

Environmental Restoration Program

**OPERABLE UNIT 9
HYDROGEOLOGIC INVESTIGATION:
BEDROCK REPORT**

**MOUND PLANT
MIAMISBURG, OHIO**

Volume I – Text

January 1994

**Technical Memorandum
(Revision 0)**

**U. S. Department of Energy
Albuquerque Operations Office**

**Environmental Restoration Program
EG&G Mound Applied Technologies**





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13 January 1994

EG&G Mound Applied Technologies, Inc.
Attention: Mr. Monte Williams, Project Officer
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Miamisburg, Ohio 45343-3000

RE: ER Program, Mound Plant
BOA No. 24251
Operable Unit 9, Hydrogeologic Investigation:
Bedrock Report

RFW WO # 05376-039-001-0500

Dear Mr. Williams:

Enclosed are replacement pages for the draft of the Operable Unit (OU) 9 Hydrogeological Investigation: Bedrock Report. During final editing, an error was discovered on Plate 3 too late to correct in time for distribution. Enclosed are the corrected Plate 3 and Figure ES.3. During our final review, we discovered that the plates were not listed on the Table of Contents. Because the list of plates is so long, it affects all the pages in the frontispiece of the report. Accordingly, we have enclosed replacement pages iii to ix in the frontispiece. We are submitting these replacements early in the review period so that the reviewers may have all the information at their disposal. This should avoid needless comments.

If you have any questions regarding this matter, please do not hesitate to call Bill Criswell at (505) 884-5050 or the Alternate Project Manager Mr. John Price at (513) 825-3440.

Sincerely,

ROY F. WESTON, INC.

John W. Thorsen, P.E.
ER Program, Subcontractor
Project Manager

CWC/gy
Attachments

WLB
1-27-94





RE: ER Program, Mound Plant
BOA No. 24251
Operable Unit 9, Hydrogeologic Investigation:
Bedrock Report

RFW WO # 05376-039-001-0500

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7 January 1994

EG&G Mound Applied Technologies, Inc.
Attention: Mr. Monte Williams, Project Officer
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RE: ER Program, Mound Plant
BOA No. 24251
Operable Unit 9, Hydrogeologic Investigation:
Bedrock Report

RFW WO # 05376-039-001-0500

Dear Mr. Williams:

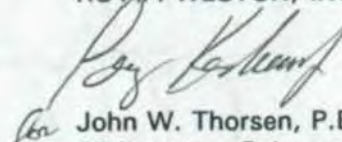
Enclosed is the draft of the Operable Unit (OU) 9 Hydrogeological Investigation: Bedrock Report. This report contains the methods and results of the field investigations conducted in 1993 on the bedrock beneath the Mound Plant. Under the term of the Federal Facility Agreement (FFA), this report is a technical memorandum and is considered a secondary document. The approved schedule indicates that the hydrogeological report is due 21 January 1994, but this was modified at the December FFA meeting. The revised schedule breaks the hydrogeological report into three parts: Bedrock Report; Soil Chemistry Report; and the Glacial Report. The submission date for the Bedrock Report is moved up to 10 January; the Soil Chemistry Report is due 21 January and the Glacial Report is due 21 March 1994. In accordance with the FFA, all draft documents are subject to a 30-day review period. Comments on the Bedrock Report are due 9 February 1994.

At the direction of Art Kleinrath, DOE Dayton Area Office, this report is being distributed to the project managers for informational purposes.

If you have any questions regarding this matter, please call Bill Criswell at (505) 884-5050 or the Alternate Project Manager Mr. John Price at (513) 825-3440.

Sincerely,

ROY F. WESTON, INC.


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10 January 1994

EG&G Mound Applied Technologies, Inc.
Attn: Mr. James Rigano
Mail Stop OSE-2
P.O. Box 3000
Miamisburg, Ohio 45343-3000

RE: BOA No. 24251
Operable Unit 9 Hydrogeologic Investigations
Borehole Geophysical Data

RFW WO # 05376-039-001

Dear Mr. Rigano:

This letter is a transmittal of copies of the borehole geophysical data obtained by Roy F. Weston, Inc. as part of the Operable Unit 9 hydrogeologic investigations. The borehole geophysical data was collected by COLOG, Inc. Golden, Colorado, in March 1993. Results and interpretations are presented in the OU 9 Hydrogeological Investigations: Bedrock Report.

Attachments to this letter include 1) copy of transmittal letter from COLOG to WESTON; 2) copies of data printouts; and 3) electronic files of geophysical data on seven 3.5-inch floppy disks. The disk formats are explained in the COLOG transmittal letter.

If you have any questions regarding this matter, please call Bill Criswell at (505) 884-5050 or the Alternate Project Manager, John Price at (513) 825-3440.

Very truly yours,

ROY F. WESTON, INC.

