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.90	12.66	41.68	0.79	2.64	5.01	7.91	3.69	14.70
RACK-W	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	19.26	11.64	1.20	3.21	9.83	10.23	11.24	32.76
RACK-X	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.08	0.10	0.06	0.00	0.35	6.92	3.90	19.34	18.10	12.42	38.48
RACK-Y	**	**	**	**	**	**	**	**	**	2.31	7.83	2.02	2.78	13.13	16.17	13.39	11.87	30.50
RACK-Z	**	**	**	**	**	**	**	**	**	0.44	1.95	0.00	3.36	7.25	13.97	20.70	13.80	38.54
RACK-AA	**	**	**	**	**	**	**	**	**	0.27	2.23	0.41	0.30	0.51	12.39	18.69	16.66	48.54
RACK-BB	**	**	**	**	**	**	**	**	**	0.08	2.59	0.37	1.48	2.96	14.43	18.87	15.91	43.30
RACK-CC	**	**	**	**	**	**	**	**	**	0.19	3.43	0.34	0.34	0.34	0.34	7.20	15.44	72.37
RACK-DD	**	**	**	**	**	**	**	**	**	0.90	1.48	0.42	1.90	2.32	15.60	17.29	13.49	46.60
RACK-EE	**	**	**	**	**	**	**	**	**	0.79	0.27	1.64	6.03	5.76	30.97	8.77	19.46	26.31
RACK-FF	**	**	**	**	**	**	**	**	**	5.10	3.95	8.27	12.94	12.58	17.97	14.02	9.71	15.46
RACK-GG	0.00	0.00	0.04	0.05	0.03	0.02	0.04	0.11	0.15	0.36	6.72	9.57	13.96	16.03	13.19	7.50	3.62	28.63
RACK-HH	0.00	0.39	0.20	0.19	0.19	0.15	0.10	0.16	0.25	0.41	8.08	9.38	11.99	14.08	16.68	6.78	3.65	27.37
RACK-RR	2.66	3.57	4.60	22.61	42.64	18.21	4.44	1.01	0.15	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RACK-YY	**	**	**	**	**	**	**	**	**	15.89	2.99	0.67	1.33	5.98	10.64	16.29	16.62	29.59
RACK-ZZ	**	**	**	**	**	**	**	**	**	4.22	6.00	4.45	8.70	11.81	18.38	16.06	11.26	19.16

APPENDIX C. GRAIN SIZE ANALYSES (VALUES EXPRESSED AS WEIGHT-PERCENTS FOR THE INDICATED FRACTION)

<u>RACK SAND QUARRY</u> (KS-88-01)

					SAND							SILT				CLAY	
	>2000	1000-2000	707-1000	500-707	354-500	250-354	177-250	125-177	88-125	63-88	44-63	31-44	22-31	16-22	8-16	4-8	2-4	<2
<u>NON-DIAMICTON SAMPLES</u>																		
RACK-AB	**	**	**	**	**	**	**	**	**	3.07	1.14	0.39	0.76	1.92	14.94	27.97	19.54	30.27
RACK-AC	**	**	**	**	**	**	**	**	**	7.56	9.45	0.92	5.93	6.11	13.71	31.13	14.26	10.93
RACK-SP0	**	**	**	**	**	**	**	**	**	10.71	7.32	5.13	11.87	12.25	20.02	11.59	6.30	14.81
RACK-SP5	**	**	**	**	**	**	**	**	**	11.87	4.91	4.34	5.52	8.47	21.08	15.82	8.89	19.10
RACK-SP10	**	**	**	**	**	**	**	**	**	2.53	2.10	1.26	4.35	8.31	25.73	34.14	12.71	8.87
RACK-SP15	**	**	**	**	**	**	**	**	**	1.90	3.42	0.38	3.05	11.40	21.68	24.71	15.59	17.87
RACK-SP20	**	**	**	**	**	**	**	**	**	0.60	4.13	0.75	0.75	5.62	24.01	21.00	13.51	29.63
RACK-SP25	**	**	**	**	**	**	**	**	**	1.05	1.88	0.38	0.38	6.02	20.31	22.95	15.80	31.23
RACK-SP30	**	**	**	**	**	**	**	**	**	0.61	1.51	0.38	2.28	1.90	21.24	39.45	4.49	27.69
RACK-SP35	**	**	**	**	**	**	**	**	**	0.38	1.51	0.19	0.19	0.38	14.40	34.47	6.43	42.05
RACK-SP40	**	**	**	**	**	**	**	**	**	0.47	3.12	0.39	0.39	1.95	12.49	31.23	8.20	41.76
RACK-SP45	**	**	**	**	**	**	**	**	**	0.15	5.14	0.73	0.73	4.41	2.20	6.61	19.82	60.21
RACK-SP50	**	**	**	**	**	**	**	**	**	0.14	11.85	11.13	15.14	17.04	18.93	11.59	6.39	7.81
RACK-SP55	**	**	**	**	**	**	**	**	**	0.57	6.39	0.36	1.06	4.62	23.72	21.67	14.20	28.41
RACK-SP60	**	**	**	**	**	**	**	**	**	0.23	2.33	0.39	3.88	1.17	16.69	23.68	17.86	33.77
RACK-SP65	**	**	**	**	**	**	**	**	**	0.15	2.68	0.77	0.76	5.36	14.15	22.57	15.69	37.87
RACK-SP70	**	**	**	**	**	**	**	**	**	0.00	9.01	4.50	9.75	10.32	17.64	16.70	9.38	22.70
RACK-SP75	**	**	**	**	**	**	**	**	**	0.08	1.68	0.58	1.09	2.09	10.03	16.72	2.93	64.80
RACK-SP80	**	**	**	**	**	**	**	**	**	0.08	3.49	1.16	6.58	6.58	18.59	16.65	12.39	34.47
RACK-SP85	**	**	**	**	**	**	**	**	**	0.11	2.68	2.95	3.75	5.89	9.64	44.19	19.28	11.52
RACK-SP90	**	**	**	**	**	**	**	**	**	0.02	3.02	0.00	0.38	0.00	15.47	69.42	2.64	9.06
RACK-SP95	**	**	**	**	**	**	**	**	**	0.04	3.01	0.00	0.38	1.50	7.14	69.15	7.14	11.65
RACK-SP100	**	**	**	**	**	**	**	**	**	0.03	1.12	0.37	0.00	1.12	8.58	52.22	22.75	13.80
RACK-BM	2.65	1.37	2.51	17.55	44.59	23.14	5.90	1.57	0.46	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RACK-BN	0.25	0.64	0.39	0.59	0.79	0.85	0.68	0.79	0.79	0.75	8.32	1.16	4.85	13.87	27.74	16.87	5.78	14.87
RACK-BP	0.26	0.49	0.24	0.28	0.32	0.41	0.42	0.69	0.87	0.76	3.39	1.58	4.52	10.18	29.64	20.59	8.60	16.74
RACK-BQ	1.01	0.95	0.56	0.50	0.47	0.59	0.58	0.85	1.30	1.16	2.63	2.37	1.58	6.84	16.31	15.26	11.57	35.48
RACK-M	0.02	0.35	0.57	5.16	8.02	6.70	3.55	3.79	3.56	1.96	8.95	3.64	5.16	6.68	10.02	8.20	4.25	19.41
RACK-BO	**	3.92	1.85	2.38	2.68	3.64	3.46	4.25	3.83	3.55	8.05	5.03	6.04	6.79	12.08	9.31	6.29	16.85
RACK-BR	**	3.19	1.37	1.68	1.66	2.22	1.95	2.48	2.57	2.42	6.82	3.69	6.82	7.38	15.49	11.25	7.38	20.80
RACK-BS	**	2.03	0.91	1.12	1.22	1.57	1.43	1.81	2.04	1.80	6.69	4.62	7.85	11.77	19.85	12.23	6.69	16.38

APPENDIX C. GRAIN SIZE ANALYSES (VALUES EXPRESSED AS WEIGHT-PERCENTS FOR THE INDICATED FRACTION)

<u>SATELLITE DISH SITE</u> (KS-88-12)

	SAND									SILT						CLAY	
	1000-2000	707-1000	500-707	354-500	250-354	177-250	125-177	88-125	63-88	44-63	31-44	22-31	16-22	8-16	4-8	2-4	<2
<u>DIAMICTON SAMPLES</u>																	
KS-88-12-C	4.56	2.34	2.80	2.66	3.78	3.35	4.08	3.89	3.26	5.50	4.23	5.07	8.03	8.25	9.51	6.34	22.34
KS-88-12-J	5.36	2.32	2.67	2.89	3.91	3.41	4.08	3.63	3.23	6.73	4.30	3.55	5.61	11.77	8.78	5.98	21.77
<u>NON-DIAMICTON SAMPLES</u>																	
KS-88-12-D	1.61	0.73	0.87	1.06	1.45	1.52	1.99	2.03	1.92	5.44	2.95	3.86	7.71	13.61	19.96	9.75	23.55
KS-88-12-E	1.27	1.10	1.55	2.00	2.91	3.04	3.84	4.01	3.68	6.08	4.96	3.83	5.86	10.59	9.01	6.98	29.29
KS-88-12-F	2.15	1.24	2.00	3.31	5.14	5.15	7.58	7.75	5.67	7.78	3.44	3.44	2.90	4.89	5.07	3.80	28.69
KS-88-12-G	4.07	1.70	2.16	2.65	3.87	3.95	5.86	5.63	4.27	4.85	4.01	3.68	5.01	8.19	7.02	4.51	28.57
KS-88-12-H	2.92	1.45	1.88	2.32	3.61	3.43	4.80	4.47	3.62	5.94	3.62	6.23	7.39	13.76	8.98	5.50	20.09

<u>DIMMICK ROAD RESERVOIR</u> (KS-89-06)

<u>DIAMICTON SAMPLES</u>																	
DIMW-K	8.72	3.83	4.55	4.29	5.99	5.14	6.29	5.36	4.22	9.59	4.51	5.08	5.36	8.18	6.77	2.82	9.30
DIMW-O	10.48	4.82	5.36	4.91	6.62	5.91	7.23	6.43	5.19	7.51	4.51	5.76	2.50	6.51	4.76	4.26	7.26
DIMW-P	4.45	1.88	2.20	2.42	3.14	2.78	3.46	3.45	3.20	8.43	5.34	4.78	7.58	10.67	8.15	5.34	22.75
DIMW-S	5.76	2.71	3.42	3.33	4.37	3.77	4.66	4.49	3.99	8.19	6.49	6.21	5.65	13.83	7.34	5.93	9.88
DIMW-T	4.15	2.16	2.16	2.19	2.90	2.60	3.34	3.24	2.98	6.16	4.40	3.96	10.56	11.88	9.68	6.82	20.81

APPENDIX D.
CLAST LITHOLOGIC ANALYSES

APPENDIX D. CLAST LITHOLOGIC DATA - RAW COUNTS

LITHOLOGIC SYMBOLS
- LS - Limestone
- DOL - Dolomite
- GSH - Green shale
- BSH - Black shale
- SS - Sandstone
- CHT - Chert
- IGN - Igneous (undiff.)
- MET - Metamorphic (undiff.)

CATEGORIES

Shape
- OBL - Oblate
- EQ - Equant
- PRO - Prolate
- BLA - Bladed

Characteristics
- STR - Striated
- FAC - Faceted

Roundness
- VA - Very angular
- A - Angular
- SA - Subangular
- SR - Subangular
- R - Rounded
- WR - Well rounded
- FC - Fossil-controlled

APPENDIX FORMAT:

SAMPLE # MATERIAL NUMBER OF CLASTS
LITHOLOGY (8 columns)

SHAPE (4 lines)
CHARACTERISTICS (2 lines)
ROUNDNESS (7 lines)

APPENDIX D. CLAST LITHOLOGIC DATA - RAW COUNTS (continued)

KS-88-04-J DIAMICTON n = 101

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	28	7	4	0	1	0	0	0
EQU	13	12	1	0	2	1	2	1
PRO	8	3	2	0	0	0	2	0
BLA	10	0	3	1	0	0	0	0
STR	4	2	0	1	0	0	0	0
FAC	3	0	0	0	0	0	0	0
VA	0	0	0	0	0	0	0	0
A	29	2	5	2	1	0	0	0
SA	20	16	4	0	1	0	3	1
SR	5	2	1	0	0	0	0	0
R	4	2	0	1	0	1	0	0
WR	0	0	0	0	0	0	0	0
FC	1	0	0	0	0	0	0	0

KS-89-03-A DIAMICTON n = 107

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	30	7	2	0	1	0	0	2
EQU	17	13	0	1	1	3	0	1
PRO	11	7	0	0	0	0	0	1
BLA	8	1	1	0	0	0	0	0
STR	2	7	0	1	1	1	0	1
FAC	1	4	0	1	1	1	0	0
VA	0	0	0	0	0	0	0	0
A	46	6	2	0	0	0	0	0
SA	16	19	1	0	1	1	0	4
SR	0	1	0	0	1	1	0	0
R	3	2	0	1	0	1	0	0
WR	0	0	0	0	0	0	0	0
FC	1	0	0	0	0	0	0	0

KS-87-09-QQ DIAMICTON n = 102

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	30	6	6	1	1	1	1	0
EQU	12	12	1	0	2	0	0	1
PRO	11	1	1	0	0	0	0	1
BLA	9	3	1	1	0	0	0	0
STR	0	4	0	2	1	0	0	0
FAC	0	0	0	1	0	0	0	0
VA	2	0	0	0	0	0	0	0
A	32	3	3	0	0	0	0	0
SA	23	14	6	2	3	1	0	1
SR	1	2	0	0	0	0	1	1
R	0	3	0	0	0	0	0	0
WR	0	0	0	0	0	0	0	0
FC	4	0	0	0	0	0	0	0

KS-88-14-A DIAMICTON n = 131

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	26	11	7	0	2	0	0	1
EQU	8	23	3	0	3	0	1	0
PRO	10	8	4	0	3	0	1	0
BLA	8	5	7	0	0	0	0	0
STR	0	7	1	0	0	0	0	0
FAC	0	5	0	0	0	0	0	0
VA	0	0	0	0	0	0	0	0
A	36	13	12	0	3	0	0	1
SA	14	26	8	0	5	0	2	0
SR	1	5	1	0	0	0	0	0
R	1	3	0	0	0	0	0	0
WR	0	0	0	0	0	0	0	0
FC	0	0	0	0	0	0	0	0

APPENDIX D. CLAST LITHOLOGIC DATA - RAW COUNTS (continued)

TL-87-210-B DIAMICTON n = 103

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	30	8	2	3	0	0	0	0
EQU	11	18	2	0	2	0	3	1
PRO	5	4	1	0	1	0	0	0
BLA	10	0	2	0	0	0	0	0
STR	1	5	0	2	1	0	1	0
FAC	1	1	0	1	0	0	0	0
VA	5	0	0	0	0	0	0	0
A	40	7	1	2	0	0	0	0
SA.	11	17	4	1	3	0	3	1
SR	0	5	2	0	0	0	0	0
R	0	0	0	0	0	0	0	0
WR	0	1	0	0	0	0	0	0
FC	0	0	0	0	0	0	0	0

KS-88-03-B DIAMICTON n = 109

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	30	4	2	0	1	0	1	1
EQU	20	14	0	0	0	1	0	0
PRO	12	7	0	0	1	0	0	0
BLA	11	2	0	1	0	0	1	0
STR	0	1	0	0	0	0	0	0
FAC	0	0	0	0	0	0	0	1
VA	4	0	0	0	0	0	0	0
A	49	13	2	1	0	1	1	0
SA	19	10	0	0	2	0	0	1
SR	0	3	0	0	0	0	1	0
R	1	1	0	0	0	0	0	0
WR	0	0	0	0	0	0	0	0
FC	0	0	0	0	0	0	0	0

KS-88-04-B DIAMICTON n = 101

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	24	6	1	0	0	0	1	0
EQU	13	14	0	0	3	1	2	3
PRO	11	8	0	0	0	0	0	3
BLA	9	2	0	0	0	0	0	0
STR	2	4	0	0	0	0	1	0
FAC	1	3	0	0	0	0	1	1
VA	1	0	0	0	0	0	0	0
A	26	1	1	0	0	0	0	1
SA	24	17	0	0	1	1	1	5
SR	4	8	0	0	2	0	1	0
R	2	4	0	0	0	0	1	0
WR	0	0	0	0	0	0	0	0
FC	0	0	0	0	0	0	0	0

KS-89-03-B DIAMICTON n = 104

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	32	7	4	0	1	0	0	1
EQU	18	12	1	0	4	1	0	0
PRO	7	1	1	0	1	2	0	0
BLA	10	0	0	1	0	0	0	0
STR	3	1	0	0	1	0	0	0
FAC	2	0	0	0	0	0	0	0
VA	1	0	0	0	0	0	0	0
A	36	6	4	1	2	2	0	0
SA	24	7	2	0	2	1	0	1
SR	4	3	0	0	2	0	0	0
R	1	4	0	0	0	0	0	0
WR	0	0	0	0	0	0	0	0
FC	1	0	0	0	0	0	0	0

APPENDIX D. CLAST LITHOLOGIC DATA - RAW COUNTS (continued)

KS-87-09-00 DIAMICTON n = 128

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	32	8	1	1	4	0	0	3
EQU	17	17	0	0	9	1	2	1
PRO	16	7	1	0	2	0	0	0
BLA	5	0	0	0	0	0	0	1
STR	1	5	1	0	4	0	0	2
FAC	3	0	0	0	3	0	1	1
VA	0	0	0	0	0	0	0	0
A	36	3	0	0	2	1	0	1
SA	29	27	1	1	9	0	1	2
SR	4	2	1	0	2	0	0	2
R	1	0	0	0	2	0	1	0
WR	0	0	0	0	0	0	0	0
FC	0	0	0	0	0	0	0	0

KS-88-06-D DIAMICTON n = 118

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	37	8	2	0	0	0	0	0
EQU	14	10	3	0	2	1	0	2
PRO	19	7	3	0	0	1	0	0
BLA	9	0	0	0	0	0	0	0
STR	0	1	0	0	1	0	0	1
FAC	0	0	0	0	1	0	0	0
VA	0	0	0	0	0	0	0	0
A	25	3	3	0	1	1	0	0
SA	47	19	5	0	0	1	0	2
SR	4	1	0	0	1	0	0	0
R	2	2	0	0	0	0	0	0
WR	0	0	0	0	0	0	0	0
FC	1	0	0	0	0	0	0	0

KS-89-02-A DIAMICTON n = 123

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	31	9	13	2	1	0	0	0
EQU	11	8	2	0	0	1	2	1
PRO	12	9	1	0	0	0	0	0
BLA	6	4	9	0	1	0	0	0
STR	1	5	2	2	1	0	0	0
FAC	1	3	0	0	0	0	0	0
VA	0	0	0	0	0	1	0	0
A	33	6	10	0	1	0	0	0
SA	26	13	15	2	1	0	1	0
SR	0	6	0	0	0	0	1	1
R	1	5	0	0	0	0	0	0
WR	0	0	0	0	0	0	0	0
FC	0	0	0	0	0	0	0	0

KS-89-01-G DIAMICTON n = 114

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	38	3	6	3	0	0	0	0
EQU	18	10	3	0	0	0	0	0
PRO	8	3	6	0	3	0	0	0
BLA	10	3	0	0	0	0	0	0
STR	3	0	0	3	0	0	0	0
FAC	3	0	0	0	0	0	0	0
VA	0	0	0	0	0	0	0	0
A	42	0	3	0	0	0	0	0
SA	34	16	10	3	3	0	0	0
SR	0	3	0	0	0	0	0	0
R	0	0	0	0	0	0	0	0
WR	0	0	0	0	0	0	0	0
FC	0	0	0	0	0	0	0	0

APPENDIX D. CLAST LITHOLOGIC DATA - RAW COUNTS (continued)

KS-88-14-C DIAMICTON n = 100

	LS	DOL	GSH	BSH	SS	CHT	IGN	MET
OBL	26	6	6	2	6	0	0	0
EQU	4	10	2	2	4	2	2	0
PRO	12	4	0	2	4	0	0	0
BLA	6	0	0	0	0	0	0	0
STR	2	4	0	6	4	0	0	0
FAC	2	4	0	0	2	0	0	0
VA	0	0	0	0	0	0	0	0
A	36	12	6	0	0	2	0	0
SA	8	4	2	4	4	0	0	0
SR	2	0	0	2	0	0	2	0
R	2	4	0	0	10	0	0	0
WR	0	0	0	0	0	0	0	0
FC	0	0	0	0	0	0	0	0

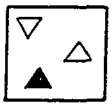
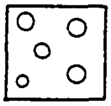
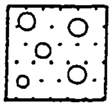
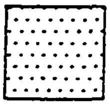
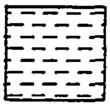
PLEASE NOTE:

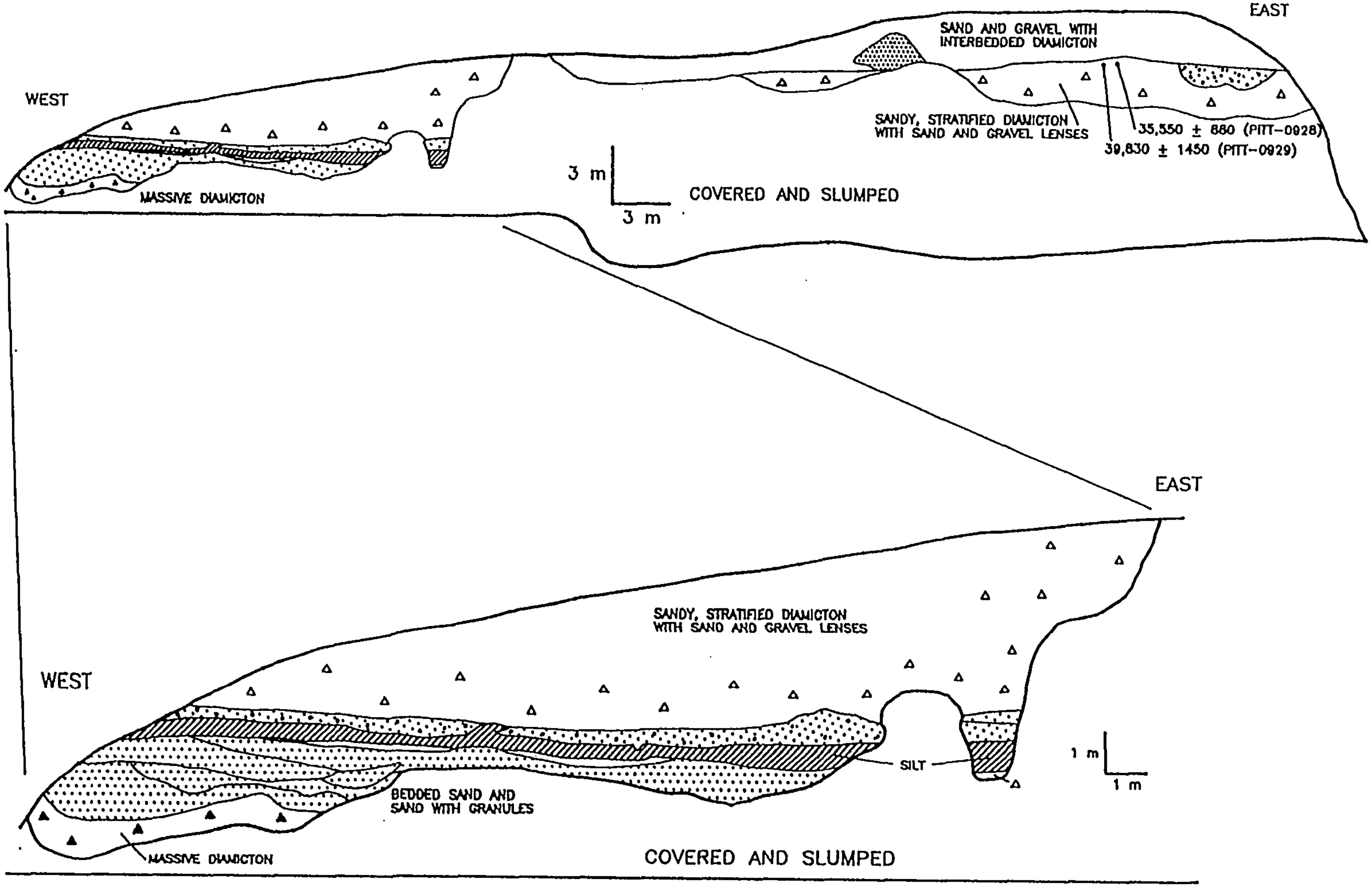
Page(s) missing in number only; text follows.
Filmed as received.

UMI

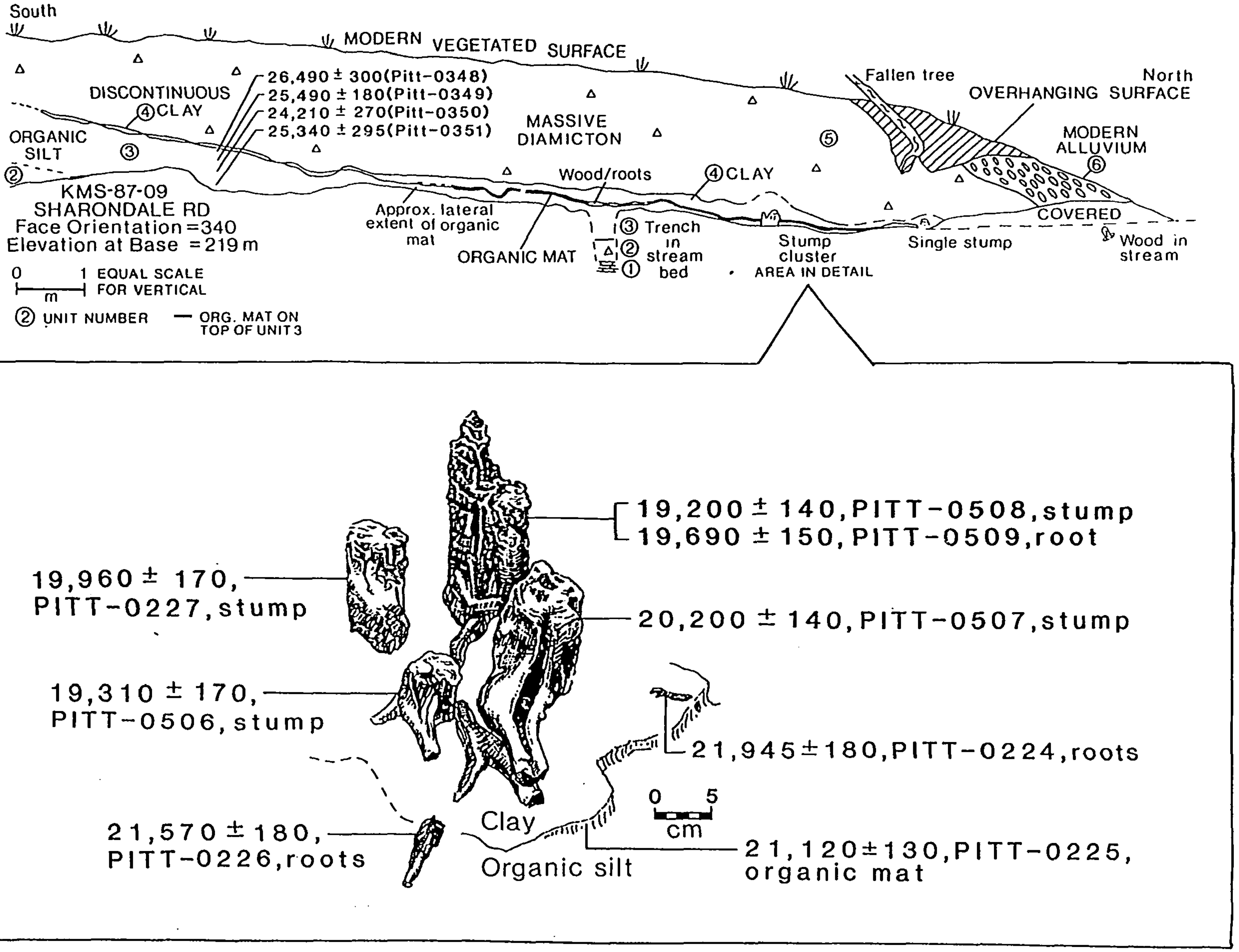
APPENDIX E.
FACEMAPS OF STUDIED EXPOSURES

LEGEND FOR FACEMAPS

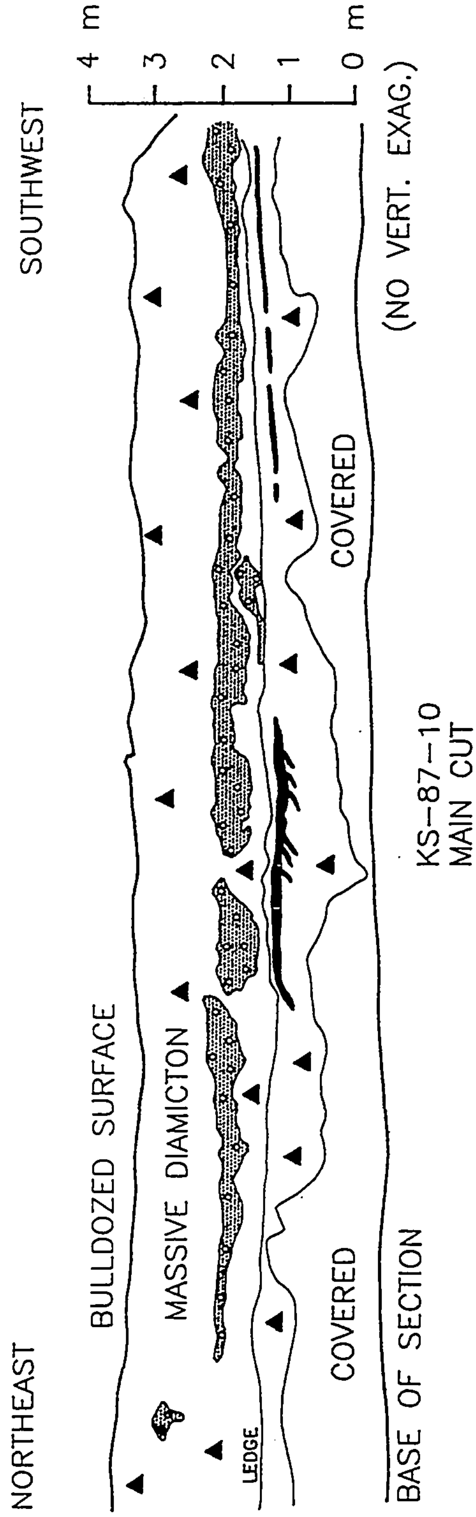
SYMBOLS	ABBREVIATIONS	MATERIAL
		diamicton
	gr	gravel
	s&g	sand and gravel
	sd, sand	sand
	st, silt	silt
	cy, clay	clay
	or, pt	peat, organic silt

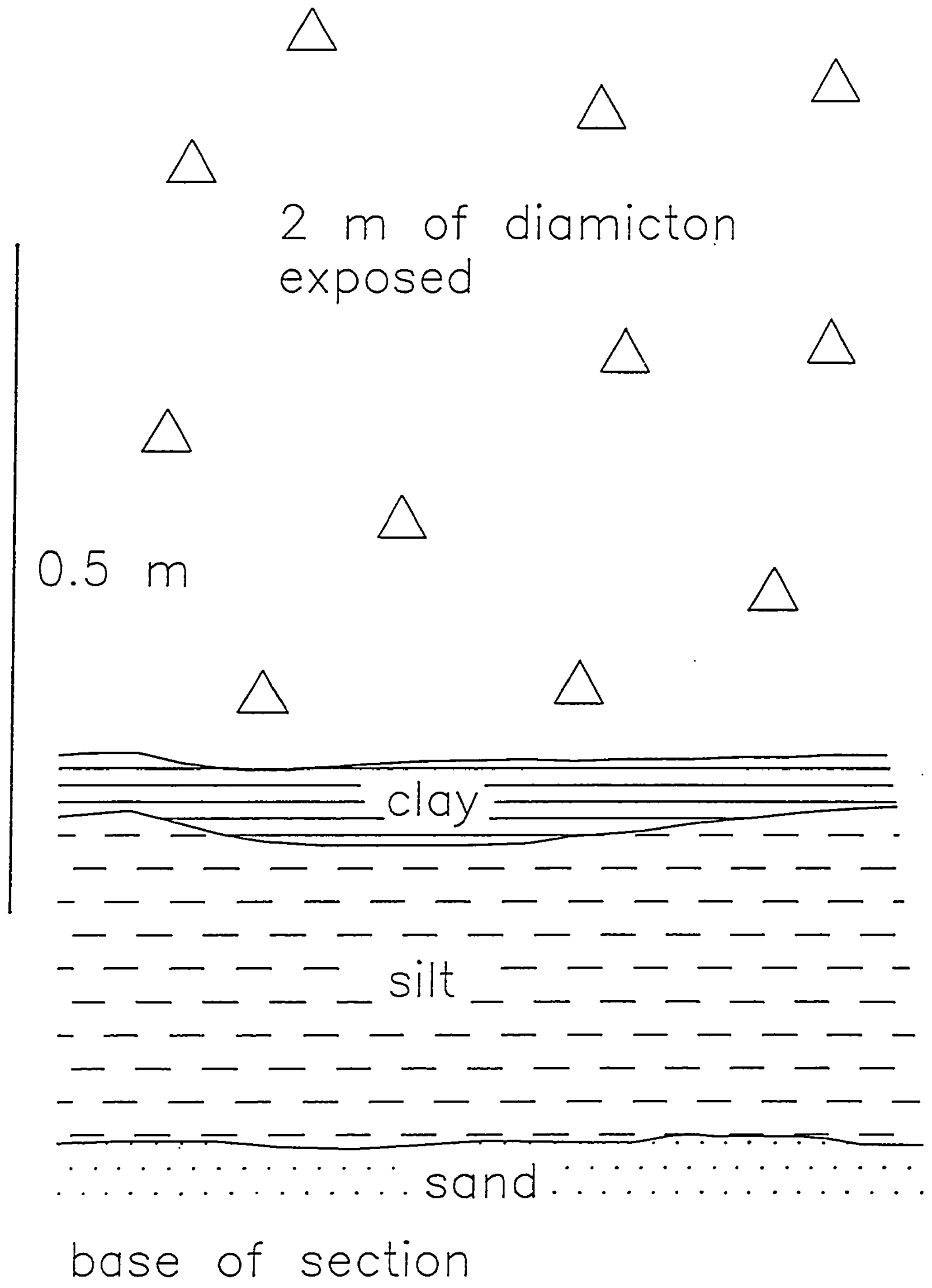


KS–87–04
DAY CARE CENTER

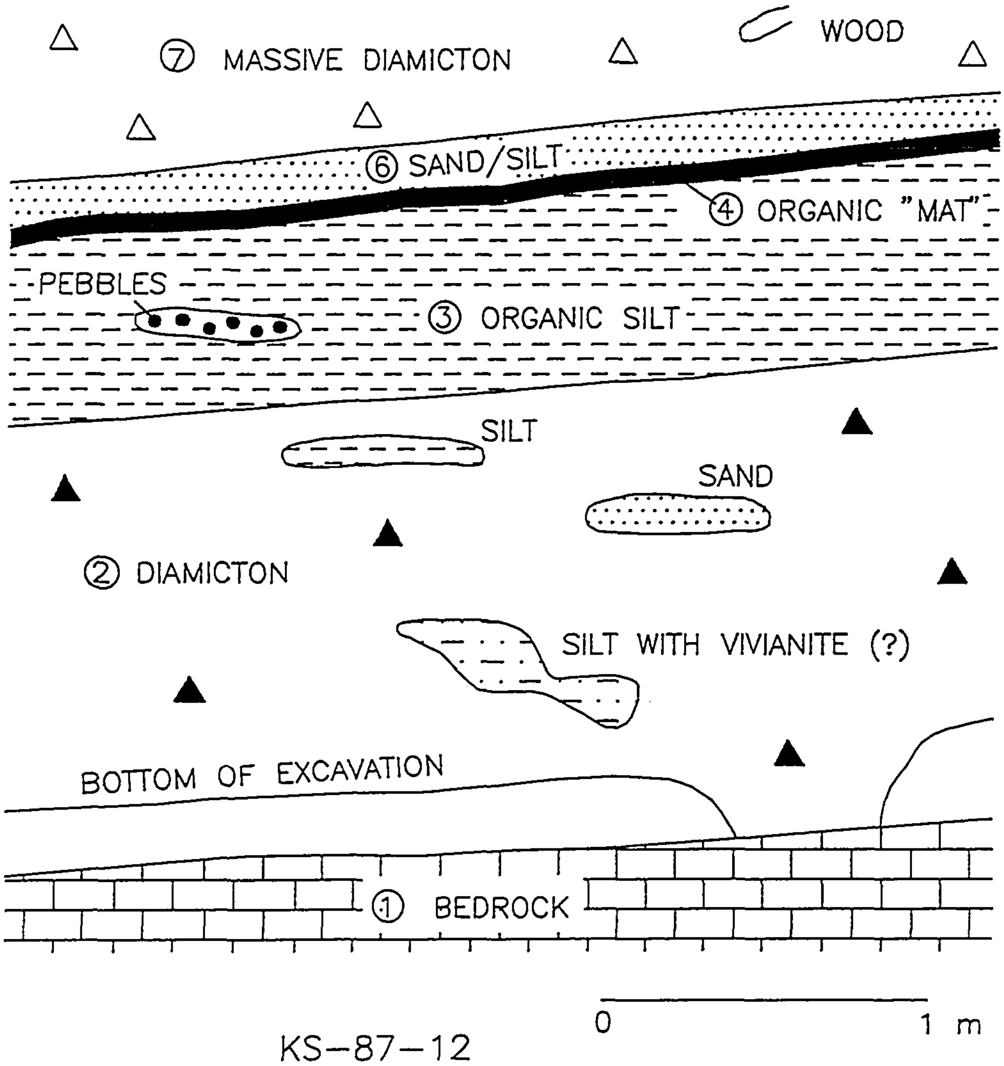


South
MODERN VEGETATED SURFACE
North
26,490 ± 300(Pitt-0348)
25,490 ± 180(Pitt-0349)
24,210 ± 270(Pitt-0350)
25,340 ± 295(Pitt-0351)
DISCONTINUOUS ④CLAY
ORGANIC SILT ③
②
MASSIVE DIAMICTON
⑤
Fallen tree
OVERHANGING SURFACE
MODERN ALLUVIUM ⑥
Wood/roots
④CLAY
KMS-87-09
SHARONDALE RD
Face Orientation = 340
Elevation at Base = 219 m
Approx. lateral extent of organic mat
ORGANIC MAT
③ Trench
② in stream
① bed
Stump cluster
AREA IN DETAIL
Single stump
COVERED
Wood in stream
0 1 m EQUAL SCALE FOR VERTICAL
② UNIT NUMBER
ORG. MAT ON TOP OF UNIT 3
19,200 ± 140, PITT-0508, stump
19,690 ± 150, PITT-0509, root
19,960 ± 170, PITT-0227, stump
20,200 ± 140, PITT-0507, stump
19,310 ± 170, PITT-0506, stump
21,945±180, PITT-0224, roots
0 5 cm
Clay
21,570 ± 180, PITT-0226, roots
Organic silt
21,120±130, PITT-0225, organic mat

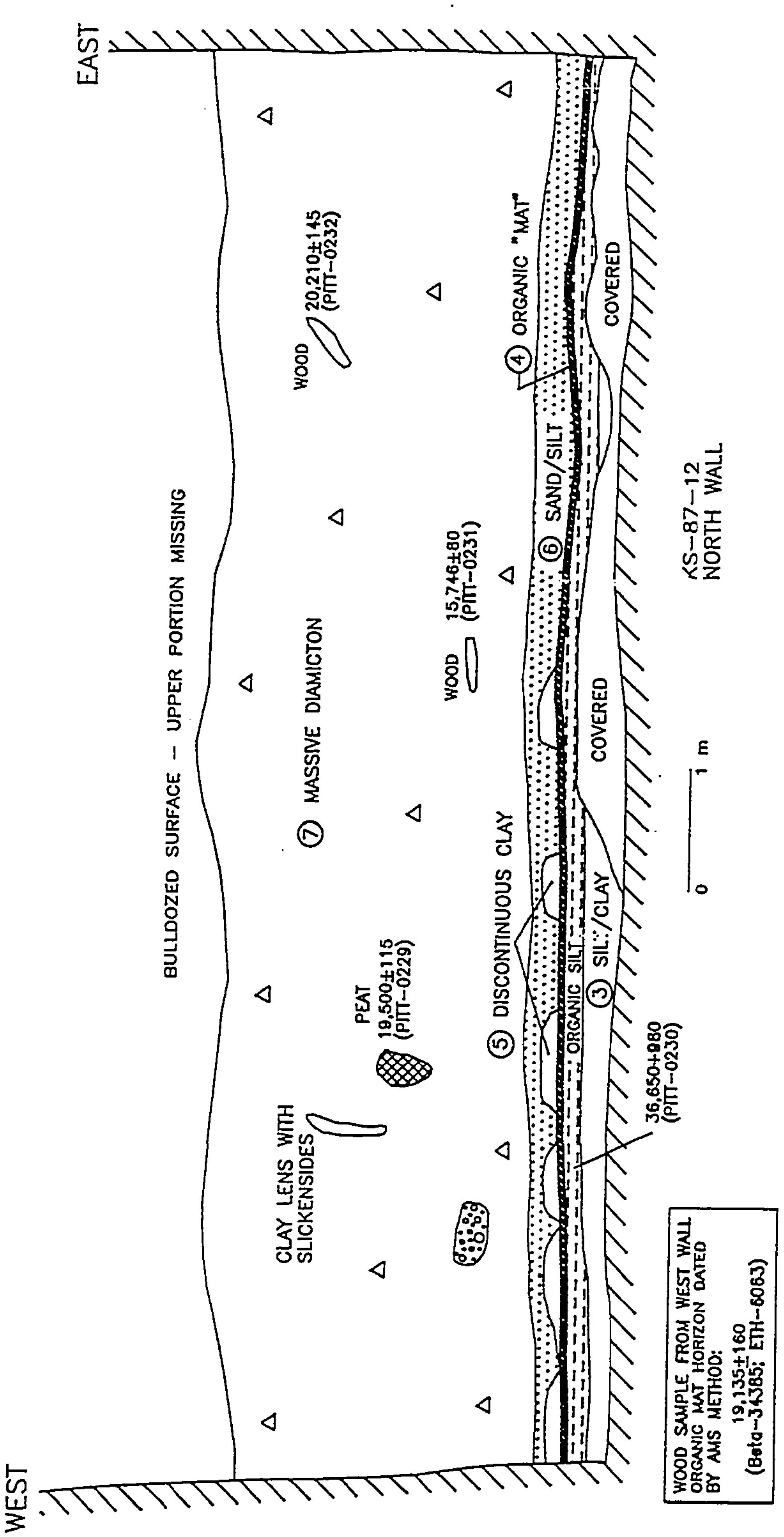

NORTHEAST
SOUTHWEST
BULLDOZED SURFACE
MASSIVE DIAMICTON
LEDGE
COVERED
COVERED
BASE OF SECTION
KS-87-10
MAIN CUT
4 m
3
2
1
0 m
(NO VERT. EXAG.)

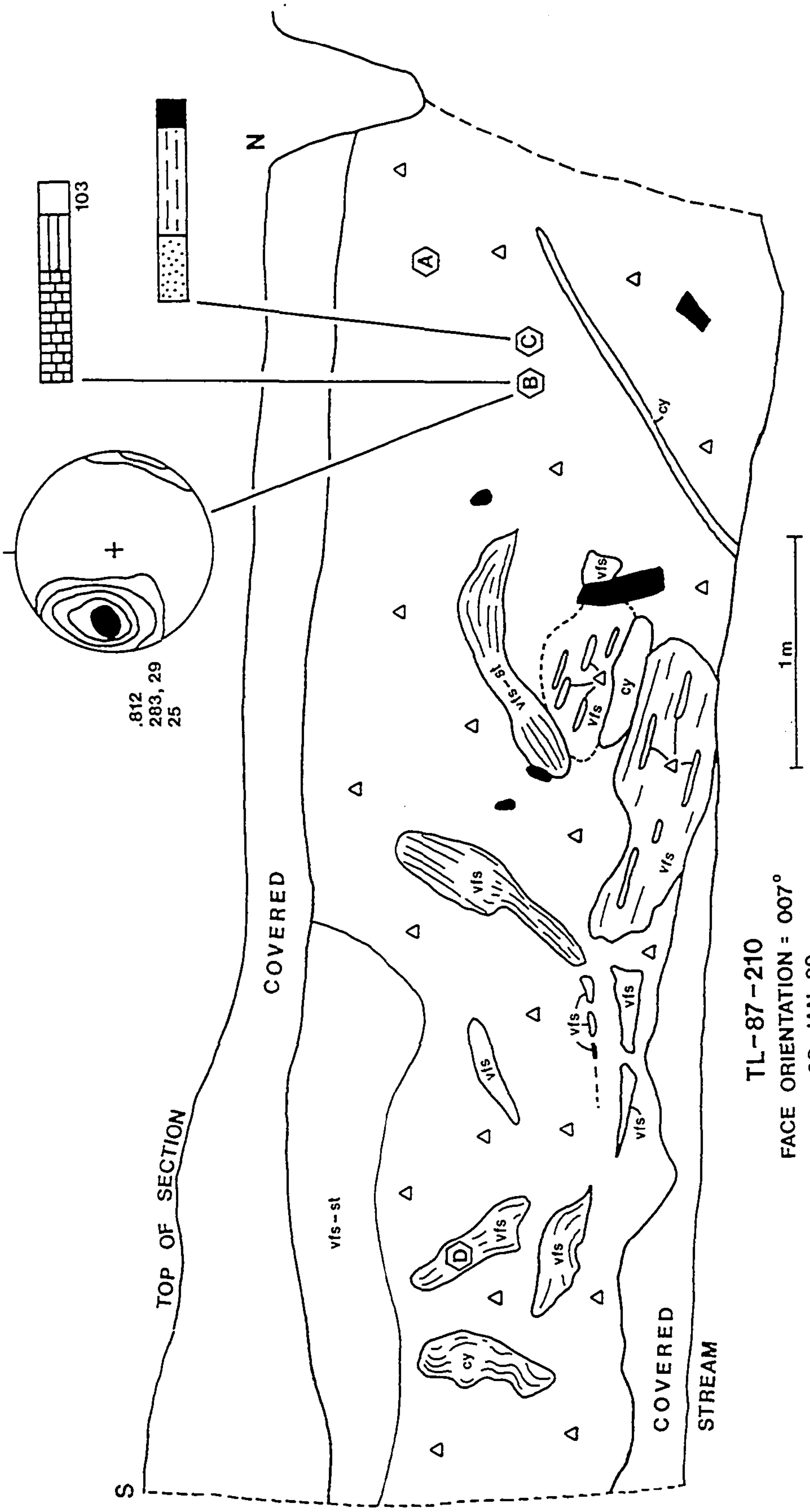


KS-87-11

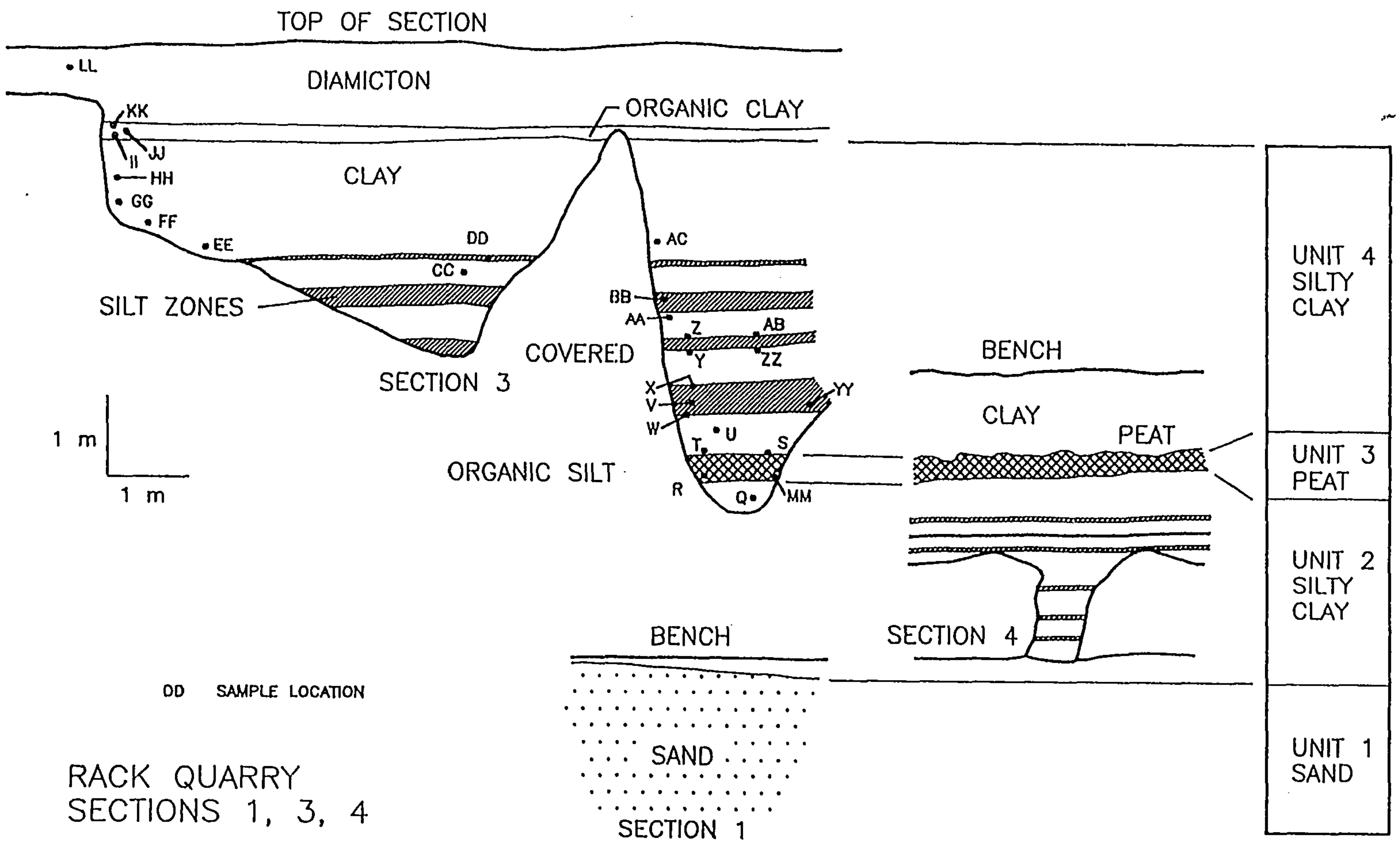


KS–87–12
EAST WALL

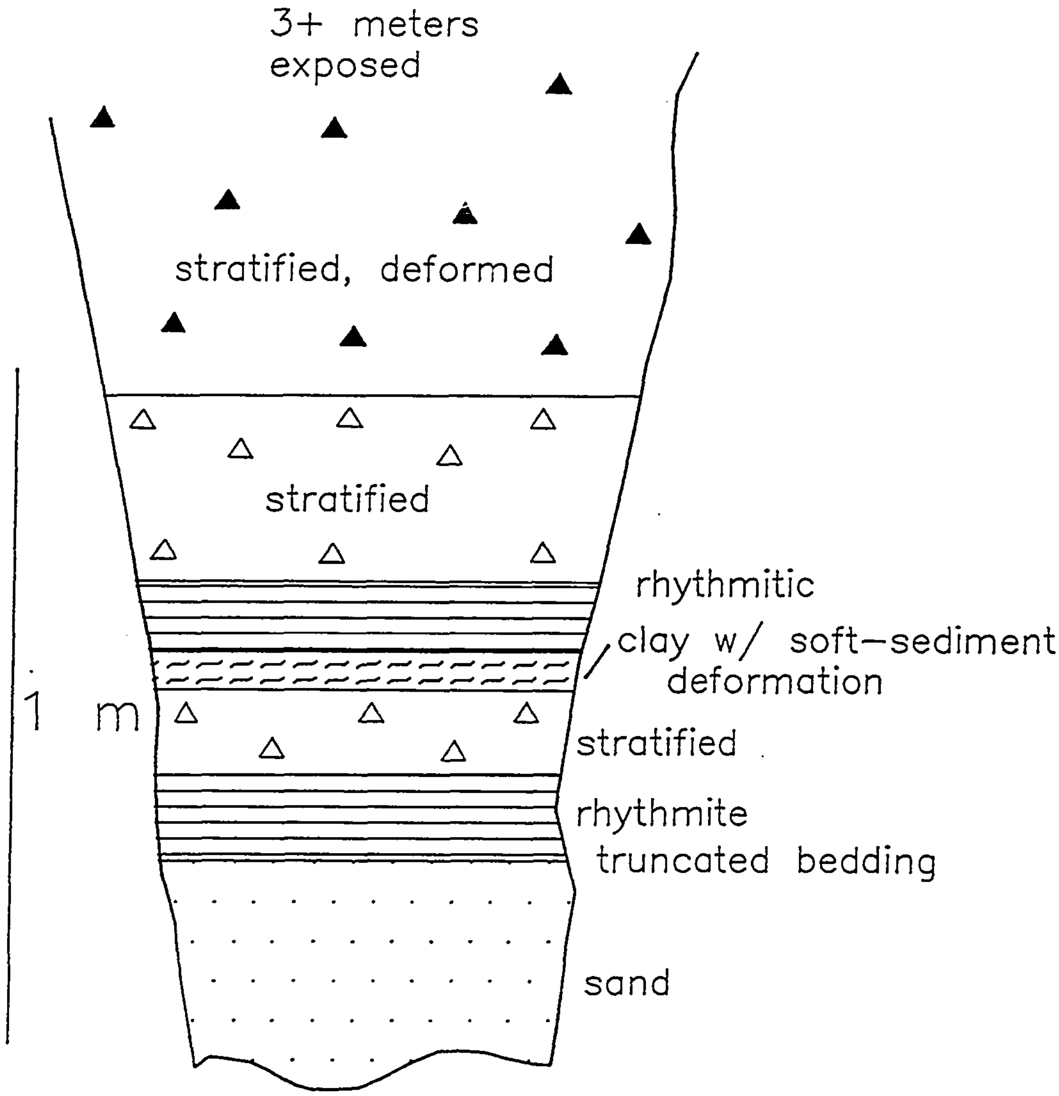

WEST
EAST
BULLDOZED SURFACE – UPPER PORTION MISSING
⑦ MASSIVE DIAMICTON
WOOD
20,210±145
(PlTT-0232)
CLAY LENS WITH SLICKENSIDES
PEAT
19,500±115
(PITT-0229)
WOOD
15,746±80
(PITT-0231)
④ ORGANIC "MAT"
⑥ SAND/SILT
⑤ DISCONTINUOUS CLAY
ORGANIC SILT
③ SILT/CLAY
COVERED
COVERED
36,650+880
(PITT-0230)
0
1 m
KS-87-12
NORTH WALL
WOOD SAMPLE FROM WEST WALL ORGANIC MAT HORIZON DATED BY AMS METHOD:
19,135±160
(Beta-34385; ETH-6063)



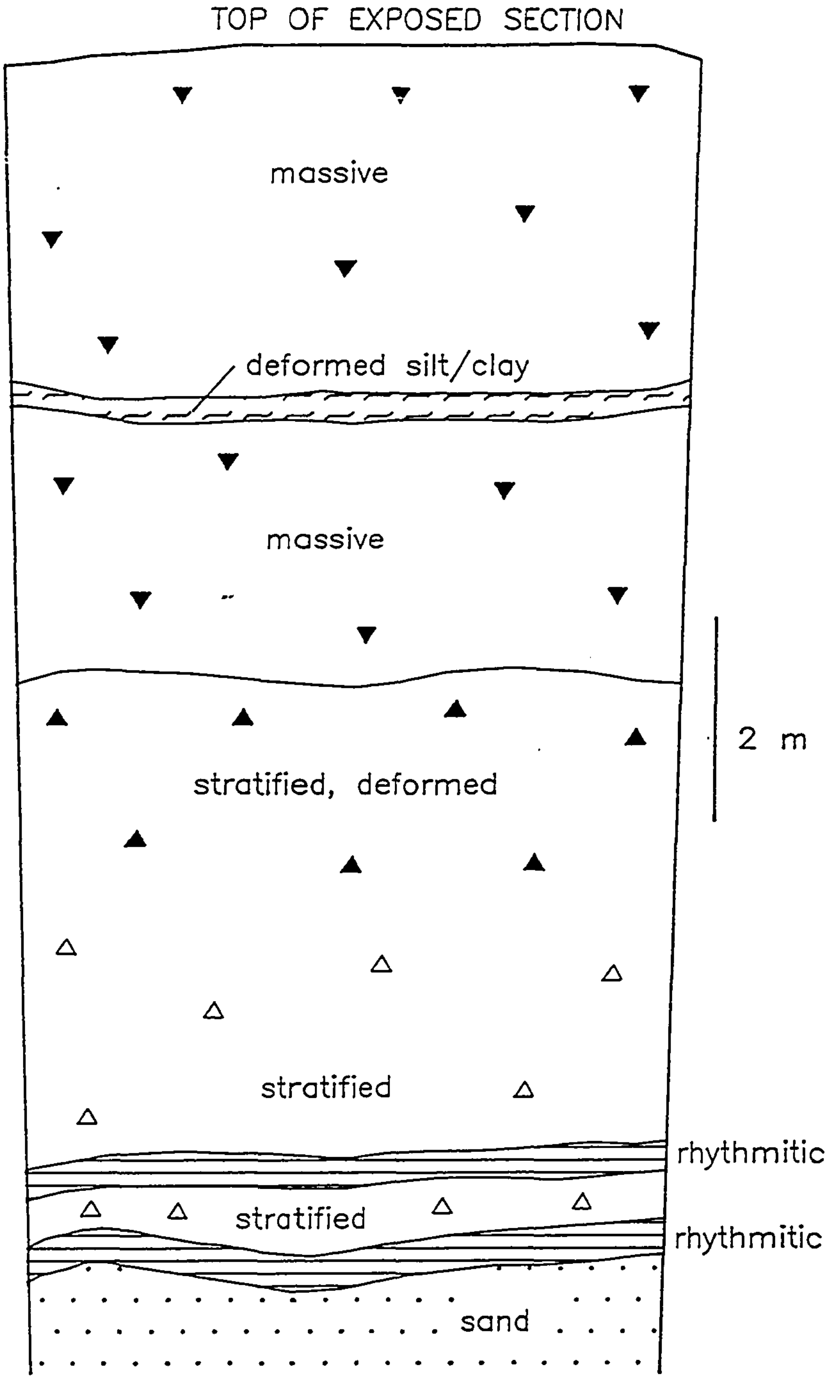
TL-87-210
FACE ORIENTATION = 007°
28 JAN 89
1m
N
S
TOP OF SECTION
COVERED
COVERED
STREAM
vfs-st
vfs
cy
A
B
C
D
103
.812
283, 29
25



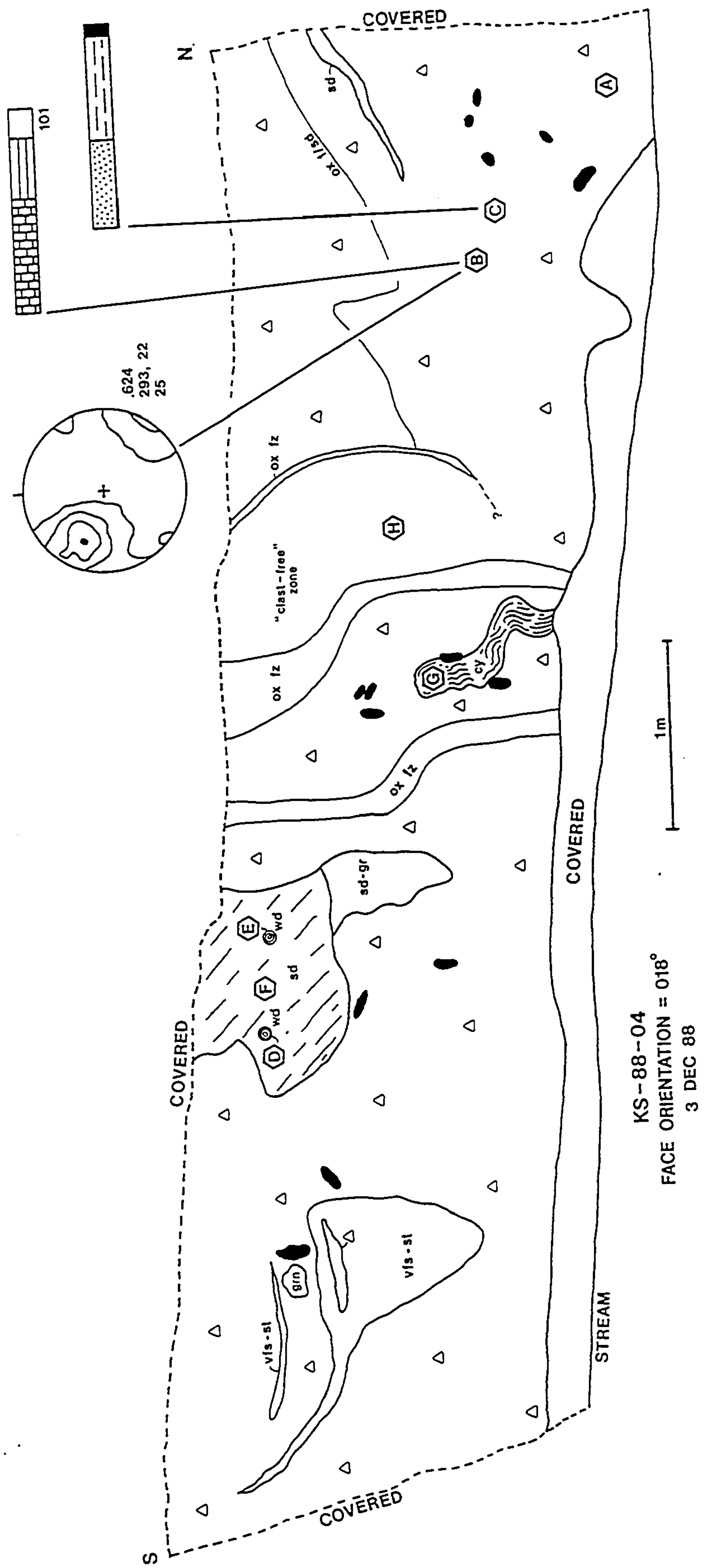
RACK QUARRY
SECTIONS 1, 3, 4

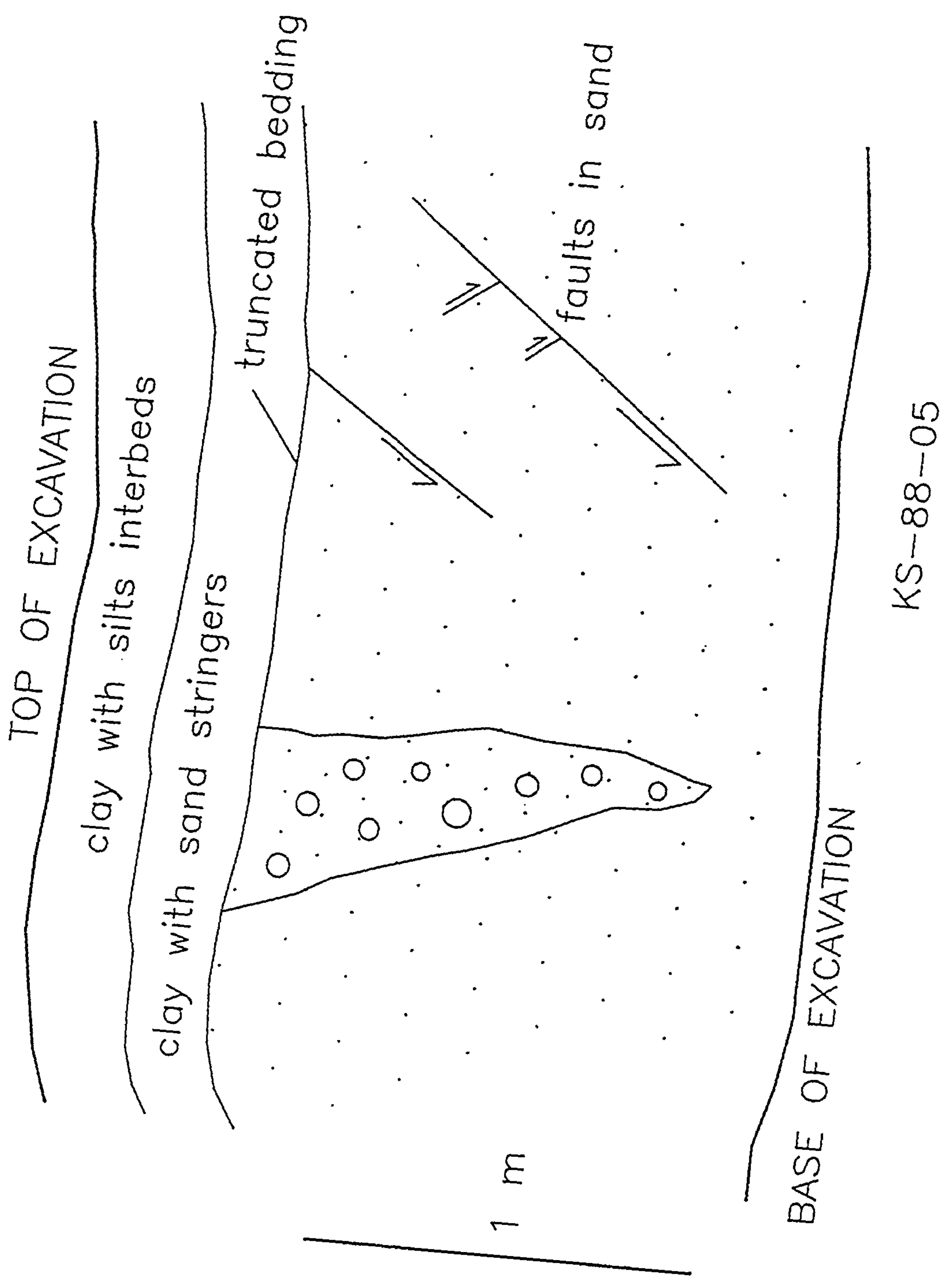


SECTION 6
RACK QUARRY

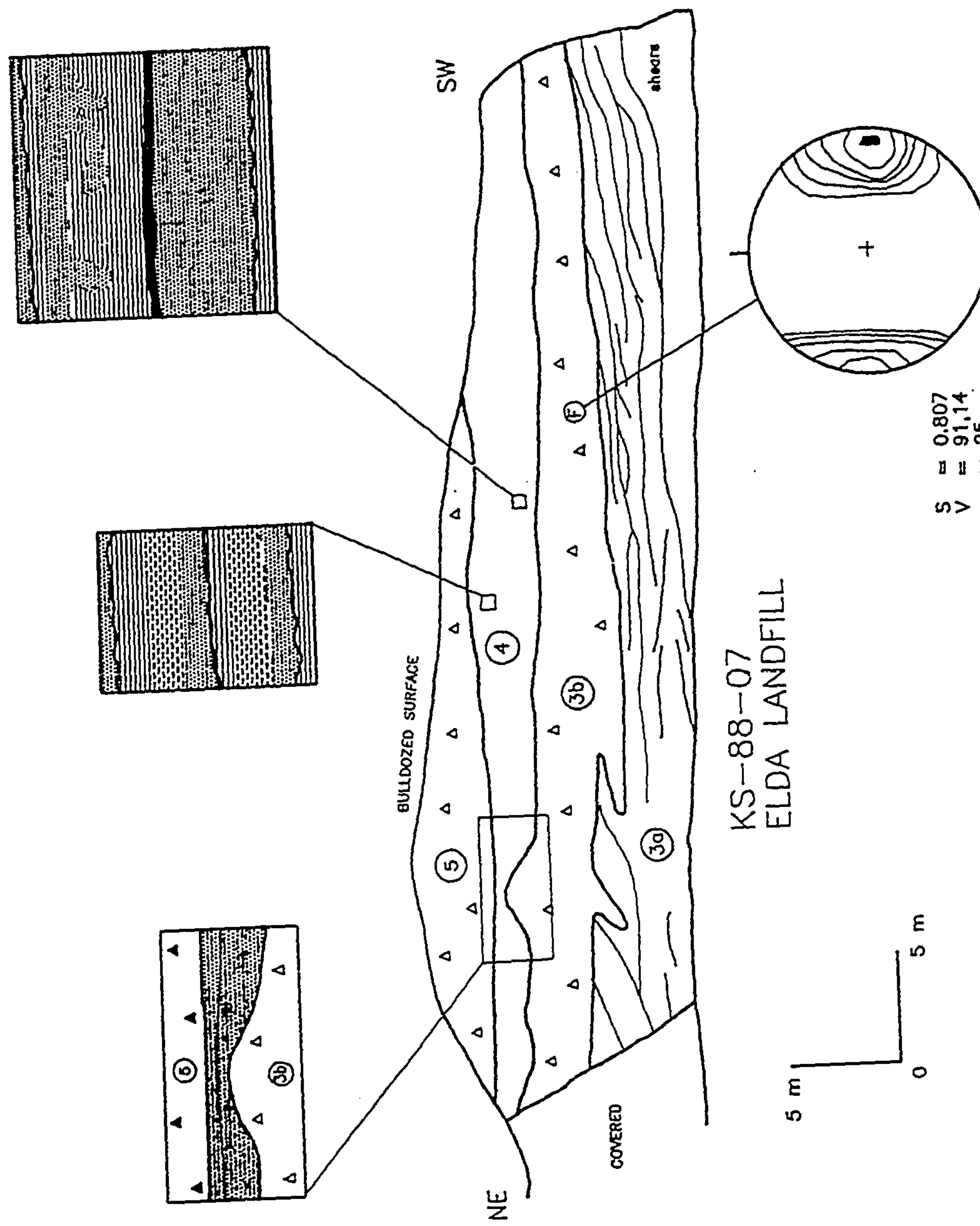


SECTIONS 7 AND 8
RACK QUARRY

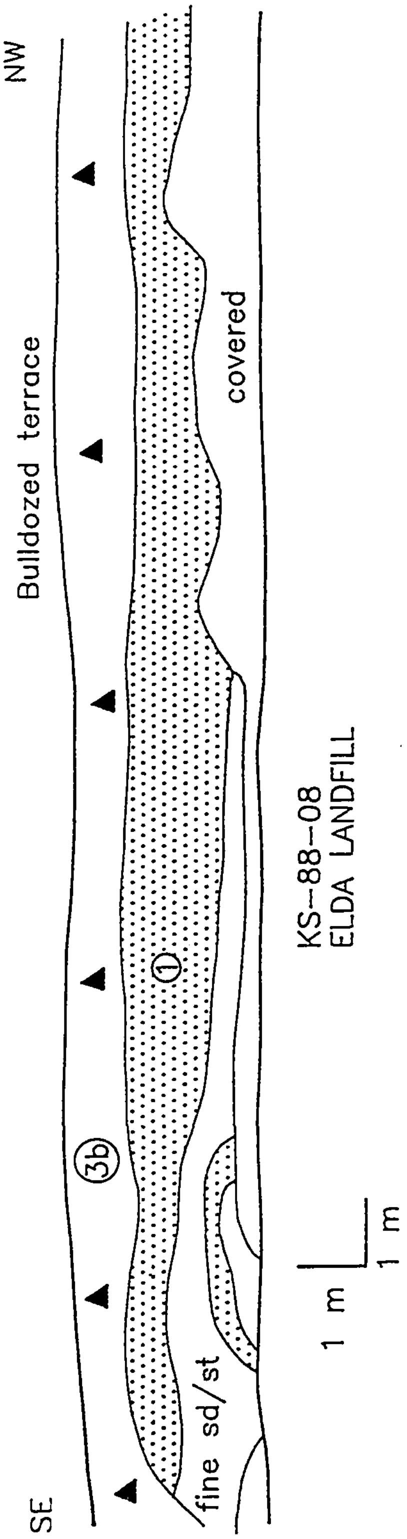

KS-88-04
FACE ORIENTATION = 018°
3 DEC 88
1m
N
S
COVERED
COVERED
COVERED
COVERED
STREAM
.624
293, 22
25
101
ox lz
ox lz
ox lz
ox l/sd
"clast-free" zone
sd
sd-gr
sd
wd
wd
cy
vfs-st
vfs-st
grn
A
B
C
D
E
F
G
H

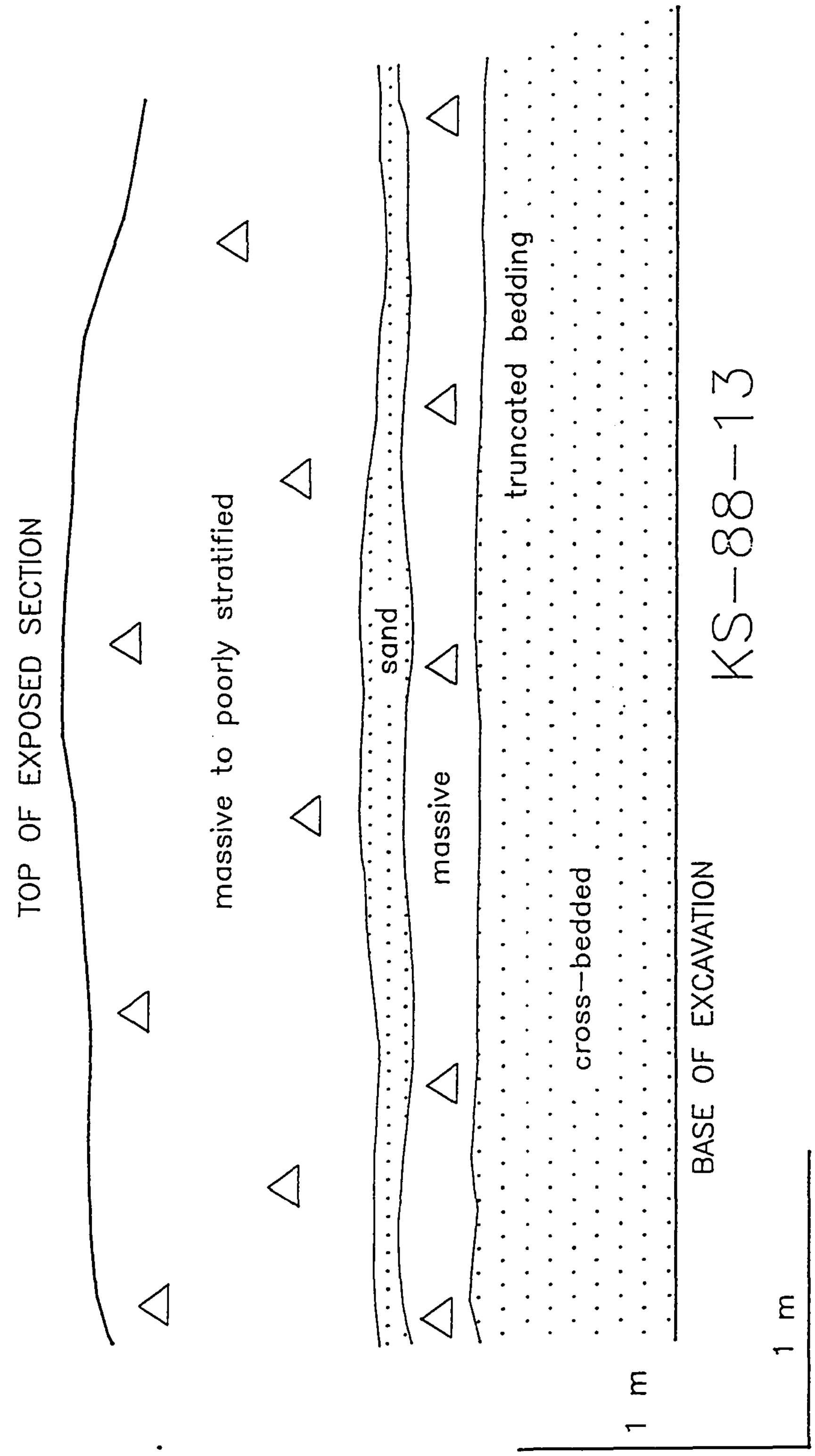


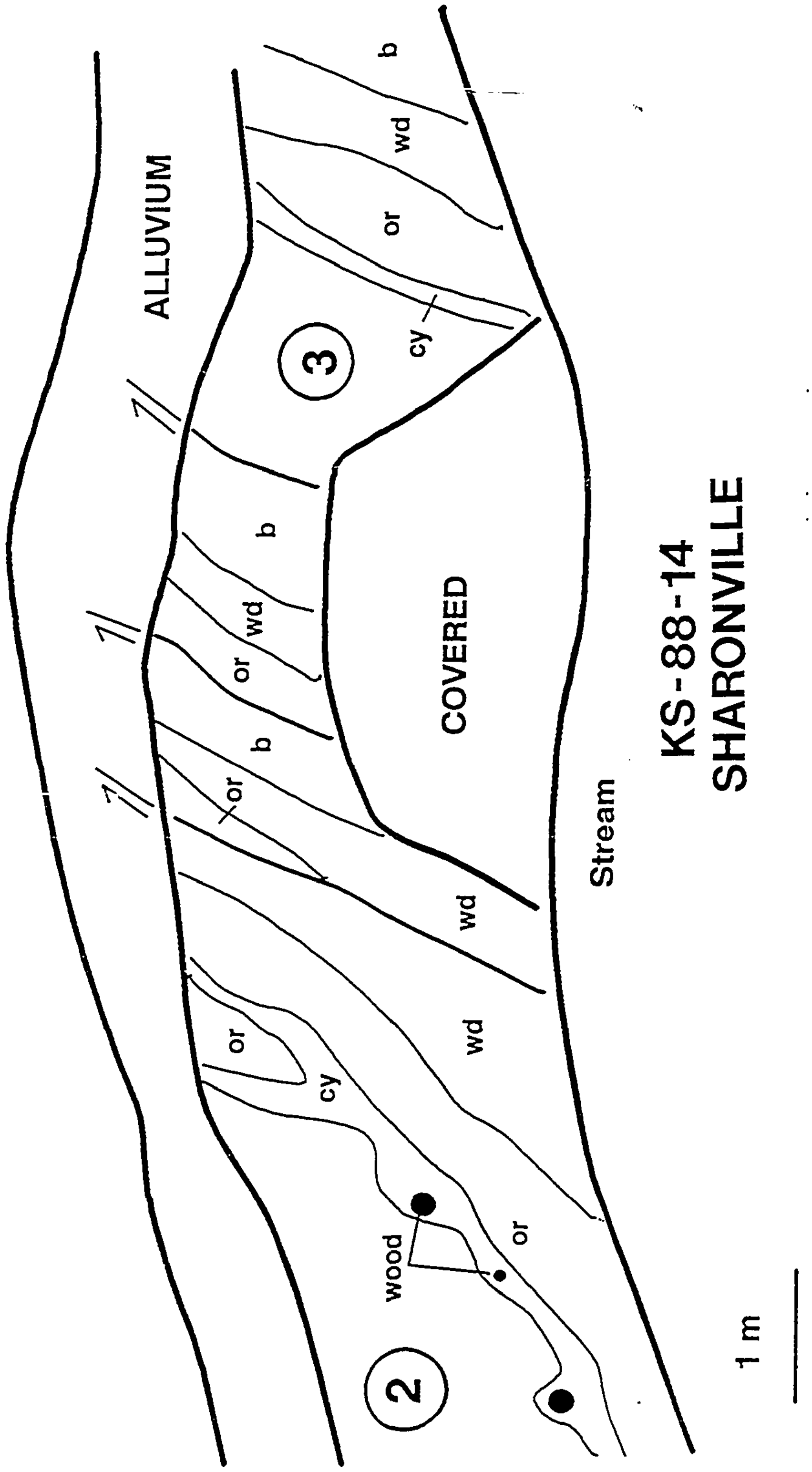
TOP OF EXCAVATION
clay with silts interbeds
clay with sand stringers
truncated bedding
faults in sand
KS—88—05
BASE OF EXCAVATION
1 m

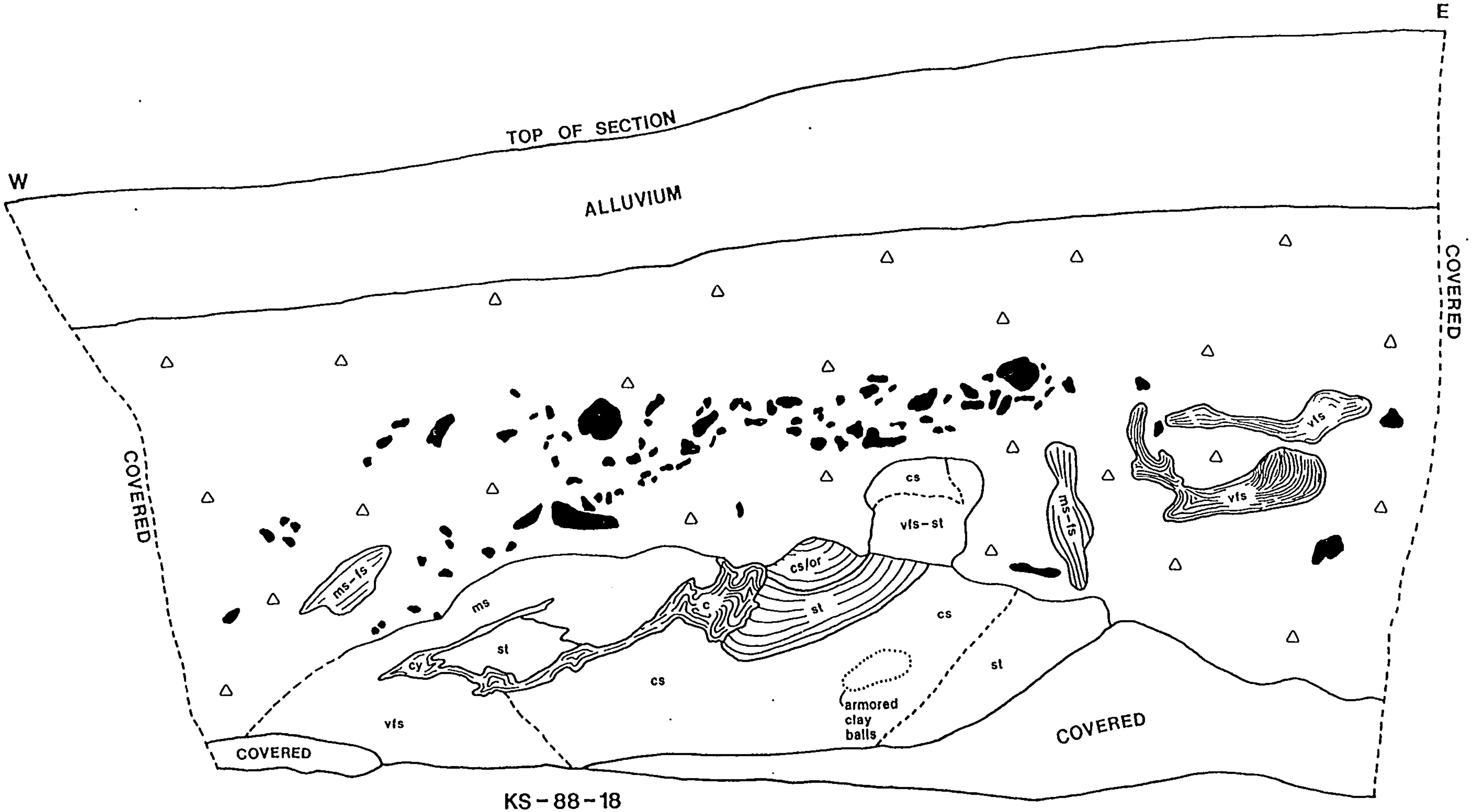


KS-88-07
ELDA LANDFILL
SW
NE
BULLDOZED SURFACE
COVERED
shears
5
4
3a
3b
F
6
S = 0.807
V = 91,14
n = 25
5 m
0
5 m

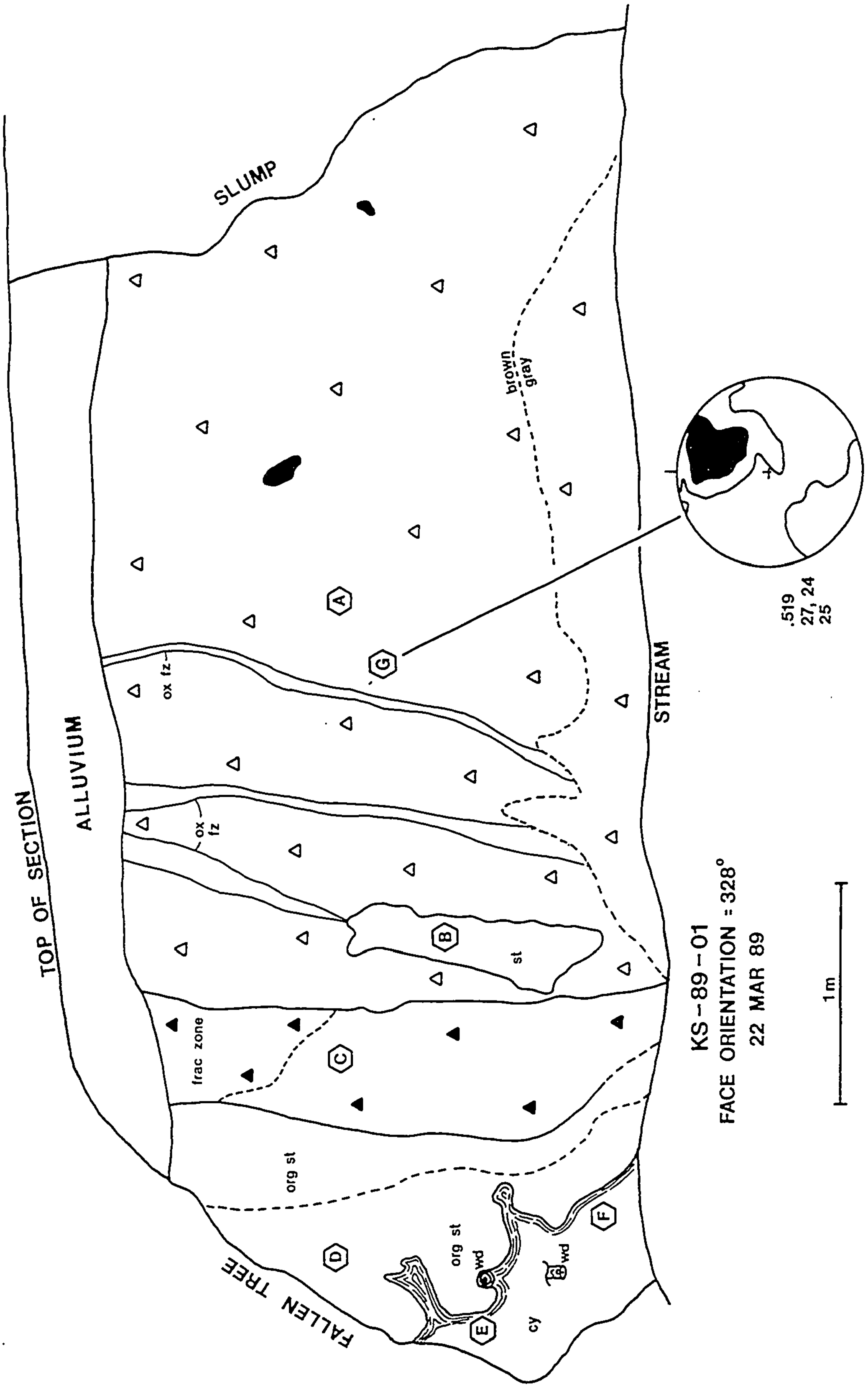

NW
Bulldozed terrace
covered
KS–88–08
ELDA LANDFILL
3b
1
fine sd/st
SE
1 m
1 m

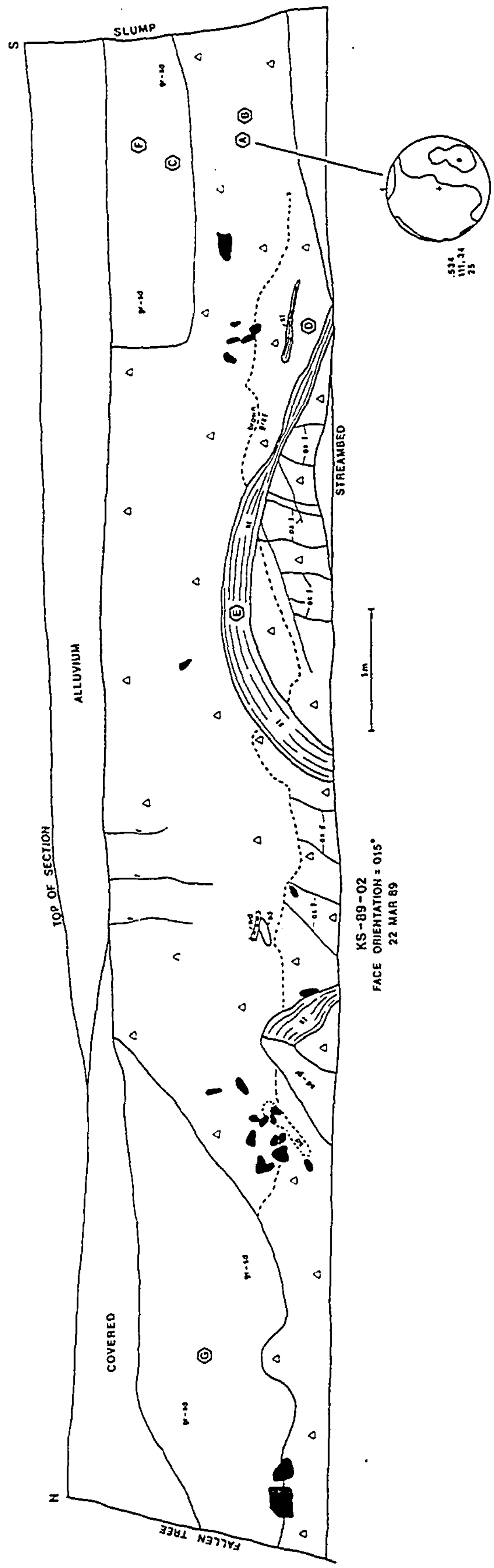

TOP OF EXPOSED SECTION
massive to poorly stratified
sand
massive
truncated bedding
cross-bedded
BASE OF EXCAVATION
KS-88-13
1 m
1 m

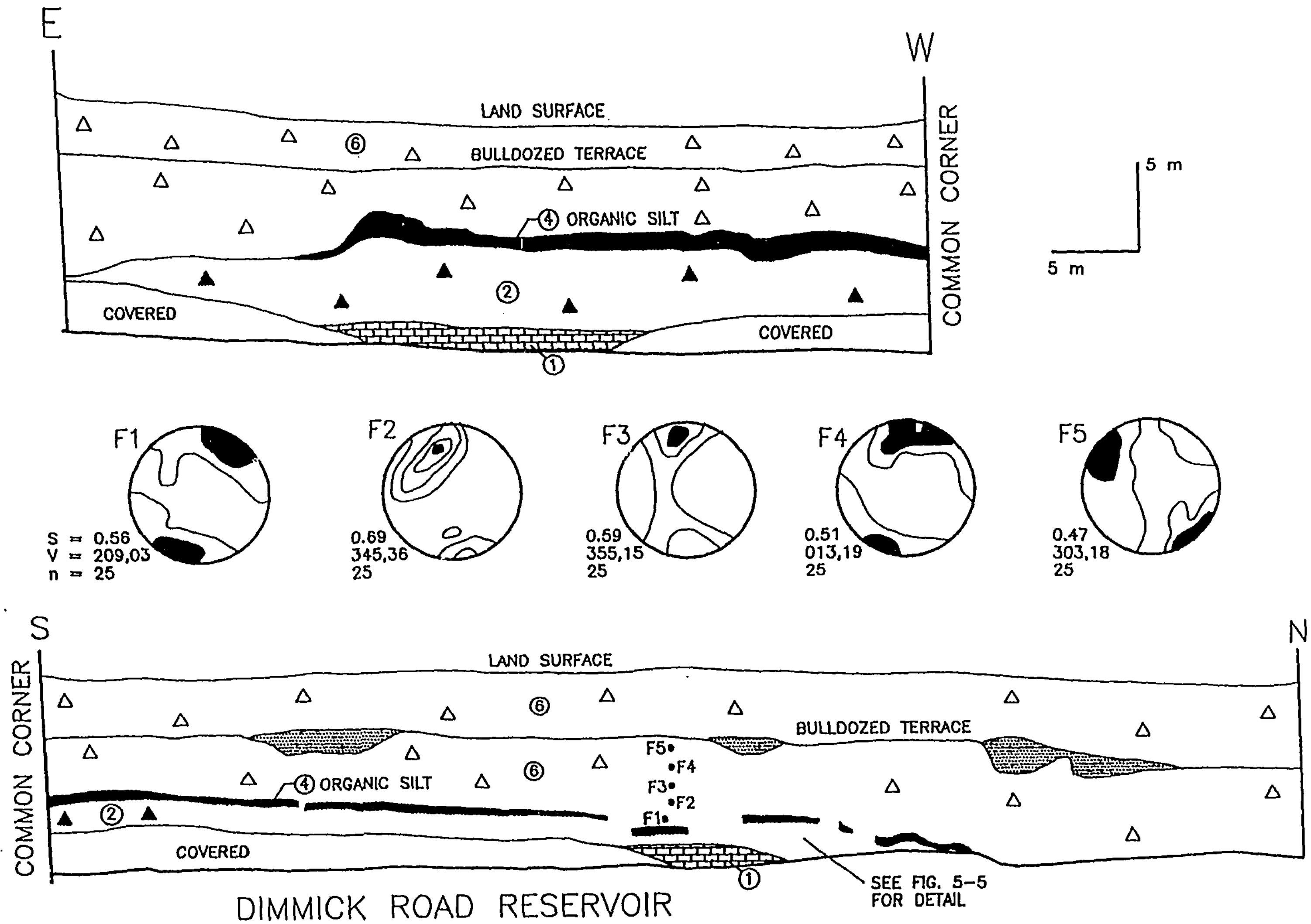

KS-88-14
SHARONVILLE
ALLUVIUM
COVERED
Stream
1 m
wood
2
3
or
wd
b
cy

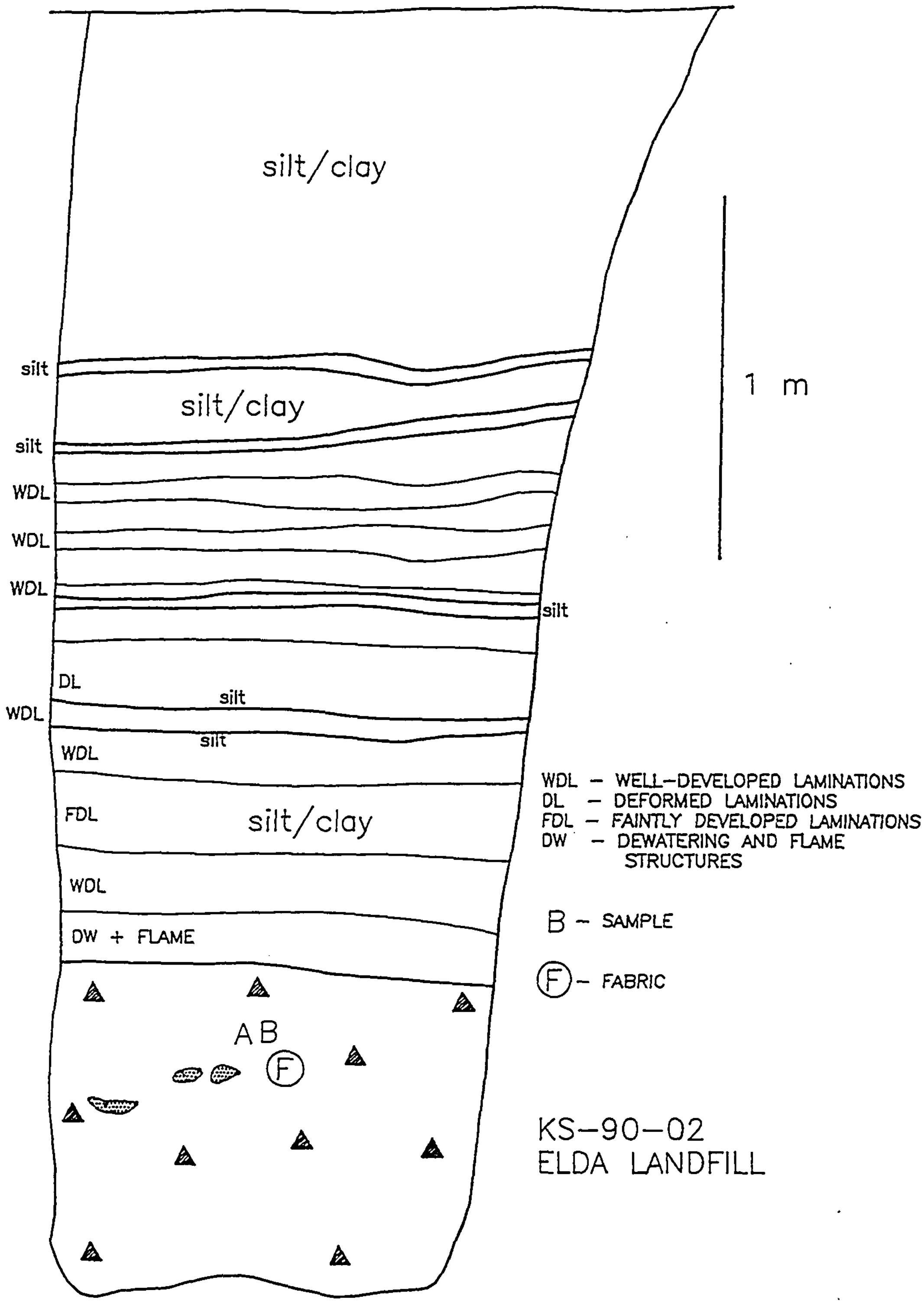


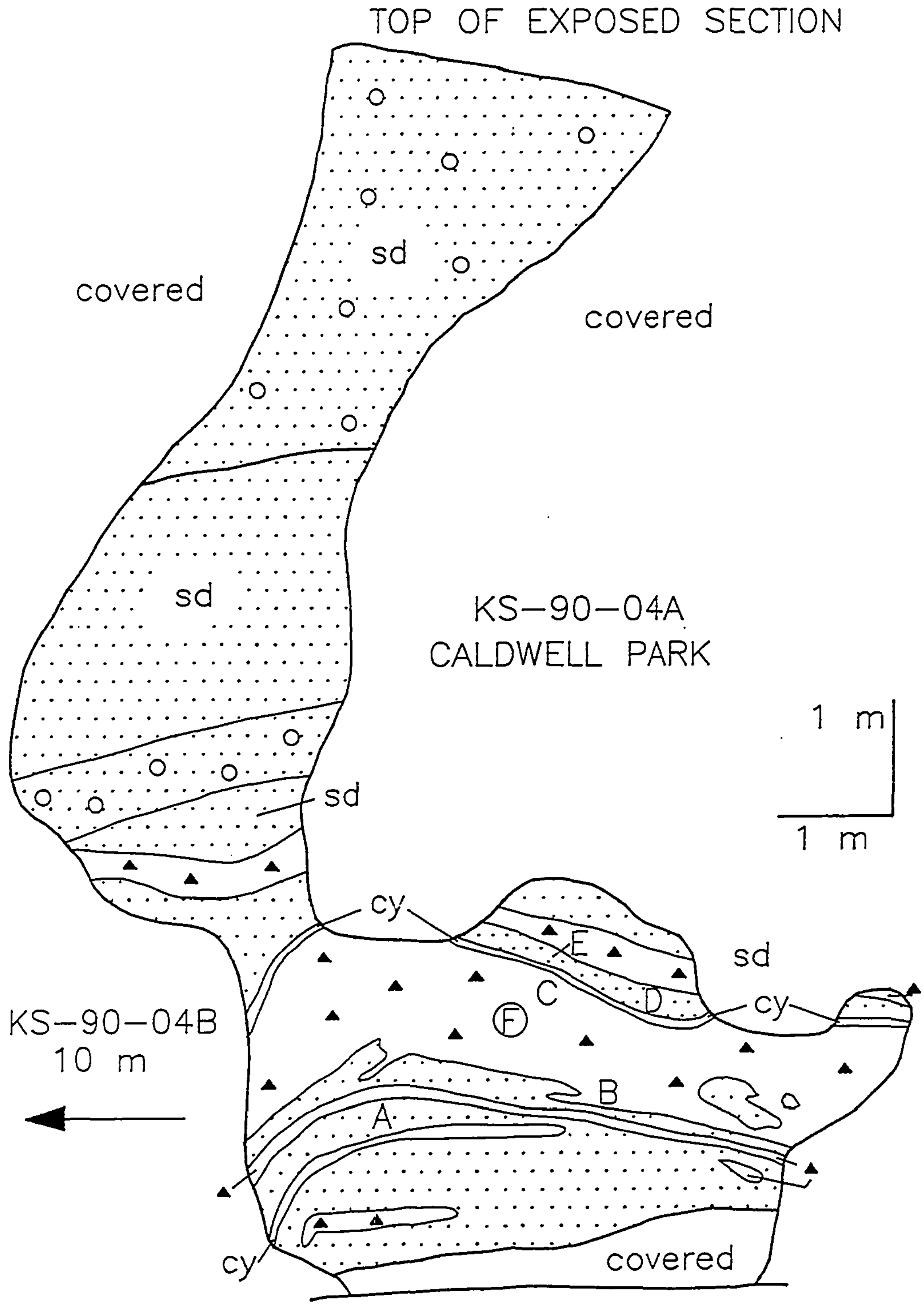
KS-88-18
FACE ORIENTATION =
22 NOV 88

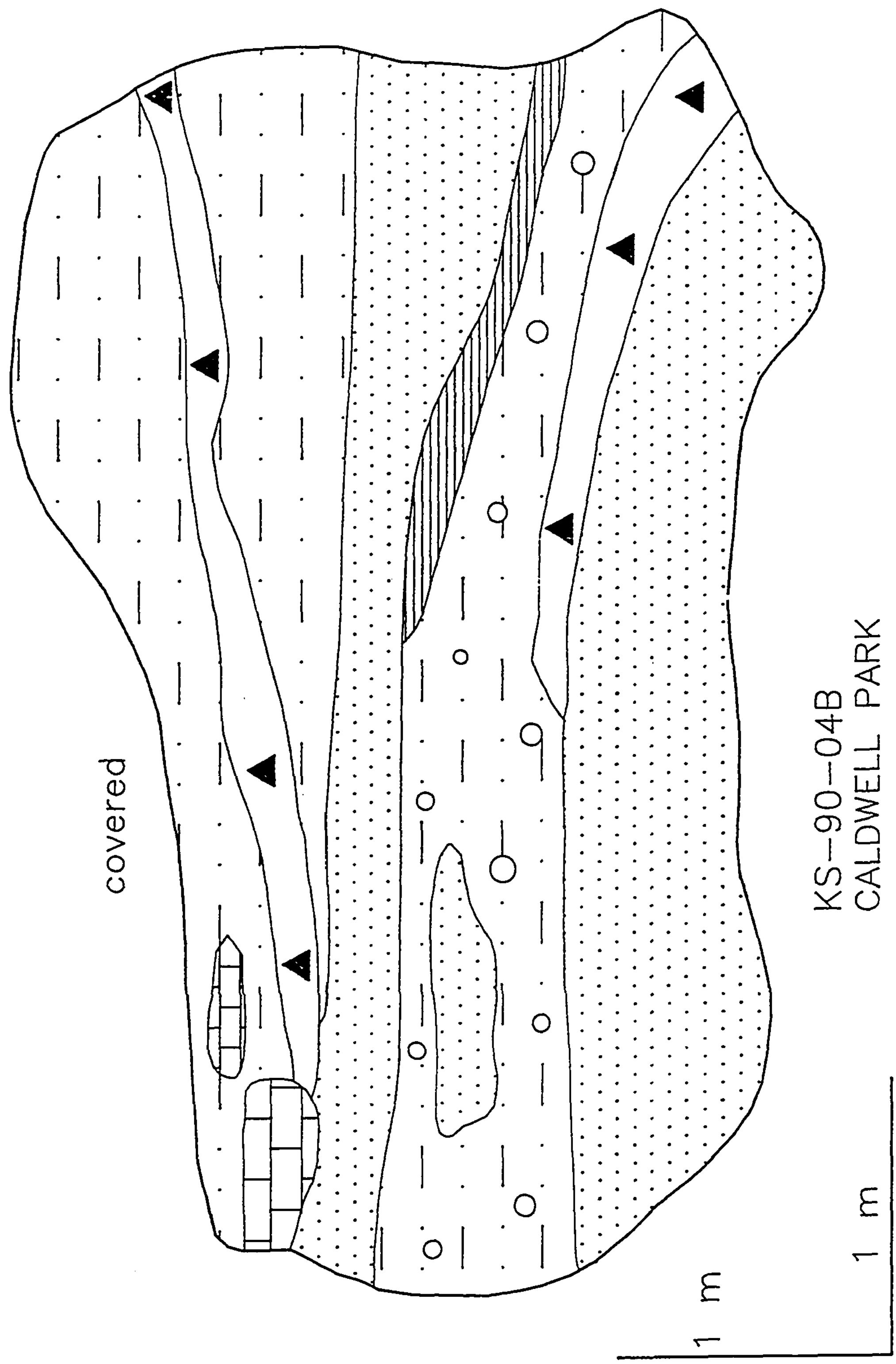

TOP OF SECTION
ALLUVIUM
SLUMP
STREAM
FALLEN TREE
brown
gray
ox fz
ox fz
frac zone
org st
org st
st
wd
wd
cy
A
B
C
D
E
F
G
.519
27, 24
25
KS-89-01
FACE ORIENTATION = 328°
22 MAR 89
1m

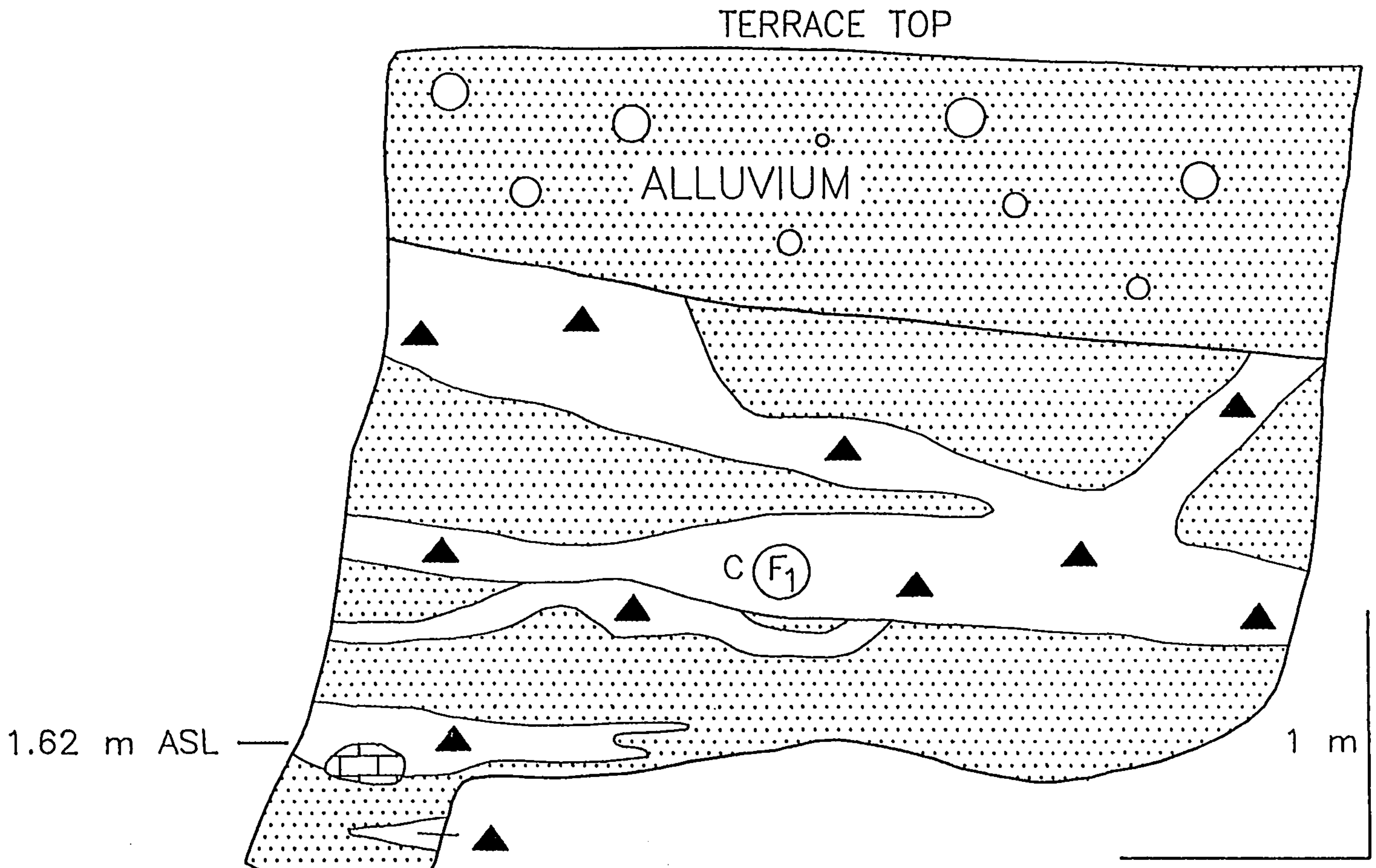

S
SLUMP
N
FALLEN TREE
TOP OF SECTION
ALLUVIUM
COVERED
STREAMBED
1m
KS-89-02
FACE ORIENTATION = 015°
22 MAR 89


E
W
LAND SURFACE
BULLDOZED TERRACE
ORGANIC SILT
COVERED
COVERED
COMMON CORNER
5 m
5 m
F1
S = 0.56
V = 209,03
n = 25
F2
0.69
345,36
25
F3
0.59
355,15
25
F4
0.51
013,19
25
F5
0.47
303,18
25
S
N
LAND SURFACE
BULLDOZED TERRACE
ORGANIC SILT
COVERED
COMMON CORNER
F5
F4
F3
F2
F1
SEE FIG. 5-5
FOR DETAIL
DIMMICK ROAD RESERVOIR

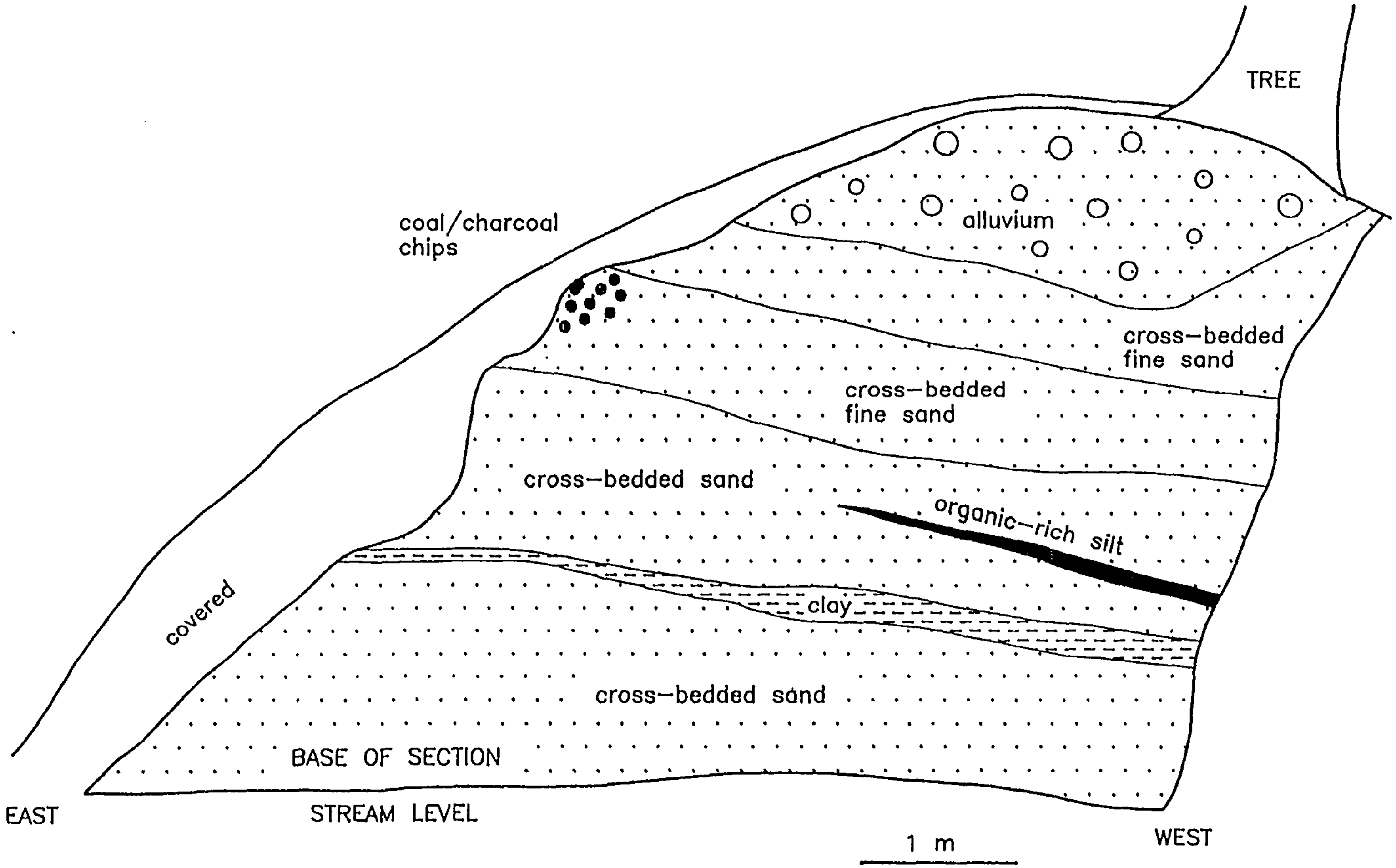

silt/clay
silt
silt/clay
silt
WDL
WDL
WDL
silt
DL
silt
WDL
silt
WDL
FDL
silt/clay
WDL
DW + FLAME
A B
F
1 m
WDL – WELL-DEVELOPED LAMINATIONS
DL – DEFORMED LAMINATIONS
FDL – FAINTLY DEVELOPED LAMINATIONS
DW – DEWATERING AND FLAME STRUCTURES
B – SAMPLE
F – FABRIC
KS-90-02
ELDA LANDFILL


TOP OF EXPOSED SECTION
covered
sd
covered
sd
KS–90–04A
CALDWELL PARK
1 m
1 m
sd
cy
E
sd
C
D
cy
F
KS–90–04B
10 m
B
A
cy
covered

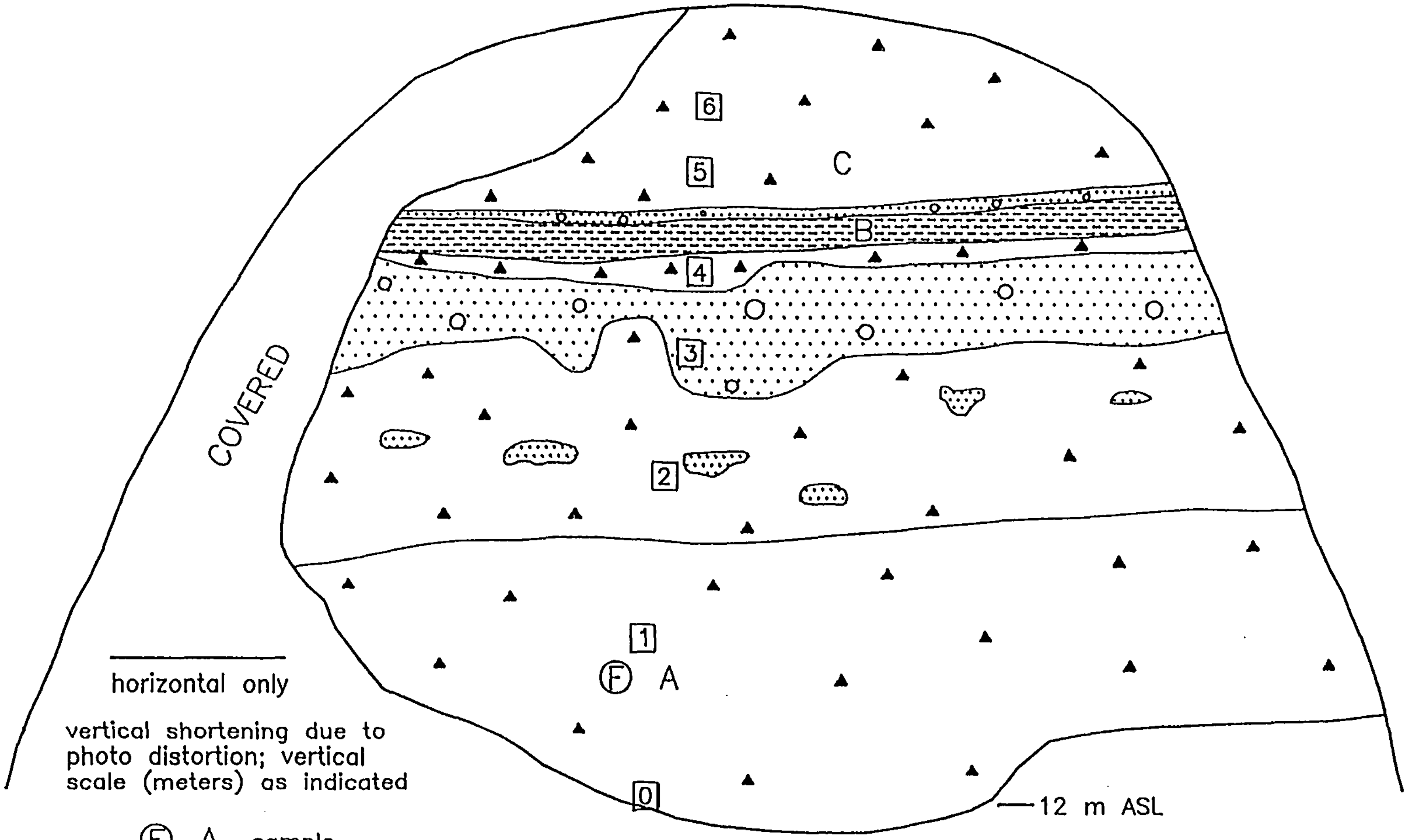

covered
KS-90-04B
CALDWELL PARK
1 m
1 m



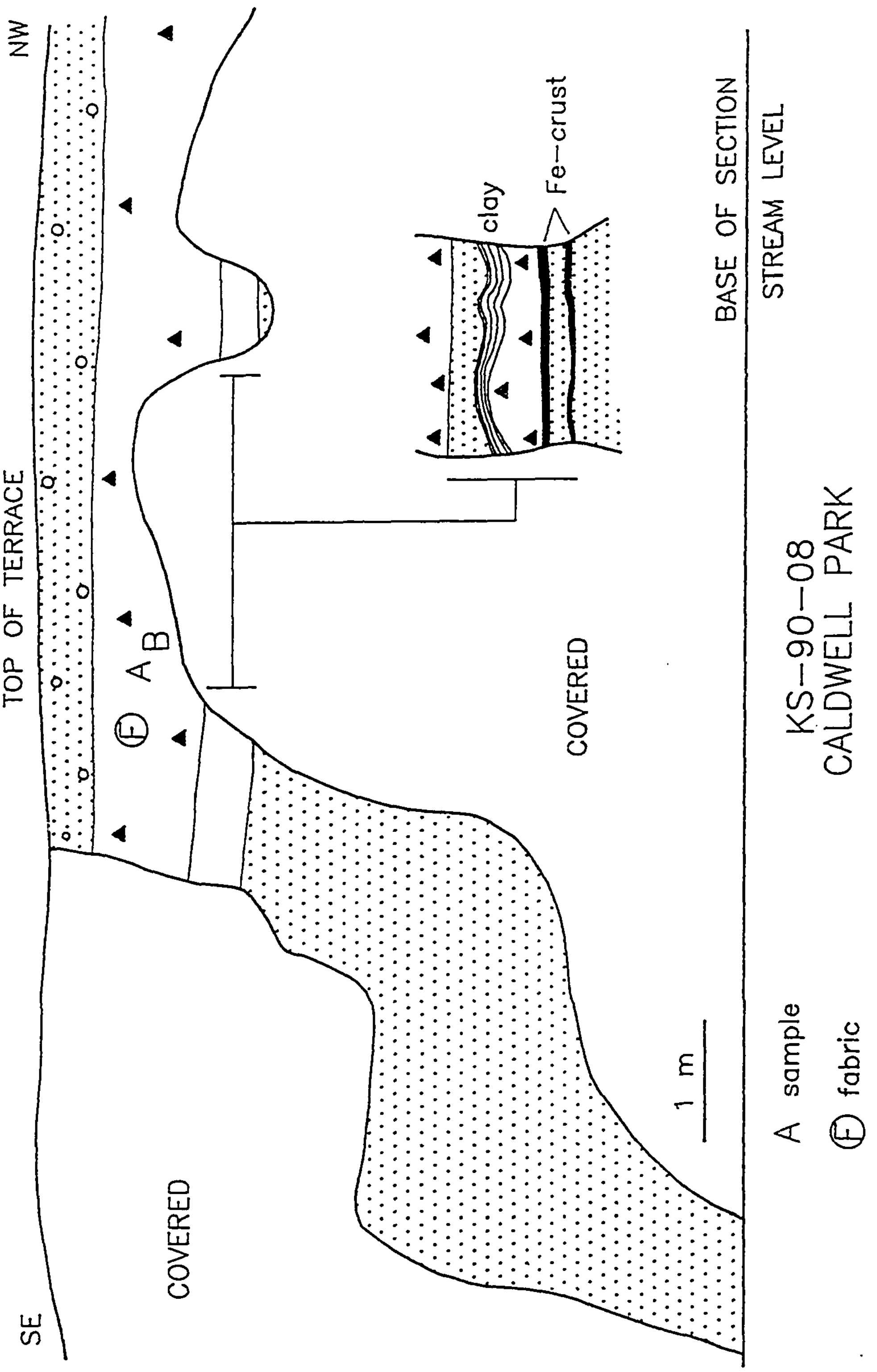
KS–90–05
CALDWELL PARK

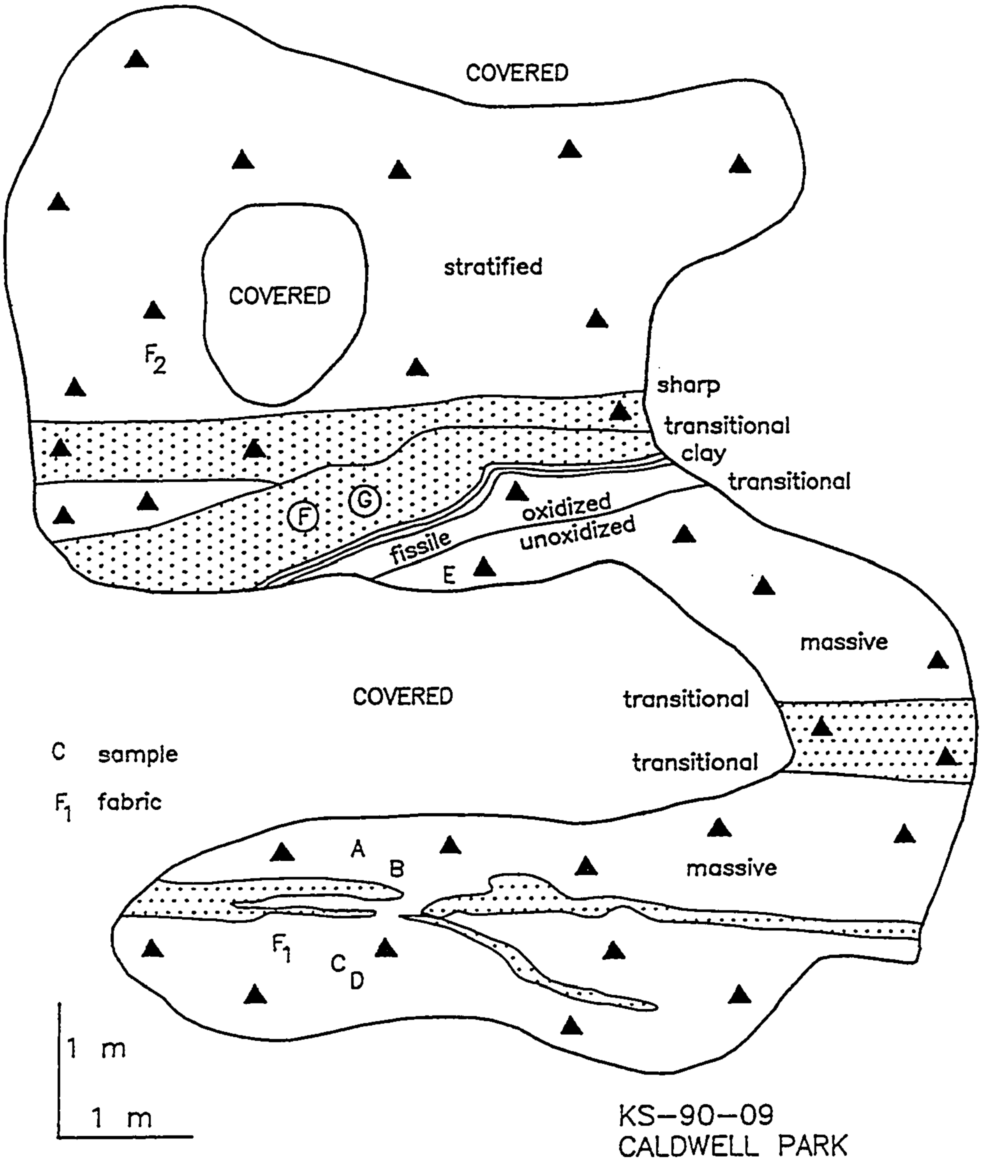


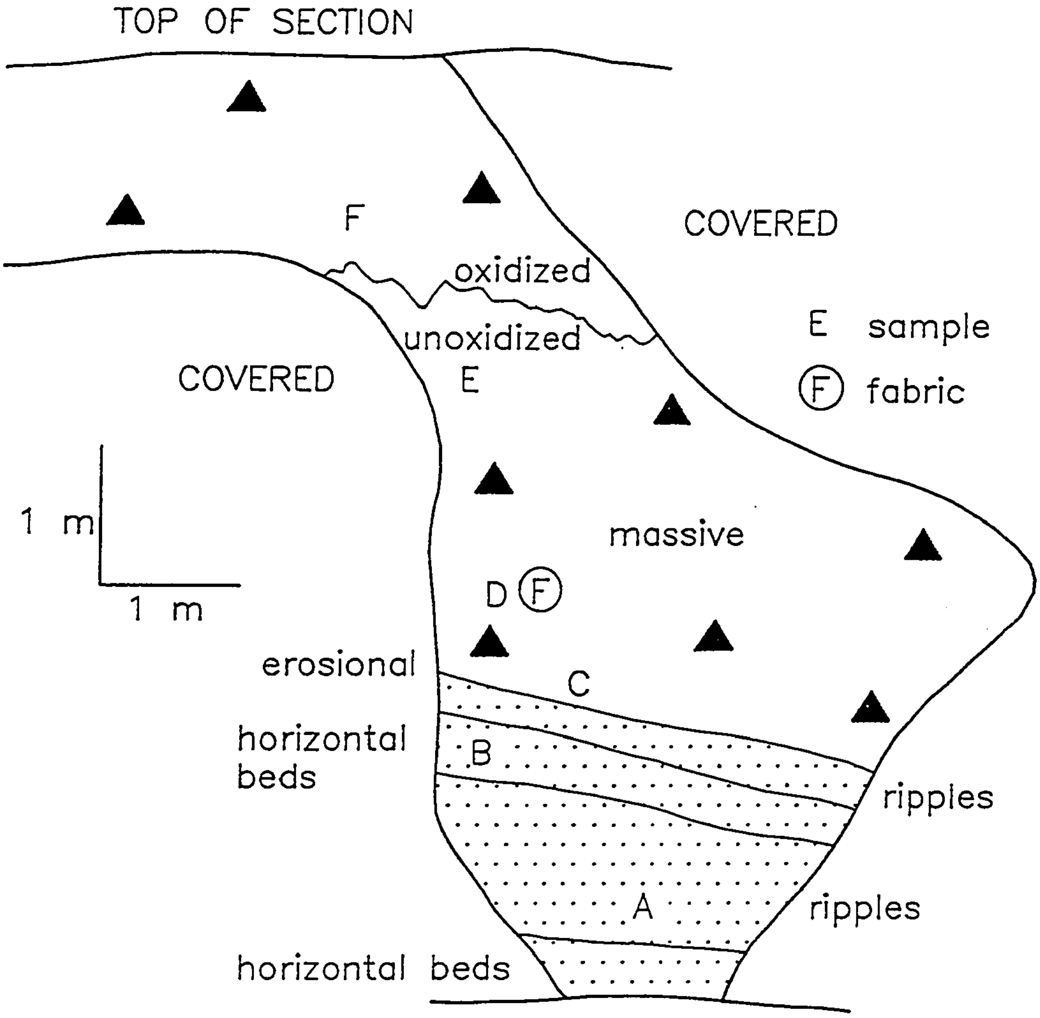
KS-90-06
CALDWELL PARK



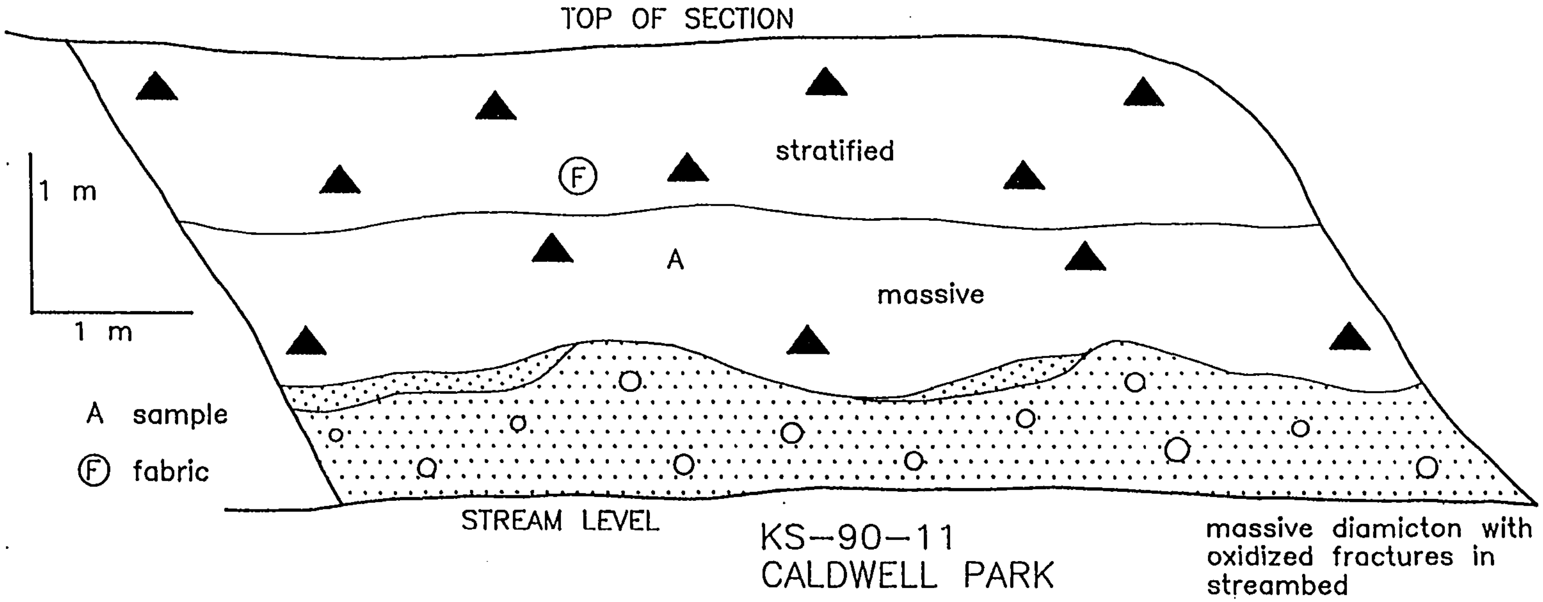
KS-90-07
CALDWELL PARK

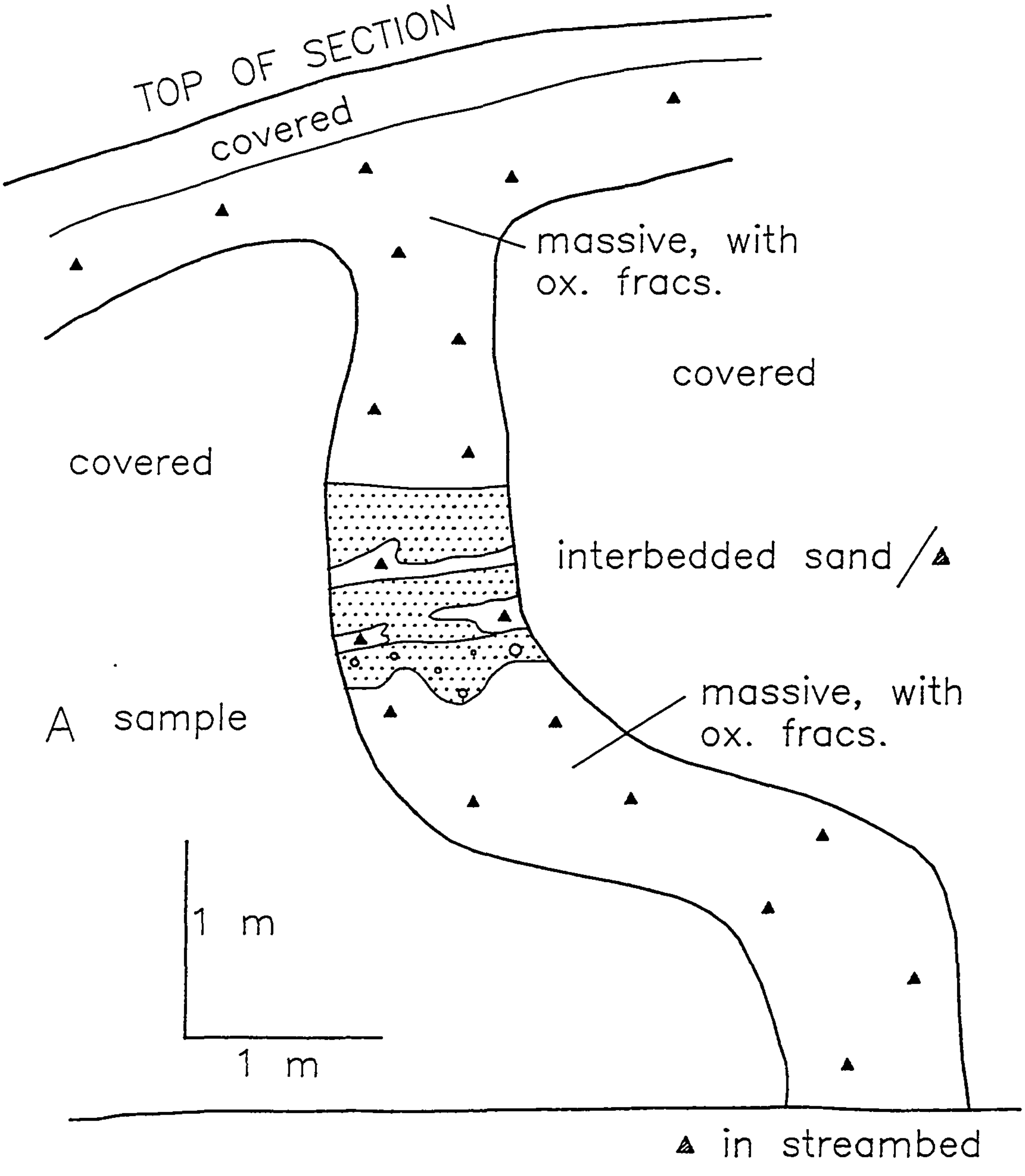

TOP OF TERRACE
NW
SE
COVERED
COVERED
A
B
clay
Fe-crust
BASE OF SECTION
STREAM LEVEL
KS-90-08
CALDWELL PARK
1 m
A sample
F fabric


COVERED
stratified
COVERED
F2
sharp
transitional
clay
transitional
oxidized
unoxidized
fissile
F
G
E
massive
COVERED
transitional
transitional
C sample
F1 fabric
A
B
massive
F1
C
D
1 m
1 m
KS-90-09
CALDWELL PARK

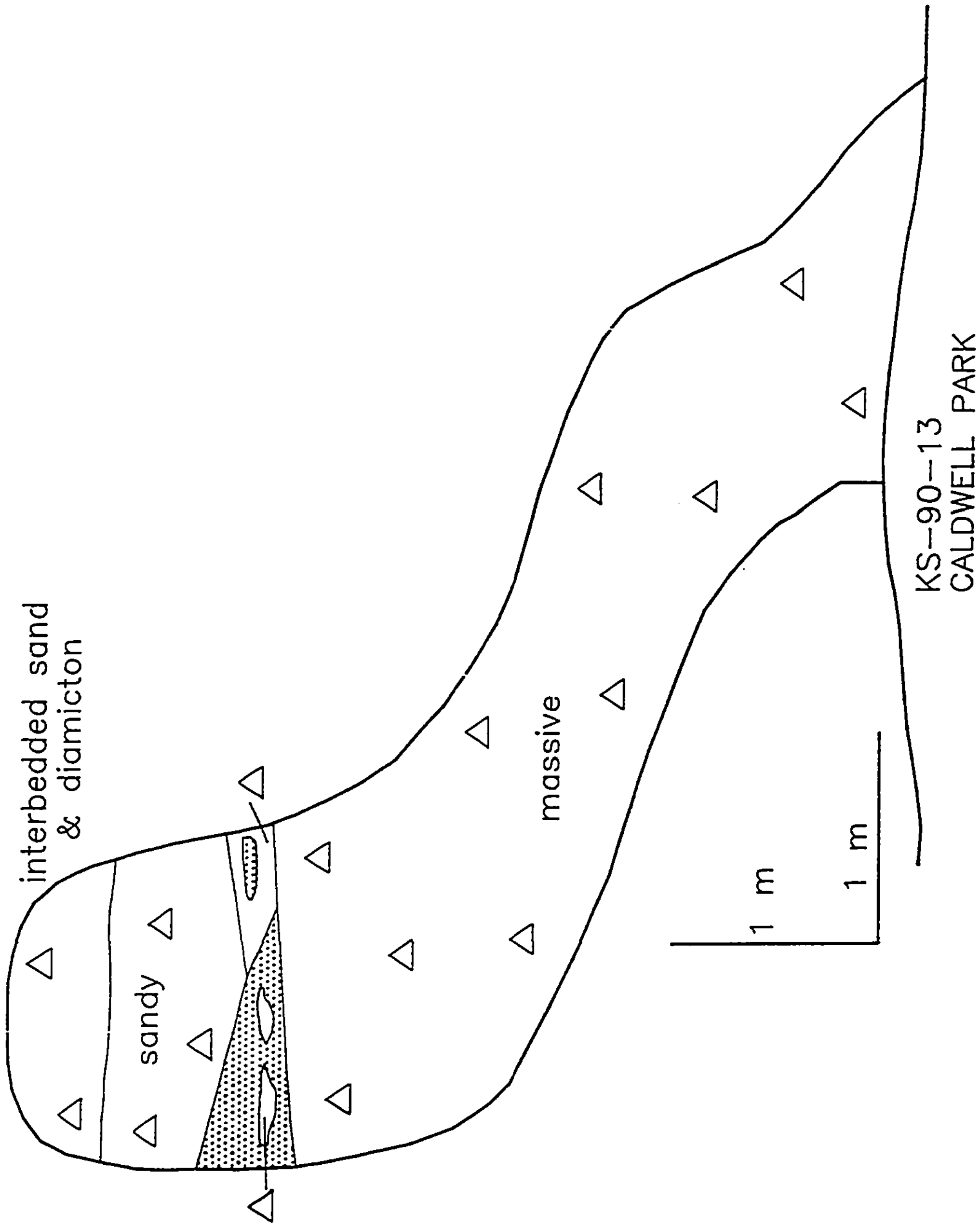


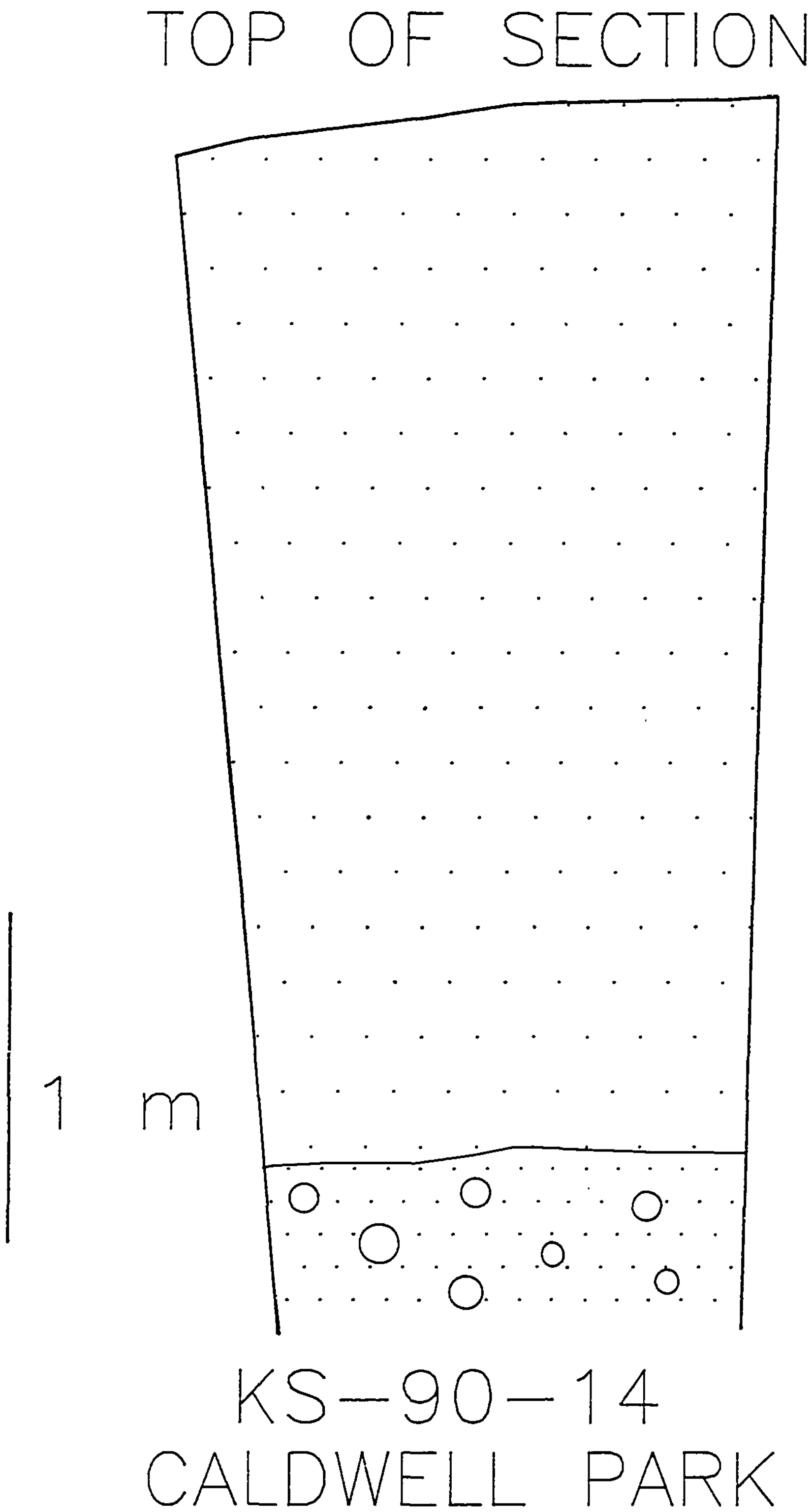
KS-90-10
CALDWELL PARK


TOP OF SECTION
stratified
massive
1 m
1 m
A
A sample
F fabric
STREAM LEVEL
KS-90-11
CALDWELL PARK
massive diamicton with oxidized fractures in streambed



KS–90–12
CALDWELL PARK


interbedded sand
& diamicton
sandy
massive
1 m
1 m
KS–90–13
CALDWELL PARK


TOP OF SECTION
1 m
KS-90-14
CALDWELL PARK

APPENDIX F.
ISOTOPIC AGE ESTIMATES

APPENDIX F. ISOTOPIC AGE ESTIMATES

SAMPLE	MATERIAL	GENUS	COMMON NAME	AGE ESTIMATE	LAB NUMBER	STRATIGRAPHIC POSITION	METHOD
SHARONVILLE							
TL-87-210-A	wood	*Picea*	spruce	22,550±275	PITT-0228	transported log in till	conventional RC
KS-88-03-A	wood	*Picea*	spruce	19,610±120	PITT-0352	transported log in till	conventional RC
KS-88-04-A	wood	*Picea*	spruce	21,450±170	PITT-0353	transported log in till	conventional RC
KS-88-06-A	wood	*Picea*	spruce	21,480±145	PITT-0354	transported log in till	conventional RC
KS-87-09-T	stump	*Larix*	tamarack	19,960±170	PITT-0227	stump rooted in organic silt	conventional RC
	stump	*Larix*	tamarack	19,310±170	PITT-0506	stump rooted in organic silt	conventional RC
	stump	*Larix*	tamarack	20,200±140	PITT-0507	stump rooted in organic silt	conventional RC
	stump	*Larix*	tamarack	19,200±140	PITT-0508	stump rooted in organic silt	conventional RC
	root	*Larix*	tamarack	19,690±150	PITT-0509	root in organic silt	conventional RC
KS-87-09-M	root	*Larix*	tamarack	21,945±180	PITT-0224	root in organic silt	conventional RC
KS-87-09-N	moss	---	---	21,120±130	PITT-0225	peat at base of stumps	conventional RC
KS-87-09-P	root	*Larix*	tamarack	21,570±180	PITT-0226	root in organic silt	conventional RC
KS-87-09-II	org. silt	---		26,490±300	PITT-0348	8 cm below top of unit	conventional RC
KS-87-09-JJ	org. silt	---		25,490±160	PITT-0349	20 cm below top of unit	conventional RC
KS-87-09-KK	org. silt	---		24,510±270	PITT-0350	35 cm below top of unit	conventional RC
KS-87-09-LL	org. silt	---		25,340±295	PITT-0351	47 cm below top of unit	conventional RC
GLENDALE							
KS-87-12-11	wood	no ID		15,740± 80	PITT-0231	transported log in till	conventional RC
TL-87-214-C	wood	*Picea*	spruce	20,210±145	PITT-0232	transported log in till	conventional RC
KS-87-12-5a	peat	---		19,500±115	PITT-0229	transported log in till	conventional RC
TL-87-214-DD	wood	*Salix*	willow	19,135±135	Beta-34385 ETH-6063	wood in organic "mat"	AMS RC
KS-87-12-7b	org. silt	---		36,650±980	PITT-0230	silt with organic mat	conventional RC
EVENDALE							
KS-87-04-AD	wood	no ID		35,550±880	PITT-0928	wood in diamicton	conventional RC
KS-87-04-AE	wood	no ID		39,830±1450	PITT-0929	wood in diamicton	conventional RC
RACK QUARRY							
RACK-BB	wood		juniper (?)	19,060±265	Beta-33943 ETH-5050	twig at top of peat	AMS RC
RACK-	wood		sedge (?)	19,470±115	PITT-0510	wood in middle of peat	conventional RC
RACK-BA	wood		juniper (?)	20,230±300	Beta-33944 ETH-5951	twig at base of peat	AMS RC
RACK-WW	$CaCO_3$ cement	---	---	46,536+1860 - 1830	MGS-540	cemented zone below modern water table	U/Th

APPENDIX G.
SUBSURFACE DRILLER'S AND BORING LOGS

APPENDIX G. SUBSURFACE DRILLER'S LOG DATA

Header Information:

Section Well Number:	Well Type:
Well Record Number:	Township:
Well Reference:	Other Well Reference:
Surface Elevation (ft):	Total Depth (ft):

Section Well Number: well number listed on cross-sections in Chapter 4 of this dissertation

Well Record Number: official well record number from the source of the log data (see **Well Reference** below)

Well Reference: source of the log data
ODNR - Ohio Dept. Natural Resources, Water Division, Columbus, OH
HCN - H.C. Nutting Co., Cincinnati, OH

Other Well Reference: USGS well designations for some wells

Section Well Number: 1	Well Type: Water
Well Record Number: 103	Township: Cinti 2
Well Reference: ODNR	Other Well Reference: USGS 273-1
Surface Elevation (ft): 493	Total Depth (ft): 105

Depth (ft)		
From	To	Description
0	9	yellow clay
9	13	sandy clay & gravel
13	38	blue clay
38	40	sand
40	51	blue clay
51	56	clay (gravel streaks)
56	65	well-bedded sand & gravel
65	91	clay
91	101	well-bedded sand & gravel
101	105	blue shale

Section Well Number: 2	Well Type: Water
Well Record Number: 262	Township: Cinti 2
Well Reference: ODNR	Other Well Reference: USGS 274
Surface Elevation (ft): 490	Total Depth (ft): 110

Depth (ft)		
From	To	Description
0	15	fill
15	22	muddy gravel
22	85	clay
85	89	fine sand, water
89	96	coarse gravel, sand, some clay, mixed water
96	108	clay
108	110	shale

Section Well Number: 3	Well Type: Water
Well Record Number: 33	Township: Cinti 2
Well Reference: ODNR	Other Well Reference: USGS 275
Surface Elevation (ft): 490	Total Depth (ft): 77

Depth (ft)		
From	To	Description
0	18	gravel
18	71	blue clay
71	77	gravel
77		rock

Section Well Number: 4
Well Record Number: 32
Well Reference: ODNR
Surface Elevation (ft): 500

Well Type: Water
Township: Cinti 2
Other Well Reference: USGS 276
Total Depth (ft): 90

Depth (ft) From	To	Description
0	8	clay
8	15	yellow sand
15	18	sand
18	40	blue clay
40	43	sand
43	72	blue clay
72	78	sand
78	80	hard pan
80	90	blue clay

Section Well Number: 5
Well Record Number: 569
Well Reference: ODNR
Surface Elevation (ft): 512

Well Type: Water
Township: Cinti 2
Other Well Reference:
Total Depth (ft): 138

Depth (ft) From	To	Description
0	6	fill
6	12	muddy gravel
12	65	blue clay
65	75	gray quick sand
75	90	red sand
90	98	brown coarse sand
98	115	yellow sand
115	132	clean sand & gravel
132	138	good sand and gravel

Section Well Number: 6
Well Record Number: 279279
Well Reference: ODNR
Surface Elevation (ft): 518

Well Type: Water
Township: Cinti 2
Other Well Reference:
Total Depth (ft): 130

Depth (ft) From	To	Description
0	10	fill clay & wood
10	30	gray clay
30	85	gray clay
85	95	dirty sand
95	100	large gravel
100	105	medium sand
105	110	medium sand
110	120	medium sand
120	128	coarse sand
128	129.3	coarse gravel
129.3	130	rock

Section Well Number: 7
Well Record Number: 531
Well Reference: ODNR
Surface Elevation (ft): 512

Well Type: Water
Township: Cinti 2
Other Well Reference:
Total Depth (ft): 140

Depth (ft) From	To	Description
0	6	yellow clay
6	12	yellow clay & gravel
12	18	gray muddy gravel
18	42	gray clay
42	65	sandy clay
65	70	red quick sand
70	80	yellow quick sand
80	92	gray quick sand
92	100	brown sand & gravel
100	118	yellow sand & gravel
118	138	clean sand & gravel
138	140	coarse sand & gravel

Section Well Number: 8
Well Record Number: BRG-5
Well Reference: HCN
Surface Elevation (ft): 532.8

Well Type: Construction
Township:
Other Well Reference:
Total Depth (ft): 81.5

Depth (ft) From	To	Description
0	10	clayey silty sand (fill)
10	15	silty sand
15	17.5	sandy gravel
17.5	19	fine to coarse sand
19	21.5	silty fine to coarse sand
21.5	31.5	fine to coarse sand
31.5	36.5	fine sand
36.5	45	fine to coarse sand
45	76.5	silty clay (varved)
76.5	81.5	sandy silty clay

Section Well Number: 9
Well Record Number: B-6-1
Well Reference: HCN
Surface Elevation (ft): 534.8

Well Type: Construction
Township:
Other Well Reference:
Total Depth (ft): 98

Depth (ft) From	To	Description
0	1	asphalt
1	5	silty clay (fill)
5	9	fine-coarse sand & gravel
9	15	silty sand
15	20	fine-coarse sand & gravel
20	24	fine to coarse sand
24	45	silty clay w/ silt lenses
45	54	silt
54	74	silty clay
74	84	silty sand w/ sand seams
84	85	sandy silt
85	90	silty clay
90	95	silt with clay layers
95	98	silty sand

Section Well Number: 10
Well Record Number: B-9-4
Well Reference: HCN
Surface Elevation (ft): 529.8

Well Type: Construction
Township:
Other Well Reference:
Total Depth (ft): 61.7

Depth (ft) From	To	Description
0	2.7	silty clay w/ sand seams
2.7	7	clayey silt
7	10.2	fine to coarse sand
10.2	12.7	gravelly sand
12.7	15.2	gravelly silty sand
15.2	19.2	silty sand
19.2	25.2	fine-coarse sand & gravel
25.2	30.2	silty sand
30.2	45.2	silt with sand seams
45.2	47.2	silt
47.2	61.7	clayey silt

Section Well Number: 11
Well Record Number: 571201
Well Reference: ODNR
Surface Elevation (ft): 565

Well Type: Water
Township: Sycamore
Other Well Reference:
Total Depth (ft): 168

Depth (ft) From	To	Description
0	20	clay
20	32	clay w/ limestone boulders
32	56	clay
56	86	sand & gravel
86	113	clay
113	155	fine to medium sand
155	165	coarse sand & gravel
165		bedrock?

Section Well Number: 12
Well Record Number: 142762
Well Reference: ODNR
Surface Elevation (ft): 550

Well Type: Water
Township: Sycamore
Other Well Reference:
Total Depth (ft): 141

Depth (ft) From	To	Description
0	21	yellow clay and gravel
21	36	yellow clay
36	46	dry gravel
46	87	sandy blue clay
87	101	fine muddy sand
101	141	brown sand

Section Well Number: 13	Well Type: Water
Well Record Number: 142780	Township: Sycamore
Well Reference: ODNR	Other Well Reference:
Surface Elevation (ft): 552	Total Depth (ft): 160+

Depth (ft) From	To	Description
0	2	top soil
2	20	dry gravel, blue clay, stray rock
20	31	blue clay
31	35	yellow clay
35	45	blue clay and gravel
45	83	yellow loam
83	107	fine brown sand
107	157	fine gray sand
157	160	fine gray sand w/ some gravel
160	?	clay

Section Well Number: 14	Well Type: Water
Well Record Number: 230003	Township: Sycamore
Well Reference: ODNR	Other Well Reference:
Surface Elevation (ft): 550	Total Depth (ft): 150+

Depth (ft) From	To	Description
0	15	clay
15	21	dry sand & gravel
21	32	blue clay
32	45	medium brown sand
45	53	medium gray sand
53	58	blue clay
58	61	sharp gravel
61	70	fine gray sand
70	76	fine gray sand, some gravel
76	85	blue clay
85	95	fine sand mixed w/ clay
95	103	coarse sand, little gravel
103	106	fine sand
106	114	blue clay
114	126	medium brown sand
126	131	medium sand, some gravel
131	133	blue clay
133	141	medium coarse sand, some gravel
141	146	medium sand
146	150	medium fine sand
150	?	blue ?

Section Well Number: 15

Well Record Number: 593202

Well Reference: ODNR

Surface Elevation (ft): 551

Well Type: Water

Township: Sycamore

Other Well Reference:

Total Depth (ft): 184

Depth (ft) From	To	Description
0	1	fill
1	10	gray clay
10	25	dark sandy clay
25	45	sand and gravel
45	55	gray clay
55	75	clay w/ sand & gravel
75	100	fine sand w/ gravel
100	115	fine sand
115	130	coarse sand
130	140	coarse sand w/ gravel
140	183	coarse sand w/ gravel
183	184	gray shale

Section Well Number: 16

Well Record Number: 198167

Well Reference: ODNR

Surface Elevation (ft): 550

Well Type: Water

Township: Springfield

Other Well Reference:

Total Depth (ft): 185

Depth (ft) From	To	Description
0	4	top soil
4	23	dry muddy gravel
23	37	blue clay
37	45	dry muddy gravel
45	61	clay & sand
61	87	blue clay
87	94	yellow muddy gravel
94	129	fine gray sand
129	161	medium sand
161	173	fine sand & small gravel
173	185	shale

Section Well Number: 17
Well Record Number: 142764
Well Reference: ODNR
Surface Elevation (ft): 560

Well Type: Water
Township: Sycamore
Other Well Reference:
Total Depth (ft): 201

Depth (ft) From	To	Description
0	10	yellow clay and fill
10	18	yellow clay
18	20	muddy gravel
20	33	blue clay
33	40	brown clay & gravel
40	50	blue clay & gravel
50	74	muddy brown sand
74	77	sand & some gravel
77	80	sandy clay
80	86	yellow clay and gravel
86	128	sand
128	190	gray sand
190	199	sand & gravel
199	201	shale

Section Well Number: 18
Well Record Number: 358264
Well Reference: ODNR
Surface Elevation (ft): 569

Well Type: Water
Township: Sycamore
Other Well Reference:
Total Depth (ft): 185

Depth (ft) From	To	Description
0	8	well pit
8	20	yellow clay
20	31	yellow sand
31	80	blue clay
80	125	fine sand & small gravel
125	140	fine brown sand
140	176	fine gray sand
176	185	fine sand & small gravel

Section Well Number: 19 | Well Type: Water
Well Record Number: 51743 | Township: Springfield
Well Reference: ODNR | Other Well Reference:
Surface Elevation (ft): 572 | Total Depth (ft): 194

Depth (ft) From	To	Description
0	6	top soil
6	68	muddy gravel
68	74	gravel - water bearing
74	85	blue clay
85	88	fine sand
88	114	brown loam
114	125	muddy fine sand
125	145	muddy gravel
145	156	sand
156	194	sand & gravel

Section Well Number: 20 | Well Type: Water
Well Record Number: 348944 | Township: Sycamore
Well Reference: ODNR | Other Well Reference:
Surface Elevation (ft): 578 | Total Depth (ft): 199

Depth (ft) From	To	Description
0	10	overlay [?]
10	18	sandy gray clay
18	65	blue clay & gravel
65	75	sand & gravel
75	90	fine sand & gravel
90	100	fine sand & gravel
100	130	blue clay & sand
130	145	brown clay & sand
145	170	fine sand
170	179	medium sand & gravel
179	185	fine sand & gravel
185	199	medium sand & gravel

Section Well Number: 21 | Well Type: Water
Well Record Number: 497761 | Township: Sycamore
Well Reference: ODNR | Other Well Reference:
Surface Elevation (ft): 585 | Total Depth (ft): 70

Depth (ft) From	To	Description
0	2	blacktop & gravel
2	9	clay
9	32	yellow clay & gravel
32	67	sand & gravel
67	70	blue clay

Section Well Number: 22
Well Record Number: 348909
Well Reference: ODNR
Surface Elevation (ft): 530

Well Type: Water
Township: Cinti 2
Other Well Reference:
Total Depth (ft): 134

Depth (ft) From	To	Description
0	3	fill dirt
3	14	sand & pea gravel
14	92	blue & gray clay
92	98	dirty gray sand
98	114	fine brown sand & gravel
114	130	fine brown sand & gravel
130	134	coarse gray sand & gravel
134		hard pan

Section Well Number: 23
Well Record Number: 56
Well Reference: ODNR
Surface Elevation (ft): 625

Well Type: Water
Township: Columbia
Other Well Reference: USGS 315-2
Total Depth (ft): 205

Depth (ft) From	To	Description
0	10	yellow clay, some rock
10	30	blue clay, some rock
30	90	blue clay, gravel, stone
90	100	hard pan
100	110	sandy loam
110	140	fine sand, no water
140	150	gravel, rock, coarse stone
150	170	sand & gravel
170	185	coarse sand & gravel
185	205	hard blue & yellow clay
205		rock

Section Well Number: 24
Well Record Number: 198153
Well Reference: ODNR
Surface Elevation (ft): 639

Well Type: Water
Township: Columbia
Other Well Reference:
Total Depth (ft): 180

Depth (ft) From	To	Description
0	4	top soil
4	38	yellow clay
38	40	blue clay and gravel
40	115	blue clay
115	140	green clay
140	165	blue clay
165	175	yellow clay
175	180	blue shale

Section Well Number: 25
Well Record Number: 77
Well Reference: ODNR
Surface Elevation (ft): 614

Well Type: Water
Township: Columbia
Other Well Reference: USGS 317-26
Total Depth (ft): 245

Depth (ft) From	To	Description
0	25	yellow clay
25	134	blue clay
134	148	sand
148	149	hard pan
149	245	sand

Section Well Number: 26
Well Record Number: 279288
Well Reference: ODNR
Surface Elevation (ft): 560

Well Type: Water
Township: Springfield
Other Well Reference:
Total Depth (ft): 177

Depth (ft) From	To	Description
0	24	brown clay gravel
24	26	gravel
26	39	blue clay gravel
39	42	water gravel
42	57	blue clay
57	67	dirty sand - dry
67	112	dry sand
112	135	water sand
135	148	coarse sand
148	177	sand gravel
177		blue shale

Section Well Number: 27 | Well Type: Construction
Well Record Number: B-10-7 | Township:
Well Reference: HCN | Other Well Reference:
Surface Elevation (ft): 535.4 | Total Depth (ft): 92

Depth (ft) From	To	Description
0	1.5	sandy silty clay (fill)
1.5	5	silty clay
5	7	silty sand
7	9	clayey sand
9	15	fine-coarse sand & gravel w/ rock fragments and cobbles
15	20	gravelly sand w/ rock fragments
20	28.5	medium-coarse sand & gravel, some cobbles
28.5	35	silty clay w/ silt seams
35	55	silty clay w/ organic traces & sand seams
55	64	silty sand
64	70	gravelly sand
70	75	silty sand
75	80	silty sand
80	85	fine to coarse sand
85	90	silty sand w/ fine gravel
90	92	gravelly silty sand

Section Well Number: 28 | Well Type: Construction
Well Record Number: B-11-7 | Township:
Well Reference: HCN | Other Well Reference:
Surface Elevation (ft): 535.1 | Total Depth (ft): 92

Depth (ft) From	To	Description
0	5	sandy silty clay (fill)
5	10	silty clay
10	12	sandy gravel, some cobbles
12	15	sandy gravel w/ rock fragments & some cobbles
15	20	silt
20	35	silty clay
35	39	clayey sand w/ fine gravel
39	45	fine to coarse sand
45	50	fine sand
50	55	fine to coarse sand
55	70	fine to coarse sand
70	75	silty sand
75	80	silty sand
80	85	fine to coarse sand
85	90	silty sand
90	92	fine sand

Section Well Number: 29 | Well Type: Construction
Well Record Number: B-13-2 | Township:
Well Reference: HCN | Other Well Reference:
Surface Elevation (ft): 569.8 | Total Depth (ft): 56

Depth (ft)

From	To	Description
0	2	cinders and gravel (fill)
2	5	sandy silty clay
5	7	silty clay
7	14.5	sandy silty clay w/ rock fragments
14.5	15.5	silty sand w/ trace gravel
15.5	17	silty sand w/ gravel seams
17	22.5	silty sand & gravel
22.5	25	sandy gravel
25	30	sandy gravel w/ silt layers
30	34	gravelly silty sand
34	40	silt w/ trace organics
40	43	silt
43	43.8	boulder
43.8	50	clayey silt w/ rock fragments
50	53	clayey silt
53	56	shale

Section Well Number: 30 | Well Type: Construction
Well Record Number: B-13-5 | Township:
Well Reference: HCN | Other Well Reference:
Surface Elevation (ft): 574.4 | Total Depth (ft): 30

Depth (ft)

From	To	Description
0	3	silty clay, cinders (fill)
3	15	silty clay
15	17.5	clayey sand & gravel, rock fragments & cobbles
17.5	20	silty clay
20	30	shale w/ limestone fragments

Section Well Number: 31 | Well Type: Construction
Well Record Number: B-14-5 | Township:
Well Reference: HCN | Other Well Reference:
Surface Elevation (ft): 614.4 | Total Depth (ft): 31

Depth (ft)

From	To	Description
0	2	sandy silty clay (fill)
2	31	shale & limestone fragments

Section Well Number: 32 | Well Type: Water
Well Record Number: 342965 | Township: Springfield
Well Reference: ODNR | Other Well Reference:
Surface Elevation (ft): 578 | Total Depth (ft): 187

Depth (ft) From	To	Description
0	4	top soil
4	19	yellow clay
19	56	blue sandy clay w/ boulders, mixed
56	72	blue clay and gravel
72	106	blue clay, boulders, mixed
106	119	blue clay
119	120	blue clay, gravel
120	131	hard pan, gravel & clay mixed
131	138	light gravel w/ hard pan
138	163	light fine sand
163	177	coarse sand w/ medium gravel
177	182	coarse sand & small gravel
182	187	coarse sand

Section Well Number: 33 | Well Type: Water
Well Record Number: 348924 | Township: Springfield
Well Reference: ODNR | Other Well Reference:
Surface Elevation (ft): 572 | Total Depth (ft): 195

Depth (ft) From	To	Description
0	27	overlay [?]
27	40	gray fine sand
40	55	blue clay
55	75	gray sand & pea gravel
75	93	blue clay
93	130	gray sand & pea gravel
130	180	gray sand
180	193	gray sand & pea gravel
193		195 blue clay

Section Well Number: 34 | Well Type: Water
Well Record Number: 593201 | Township: Sycamore
Well Reference: ODNR | Other Well Reference:
Surface Elevation (ft): 560 | Total Depth (ft): 171

Depth (ft) From	To	Description
0	8	clay
8	13	clay & boulders
13	105	clay w/ boulders & hard pan layers
105	127	fine gray sand
127	170	medium fine gray sand
170	171	gray shale

Section Well Number: 35 | Well Type: Construction
Well Record Number: Boring 1 | Township:
Well Reference: HCN | Other Well Reference:
Surface Elevation (ft): 652 | Total Depth (ft): 21.5

Depth (ft) From	To	Description
0	2.5	silty clay, trace sand
2.5	5	lean clay
5	10	clay, traces of sand and fine gravel
10	13.5	lean clay with sand and gravel, shale fragments
13.5	20	sandy lean clay with gravel
20	21.5	poorly graded sand with gravel and silt

Section Well Number: 36 | Well Type: Construction
Well Record Number: Boring 2 | Township:
Well Reference: HCN | Other Well Reference:
Surface Elevation (ft): 672 | Total Depth (ft): 41.5

Depth (ft) From	To	Description
0	2.5	silty clay, traces of sand
2.5	5	lean clay
5	10	clay, traces of sand and gravel, shale fragments
10	15	lean clay with sand and gravel
15	17.5	clay with sand and gravel
17.5	20	sandy lean clay with gravel
20	25	sandy lean clay with gravel, limestone fragments
25	30	clayey sand with gravel
30	35	rock (no recovery)
35	41	poorly graded sand with silt
41	41.5	sandy silty clay with gravel

Section Well Number: 37 | Well Type: Construction
Well Record Number: Boring 3 | Township:
Well Reference: HCN | Other Well Reference:
Surface Elevation (ft): 732 | Total Depth (ft): 13.5

Depth (ft) From	To	Description
0	5	lean clay with trace sand, shale and limestone fragments
5	7.5	lean clay
7.5	10	lean clay with shale fragments
10	13.5	weathered shale with limestone fragments

Section Well Number: 38	Well Type: Construction
Well Record Number: Boring 4	Township:
Well Reference: HCN	Other Well Reference:
Surface Elevation (ft): 696	Total Depth (ft): 12.5

Depth (ft) From	To	Description
0	2.5	silty clay
2.5	5	lean clay
5	7.5	clay, traces of sand and gravel
7.5	12.5	clay

Section Well Number: 39	Well Type: Construction
Well Record Number: Boring 5	Township:
Well Reference: HCN	Other Well Reference:
Surface Elevation (ft): 775	Total Depth (ft): 5.5

Depth (ft) From	To	Description
0	2.5	silty clay
2.5	4.5	lean clay, traces of rock fragments
4.5	5.5	highly weathered shale

Section Well Number: 40	Well Type: Construction
Well Record Number: Boring 6	Township:
Well Reference: HCN	Other Well Reference:
Surface Elevation (ft): 752	Total Depth (ft): 14

Depth (ft) From	To	Description
0	5	lean clay, traces of sand
5	7.5	clay, traces of limestone
7.5	14	highly weathered shale

Section Well Number: 41	Well Type: Construction
Well Record Number: Boring 7	Township:
Well Reference: HCN	Other Well Reference:
Surface Elevation (ft): 727	Total Depth (ft): 10

Depth (ft) From	To	Description
0	5	lean clay with traces of sand
5	7.5	highly weathered shale
7.5	10	highly weathered shale

Section Well Number: 42 Well Type: Construction
Well Record Number: Boring 8 Township:
Well Reference: HCN Other Well Reference:
Surface Elevation (ft): 732 Total Depth (ft): 9

Depth (ft)		
From	To	Description
0	5.5	lean clay
5.5	9	highly weathered shale

Section Well Number: 43 Well Type: Construction
Well Record Number: Boring 9 Township:
Well Reference: HCN Other Well Reference:
Surface Elevation (ft): 775 Total Depth (ft): 15

Depth (ft)		
From	To	Description
0	3	lean clay with traces of sand
3	7.5	clay, traces of weathered shale
7.5	15	highly weathered shale

PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

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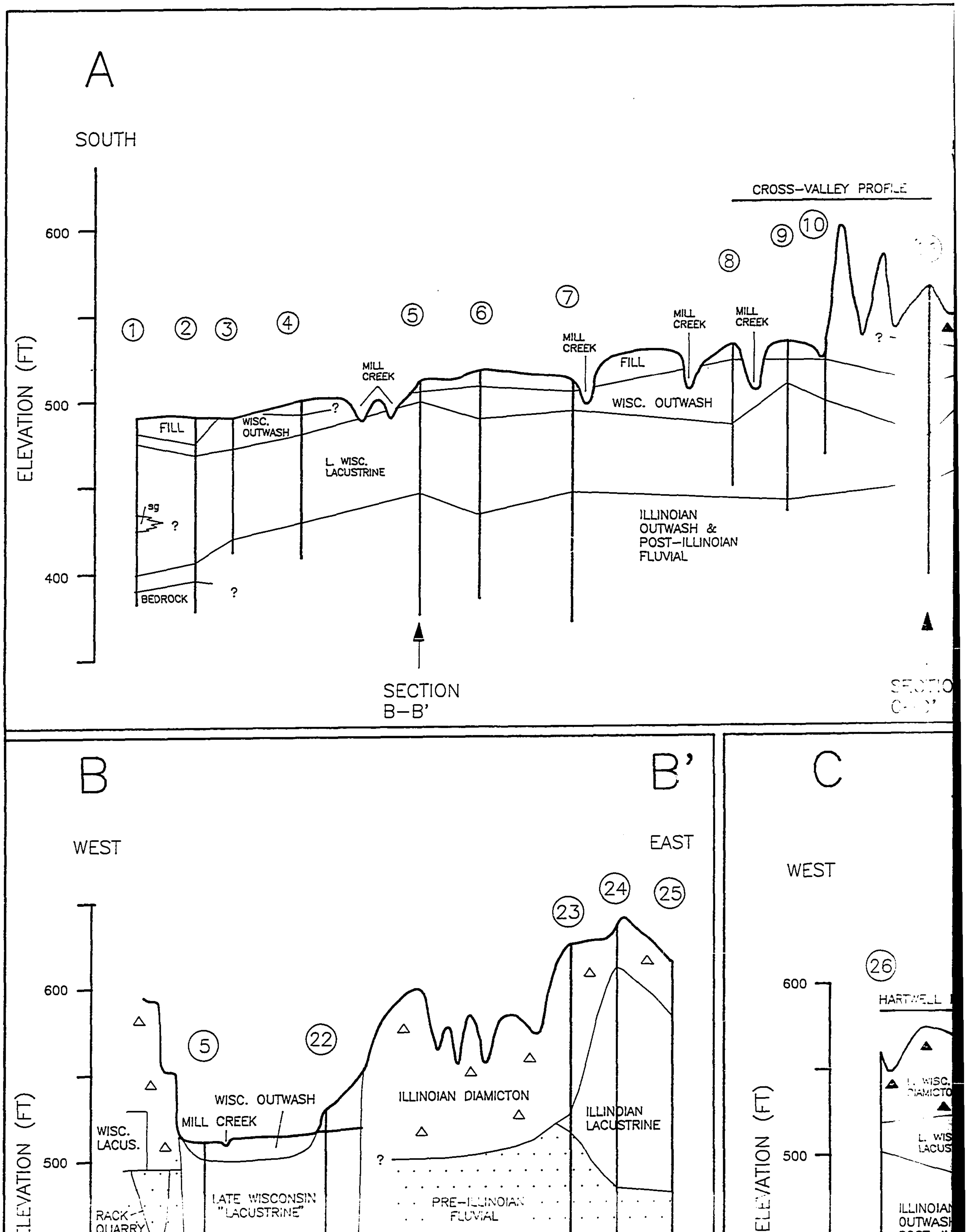
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ELEVATION (FT)
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MILL CREEK
WISC. OUTWASH
ILLINOIAN OUTWASH & POST-ILLINOIAN FLUVIAL
BEDROCK
sg
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B
B'
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EAST
ELEVATION (FT)
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RACK QUARRY
MILL CREEK
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LATE WISCONSIN "LACUSTRINE"
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ELEVATION (FT)
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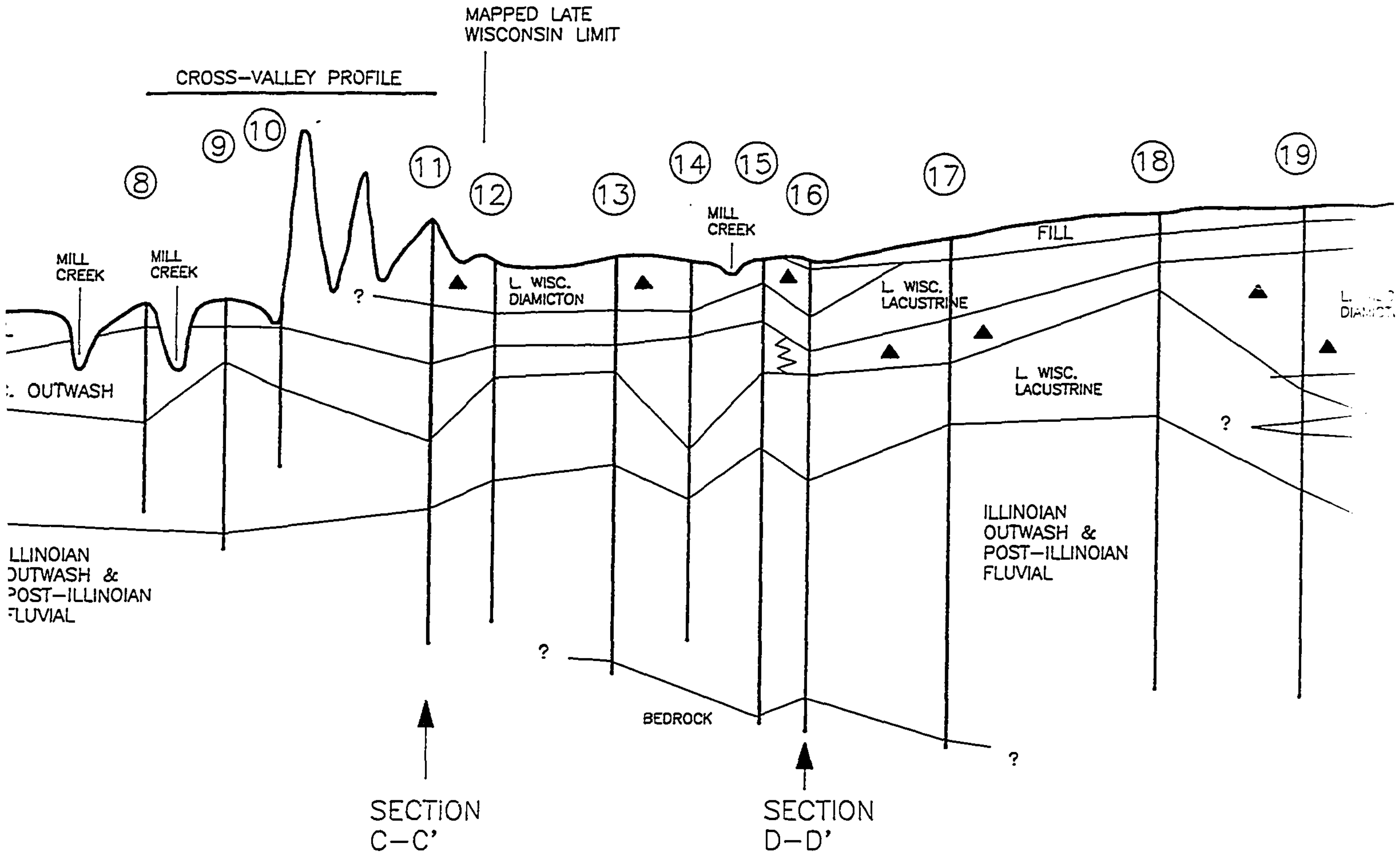
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MILL CREEK
MILL CREEK
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OUTWASH
ILLINOIAN OUTWASH & POST–ILLINOIAN FLUVIAL
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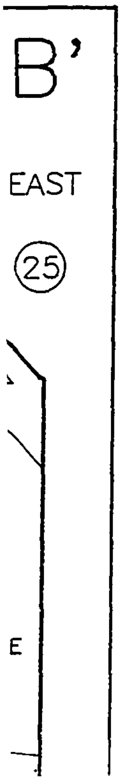
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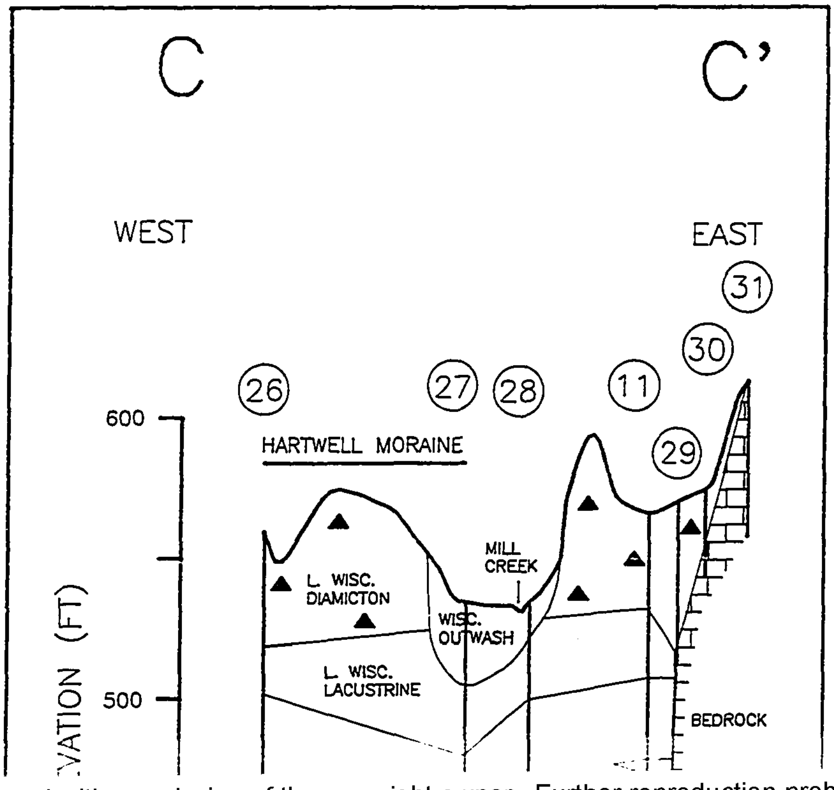
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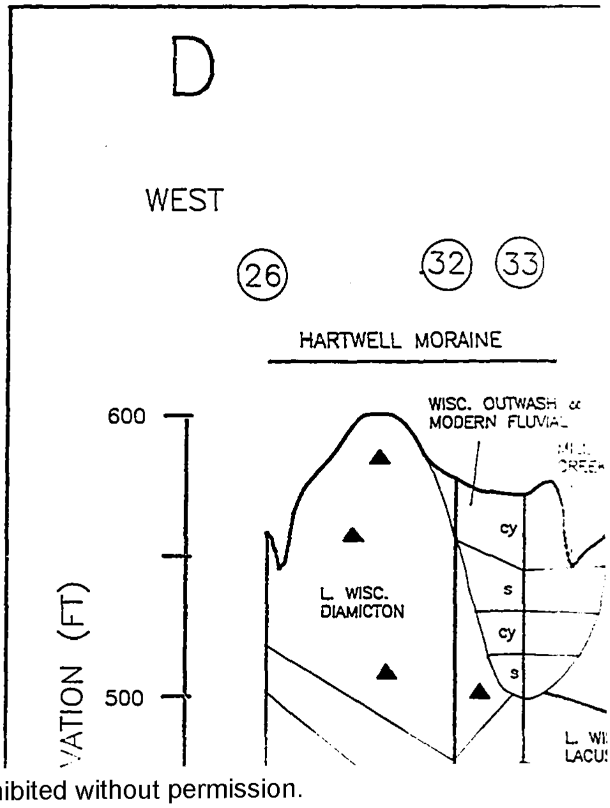
MILL CREEK
BEDROCK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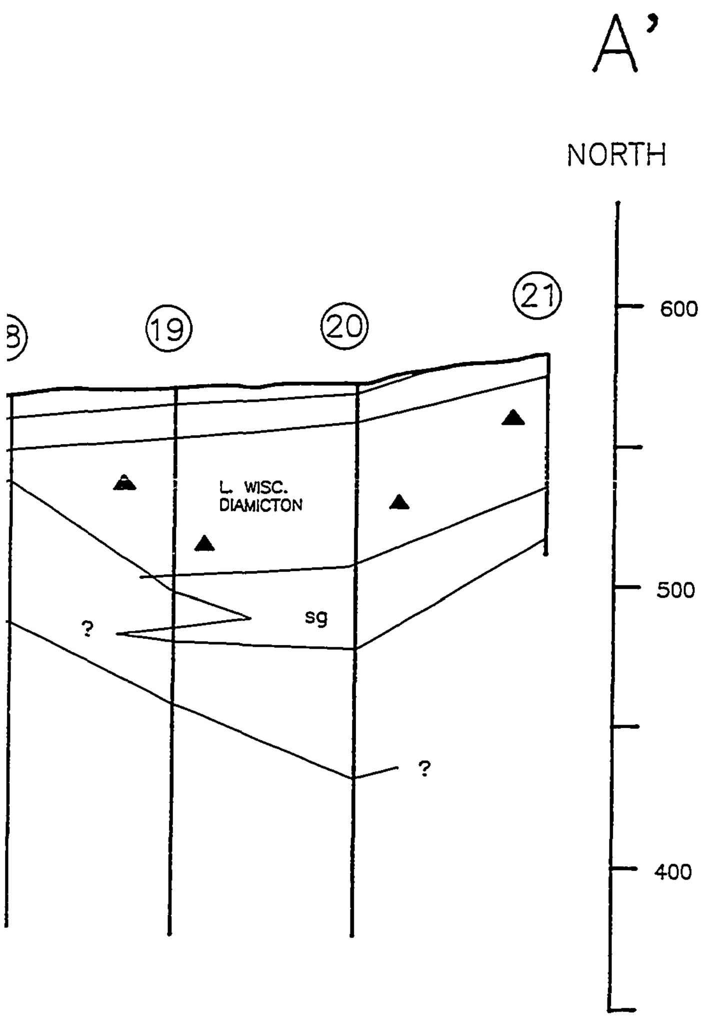
s



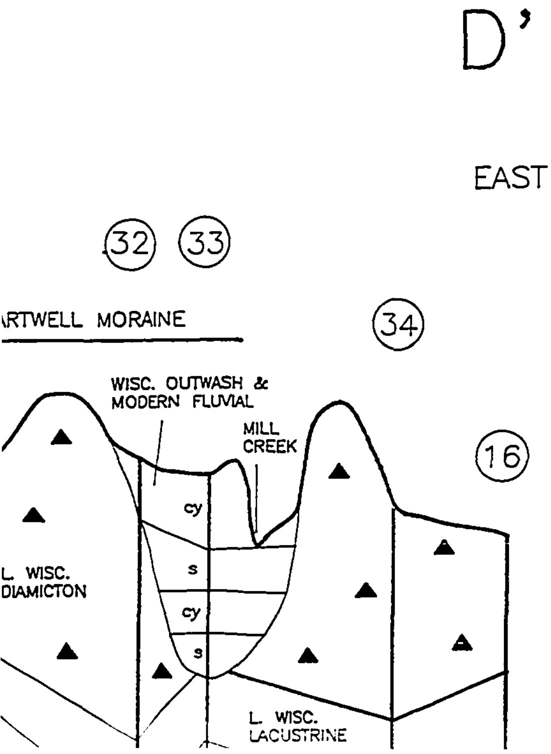


PLATE 1.

GEOLOGIC CROSS SECTIONS, CENTRAL AND NORTHERN MILL CREEK VALLEY, HAMILTON COUNTY, OHIO

LEGEND

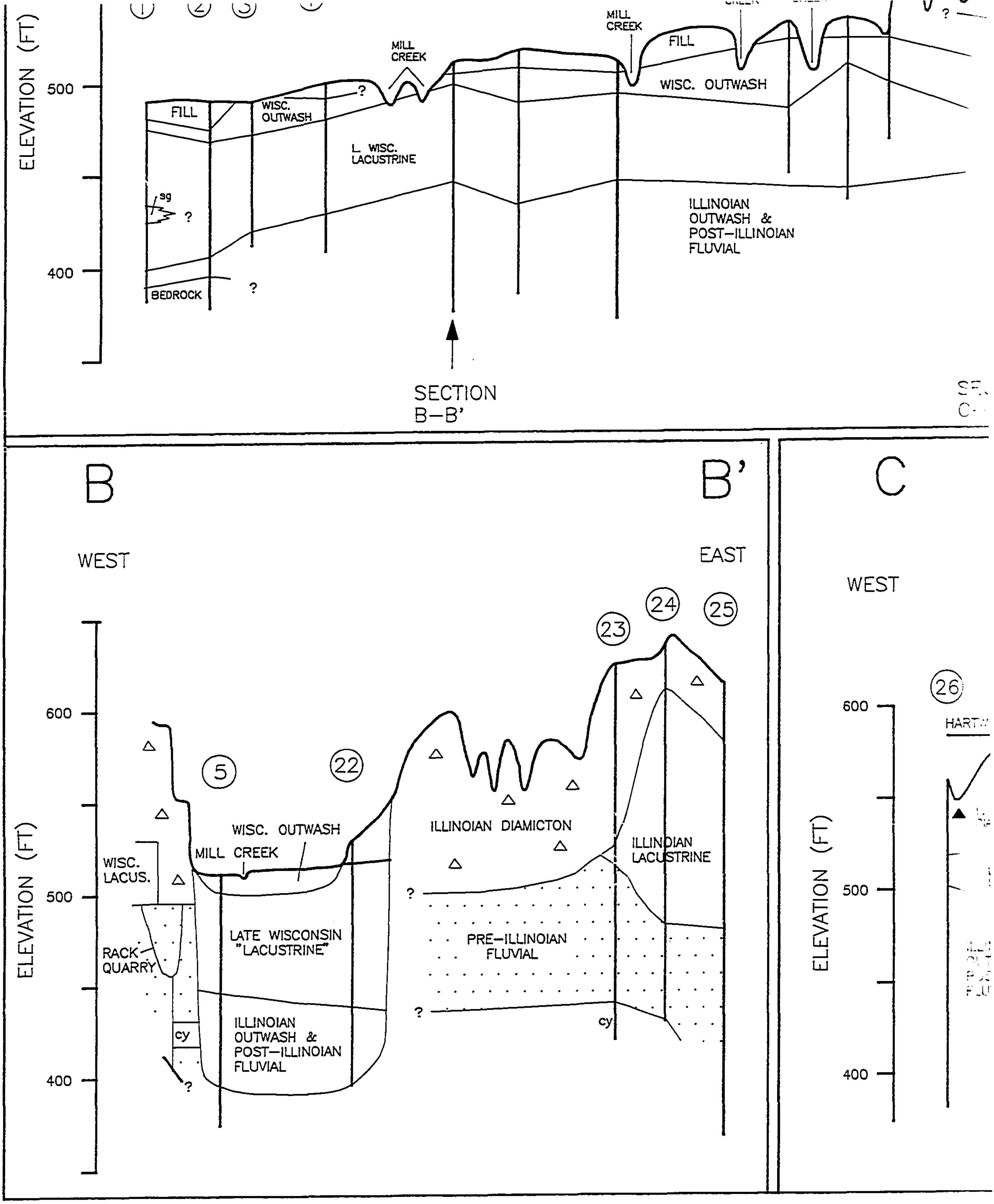
(21)	WELL / BORING NUMBER (SEE APPENDIX G FOR LOGS)
sg	SAND AND GRAVEL
s	SAND
st	SILT
cy	CLAY

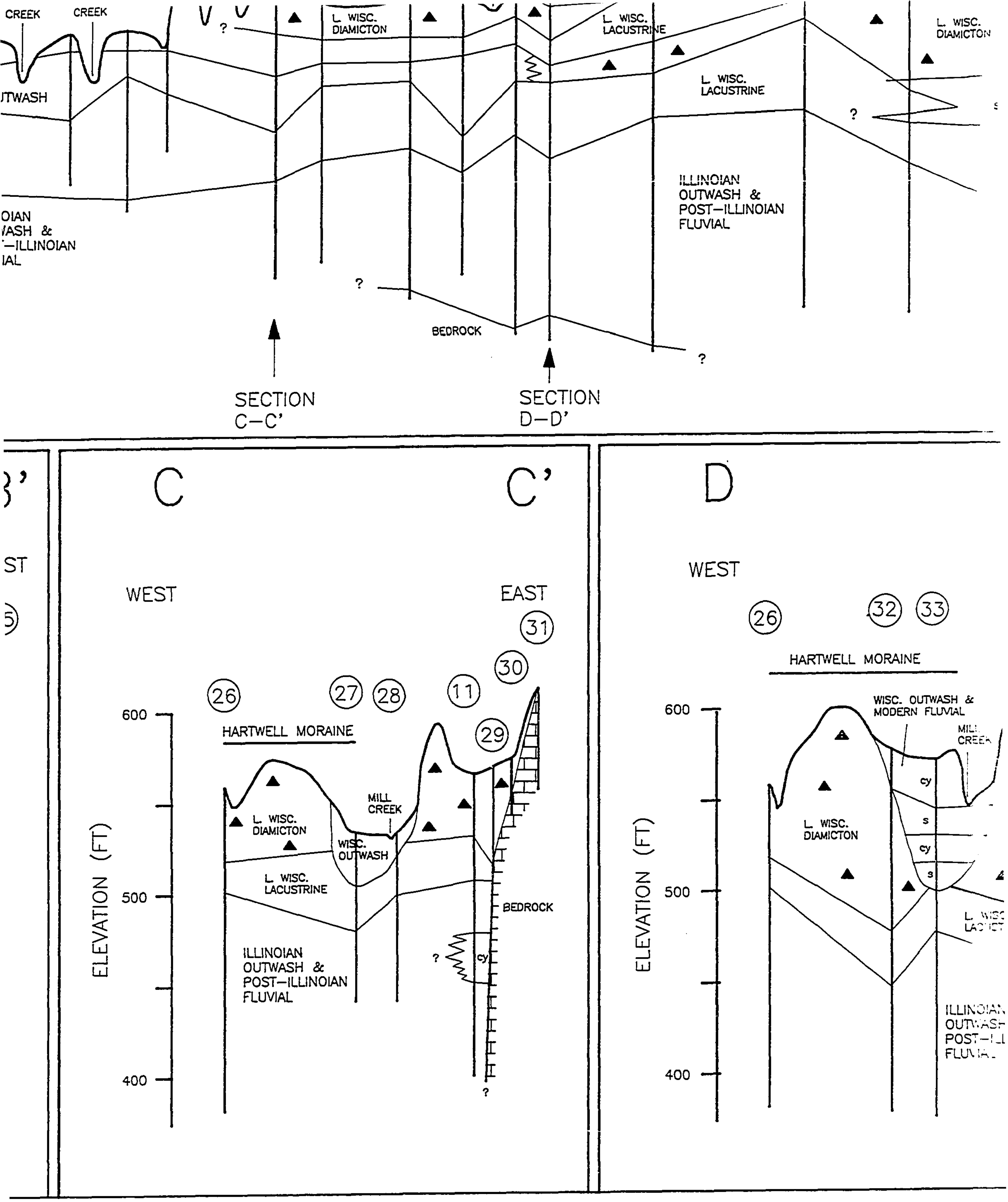
GENERALIZED STRATIGRAPHY

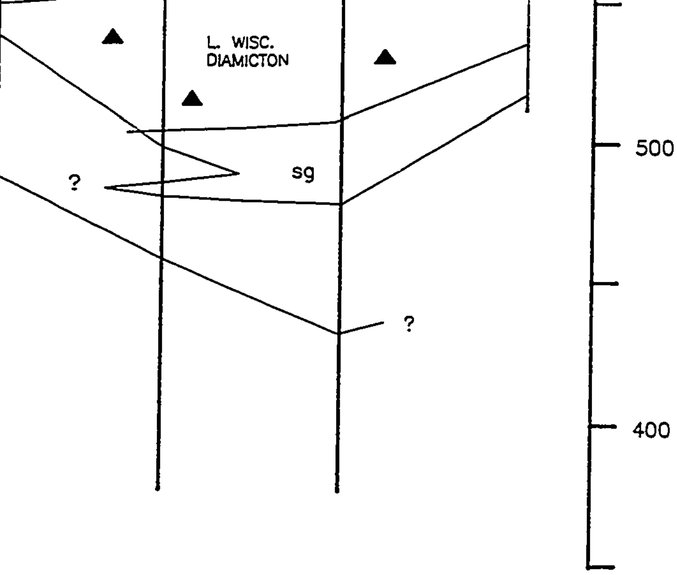
UNIT	LITHOLOGY
FILL	EARTH AND CONSTRUCTION MATERIALS
MODERN FLUVIAL / LATE WISCONSIN OUTWASH	GRAVEL, SAND, SILT, CLAY
LATE WISCONSIN DIAMICTON	DIAMICTON
POST–ILLINOIAN FLUVIAL AND / ILLINOIAN OUTWASH	SAND, GRAVEL
ILLINOIAN DIAMICTON	DIAMICTON
PRE–ILLINOIAN FLUVIAL	SAND, GRAVEL
BEDROCK	LIMESTONE AND SHALE

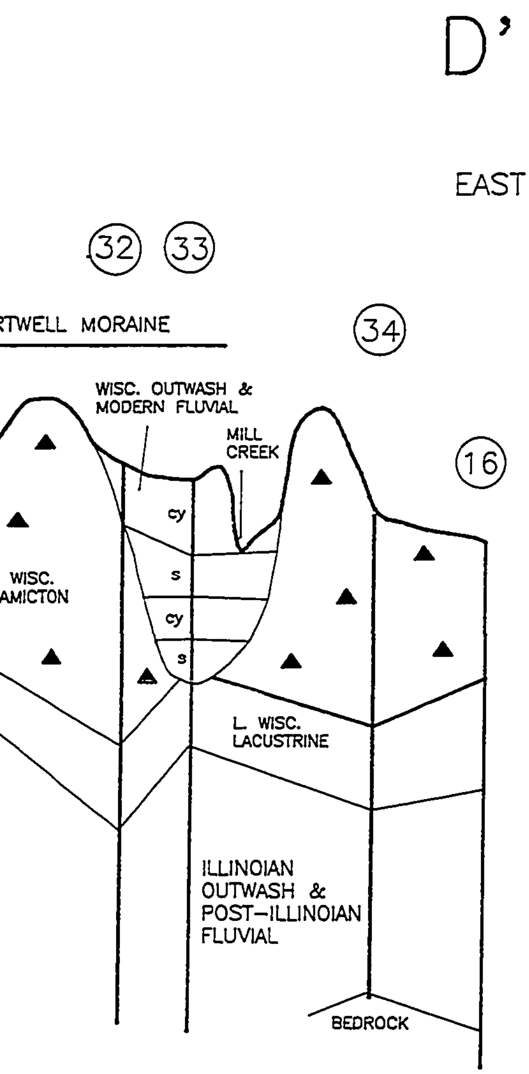
HORIZONTAL SCALE

VERTICAL SCALE


ELEVATION (FT)
500
400
MILL CREEK
MILL CREEK
FILL
FILL
WISC. OUTWASH
WISC. OUTWASH
L. WISC. LACUSTRINE
ILLINOIAN OUTWASH & POST-ILLINOIAN FLUVIAL
BEDROCK
sg
SECTION B-B'
B
B'
WEST
EAST
600
500
400
ELEVATION (FT)
5
22
23
24
25
WISC. OUTWASH
MILL CREEK
WISC. LACUS.
RACK QUARRY
cy
LATE WISCONSIN "LACUSTRINE"
ILLINOIAN OUTWASH & POST-ILLINOIAN FLUVIAL
ILLINOIAN DIAMICTON
ILLINOIAN LACUSTRINE
PRE-ILLINOIAN FLUVIAL
cy
C
WEST
26
600
500
400
ELEVATION (FT)


CREEK
CREEK
L. WISC.
DIAMICTON
L. WISC.
LACUSTRINE
L. WISC.
DIAMICTON
L. WISC.
LACUSTRINE
ILLINOIAN
OUTWASH &
POST–ILLINOIAN
FLUVIAL
BEDROCK
SECTION
C–C'
SECTION
D–D'
C
C'
WEST
EAST
HARTWELL MORAINE
MILL
CREEK
L. WISC.
DIAMICTON
WISC.
OUTWASH
L. WISC.
LACUSTRINE
BEDROCK
ILLINOIAN
OUTWASH &
POST–ILLINOIAN
FLUVIAL
ELEVATION (FT)
600
500
400
D
WEST
HARTWELL MORAINE
WISC. OUTWASH &
MODERN FLUVIAL
L. WISC.
DIAMICTON
ELEVATION (FT)
600
500
400





(21) WELL / BORING NUMBER (SEE APPENDIX G FOR LOGS)

sg SAND AND GRAVEL

s SAND

st SILT

cy CLAY

GENERALIZED STRATIGRAPHY

UNIT	LITHOLOGY
FILL	EARTH AND CONSTRUCTION MATERIALS
MODERN FLUVIAL / LATE WISCONSIN OUTWASH	GRAVEL, SAND, SILT, CLAY
LATE WISCONSIN DIAMICTON	DIAMICTON
POST-ILLINOIAN FLUVIAL AND / ILLINOIAN OUTWASH	SAND, GRAVEL
ILLINOIAN DIAMICTON	DIAMICTON
PRE-ILLINOIAN FLUVIAL	SAND, GRAVEL
BEDROCK	LIMESTONE AND SHALE

HORIZONTAL SCALE

1 MILE

1 KILOMETER

VERTICAL SCALE

AS SHOWN

V.E. = 66x

(K.M. SAVAGE, 1992)

PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

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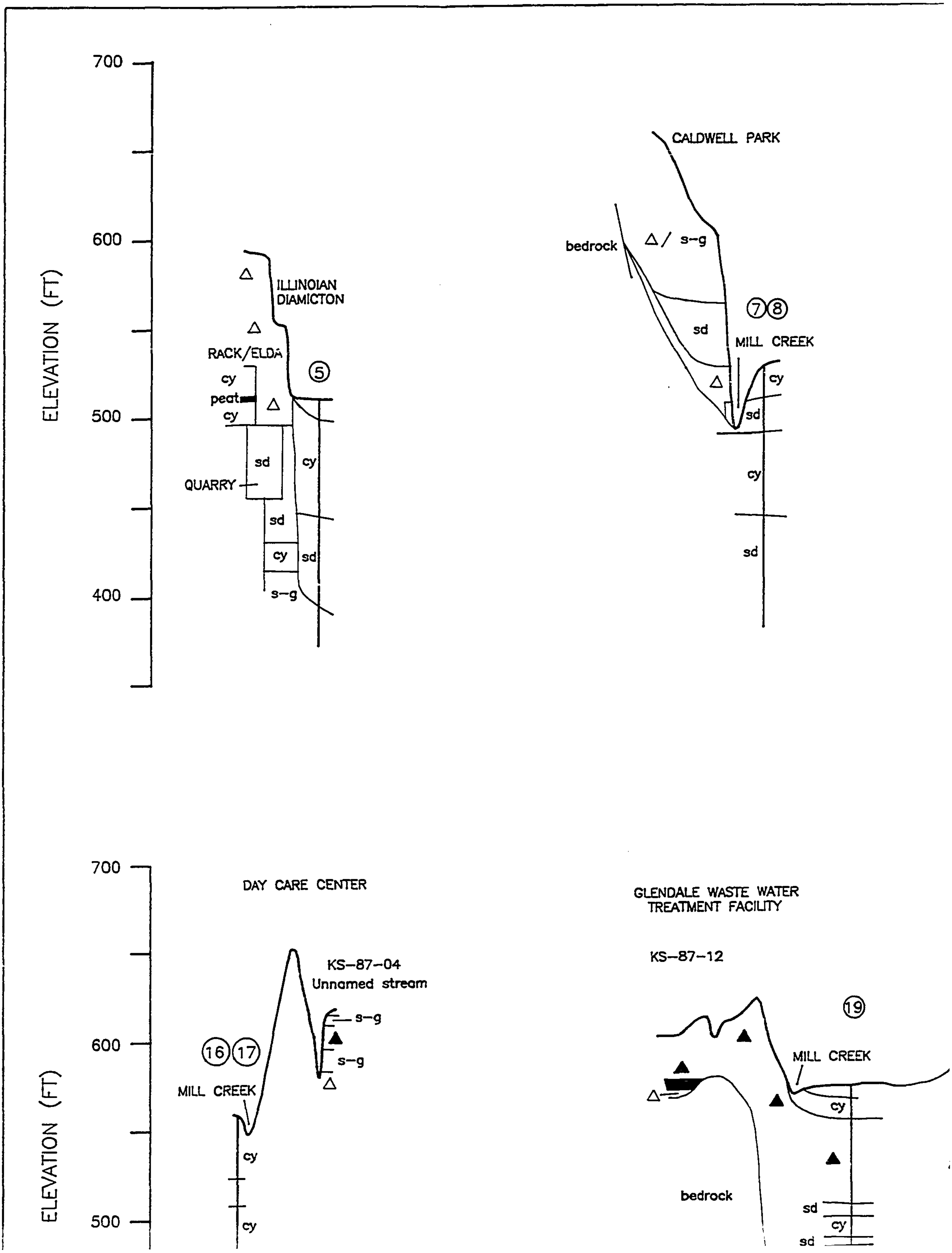

700
600
500
400
ELEVATION (FT)
ILLINOIAN
DIAMICTON
RACK/ELDA
cy
peat
cy
sd
QUARRY
cy
sd
cy
sd
s-g
5
CALDWELL PARK
bedrock
Δ/ s-g
sd
7 8
MILL CREEK
cy
sd
cy
sd
700
600
500
ELEVATION (FT)
DAY CARE CENTER
KS-87-04
Unnamed stream
s-g
s-g
16 17
MILL CREEK
cy
cy
GLENDALE WASTE WATER
TREATMENT FACILITY
KS-87-12
19
MILL CREEK
cy
bedrock
sd
cy
sd

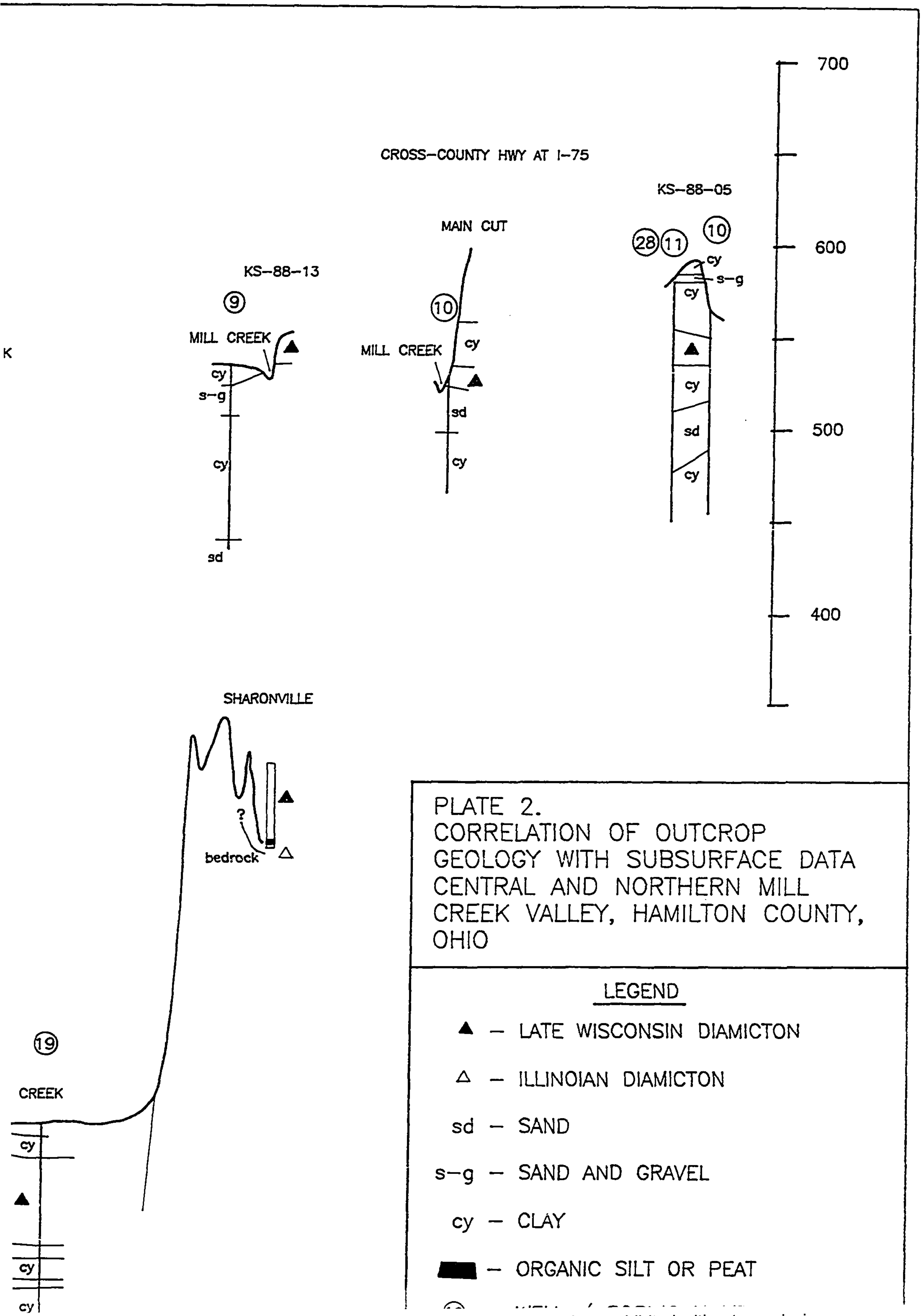


PLATE 2.
CORRELATION OF OUTCROP GEOLOGY WITH SUBSURFACE DATA CENTRAL AND NORTHERN MILL CREEK VALLEY, HAMILTON COUNTY, OHIO

LEGEND

▲ – LATE WISCONSIN DIAMICTON

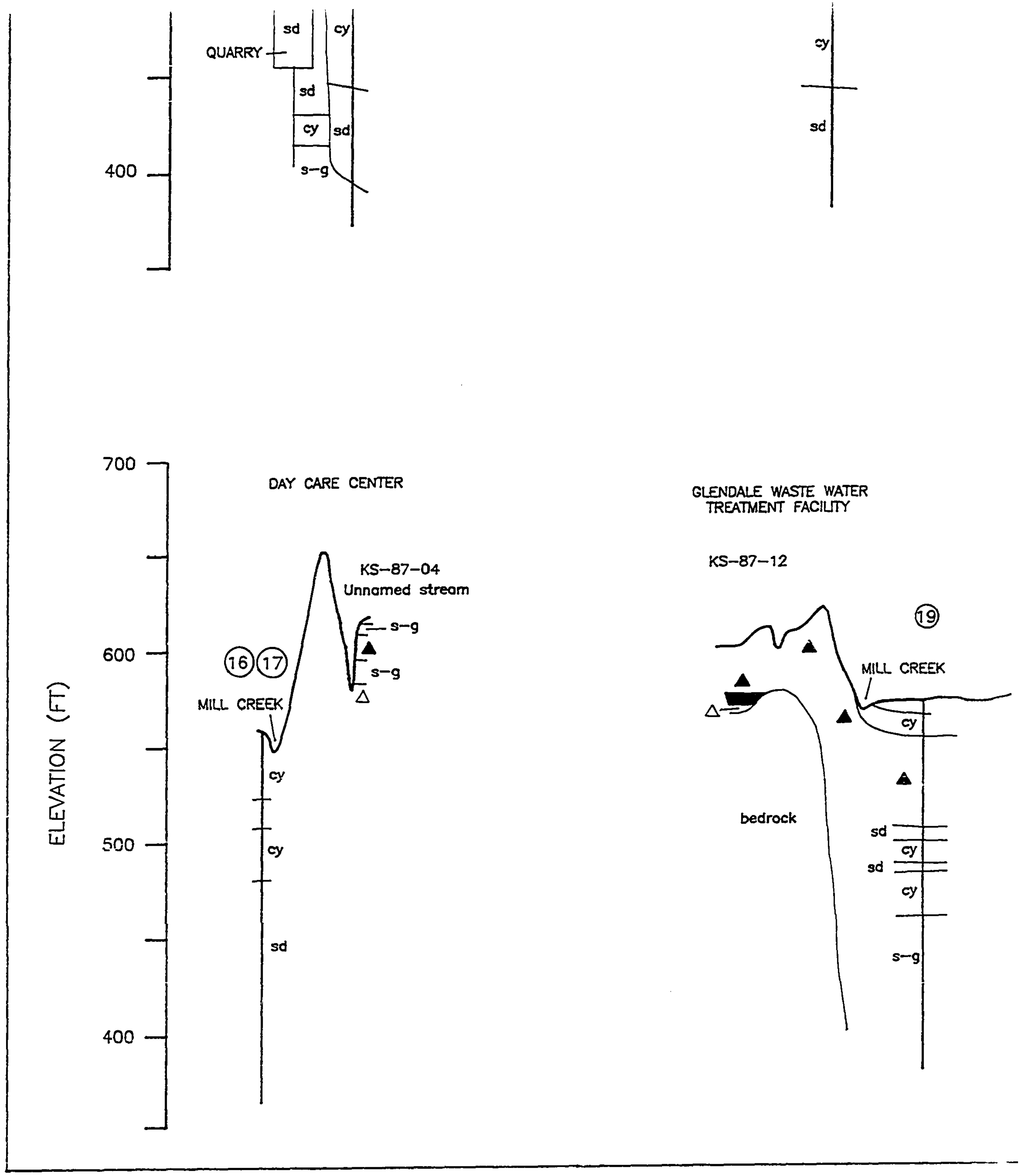
△ – ILLINOIAN DIAMICTON

sd – SAND

s–g – SAND AND GRAVEL

cy – CLAY

■ – ORGANIC SILT OR PEAT


sd
cy
QUARRY
sd
cy
sd
s-g
400
cy
sd
700
DAY CARE CENTER
KS-87-04
Unnamed stream
s-g
s-g
600
16
17
MILL CREEK
ELEVATION (FT)
cy
500
cy
sd
400
GLENDALE WASTE WATER
TREATMENT FACILITY
KS-87-12
19
MILL CREEK
cy
bedrock
sd
cy
sd
cy
s-g

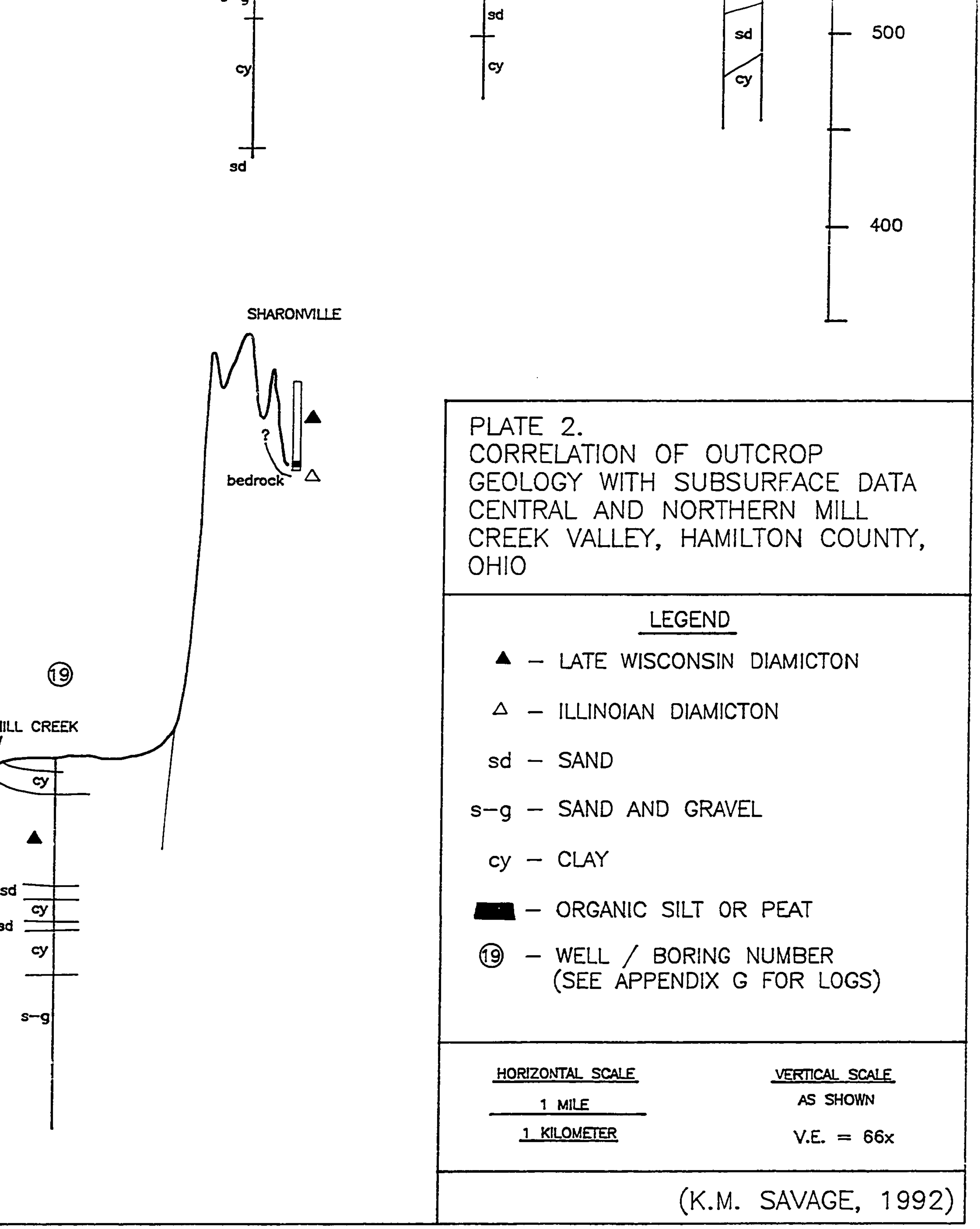


PLATE 2.
CORRELATION OF OUTCROP GEOLOGY WITH SUBSURFACE DATA CENTRAL AND NORTHERN MILL CREEK VALLEY, HAMILTON COUNTY, OHIO

LEGEND

▲ – LATE WISCONSIN DIAMICTON

△ – ILLINOIAN DIAMICTON

sd – SAND

s–g – SAND AND GRAVEL

cy – CLAY

■ – ORGANIC SILT OR PEAT

⑲ – WELL / BORING NUMBER (SEE APPENDIX G FOR LOGS)

HORIZONTAL SCALE	VERTICAL SCALE
1 MILE	AS SHOWN
1 KILOMETER	V.E. = 66x

(K.M. SAVAGE, 1992)