John W. Thorsen, P.E.
Project Manager

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ENVIRONMENTAL RESTORATION PROGRAM

**OPERABLE UNIT 9
HYDROGEOLOGIC INVESTIGATION:
BEDROCK REPORT**

**MOUND PLANT
MIAMISBURG, OHIO**

January 1994

**U.S. DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE**

**ENVIRONMENTAL RESTORATION PROGRAM
EG&G MOUND APPLIED TECHNOLOGIES**

**TECHNICAL MEMORANDUM
(REVISION 0)**

*nlb
1-27-94*

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ACRONYMS

API	American Petroleum Institute
BGS	below ground surface
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CPS	counts per second
DOE	U.S. Department of Energy
EM	electromagnetic
EPA	U.S. Environmental Protection Agency
ER	Environmental Restoration (Program)
FFA	Federal Facility Agreement
FS	feasibility study
FWS	full waveform sonic
HPF	heat pulse flowmeter
MSL	mean sea level
NPL	National Priority List
OEPA	Ohio Environmental Protection Agency
OU	operable unit
RI	remedial investigation
VDL	variable density log

ACKNOWLEDGMENTS

This report was prepared by Roy F. Weston, Inc., Albuquerque, New Mexico, under basic ordering agreement 24251 with EG&G Mound Applied Technologies, Miamisburg, Ohio. Contributing authors include Bill Criswell, Jan Curtis, Paul Darr, and Rick Morrow. Roger McCready of Terran Corporation, Fairborn, Ohio wrote Section 5 and performed calculations of hydraulic permeability. Byron Kulander of Wright State University performed the fracture logging on the core and the outcrop and drafted the summary figure of fractures. Bob Gilkeson designed the borehole geophysics program and Steve Gorin supervised the subcontractor. Colog, Inc., Golden, Colorado, conducted the borehole geophysical measurements. Northstar Drilling Inc., Little Falls, Minnesota, drilled the boreholes and collected the core. The lithologic logging was performed by Rick Morrow, Jim Davis, Julie Schucker, and Andy Sperry under supervision of Bill Criswell. Brent Huntsman, Terran Corporation, and Peter Middlebrooks supervised the special rappelling skills required for the outcrop logging. Special acknowledgement is given to Alec Bray, Mound Plant, for careful technical review of the manuscript; Cindy Carney and David Dominic, Wright State University, and John Pope, Miami University, for technical discussions of the geology and biostratigraphy of southwestern Ohio. The WESTON Albuquerque staff who developed this report include: technical editors Nancy Blackburn and Stephanie Phillips; graphics designers Darcel Sandland, Mary Reed, and James MacCornack; word processors Gary Yuhas, Roberta Trujillo, Linda Keith, and Shirley Zitterman; and production coordinator Terry Whalen.

EXECUTIVE SUMMARY

ES.1. INTRODUCTION

Operable Unit (OU) 9 is designated for site-wide studies that provide the framework for the RI/FS. Investigations that are best conducted for the entire Mound Plant and its regional setting are included in OU 9. The hydrogeologic investigations address the hydrogeologic environment of Mound Plant and the nature and extent of groundwater contamination outside the plant boundaries. Characterization of potential source terms within the plant is generally deferred to other OU investigations. Due to the breadth of scope of the OU 9 hydrogeologic investigations, the work required to fulfill the objectives is phased. Technical memoranda that describe methods and results of the OU 9 hydrogeologic investigations is subdivided into the following technical memoranda:

- Well Information Report
- Bedrock Report
- Glacial Report
- Soil Chemistry Report
- Groundwater Sweeps Report

This report is a technical memorandum of investigative work conducted as part of the Operable Unit 9 hydrogeologic investigations in accordance with the Operable Unit 9 Site-Wide Work Plan (DOE 1992a). It focuses on the groundwater flow system in the bedrock that underlies Mound Plant. This system was considered in the OU 9 Site-Wide Work Plan to be dominated by fracture flow, an assumption confirmed in this report. This report provides descriptions of the methodologies and results of work conducted to refine the physical characteristics of the bedrock flow system, including lithology, stratigraphy and alteration profile of the rocks and frequency and orientations of fractures. Investigations of the bedrock include the collection and description of continuous core from six boreholes, a complete suite of geophysical logs in the boreholes and physical measurements of lithology and fractures at an exposed outcrop in a railroad cut west of Mound Plant (Figure ES.1).

ES.2. LITHOLOGY AND STRATIGRAPHY

The objectives of the lithologic studies are to refine the lithologic database to assist in establishing the hydraulic properties of the bedrock flow system. The bedrock flow system is considered to be a complex system in which weak groundwater flow along the interface of limestone and shale beds is enhanced by local fractures. The lithologic studies provide criteria for correlation of rocks across the Site and establishing stratigraphic contacts.

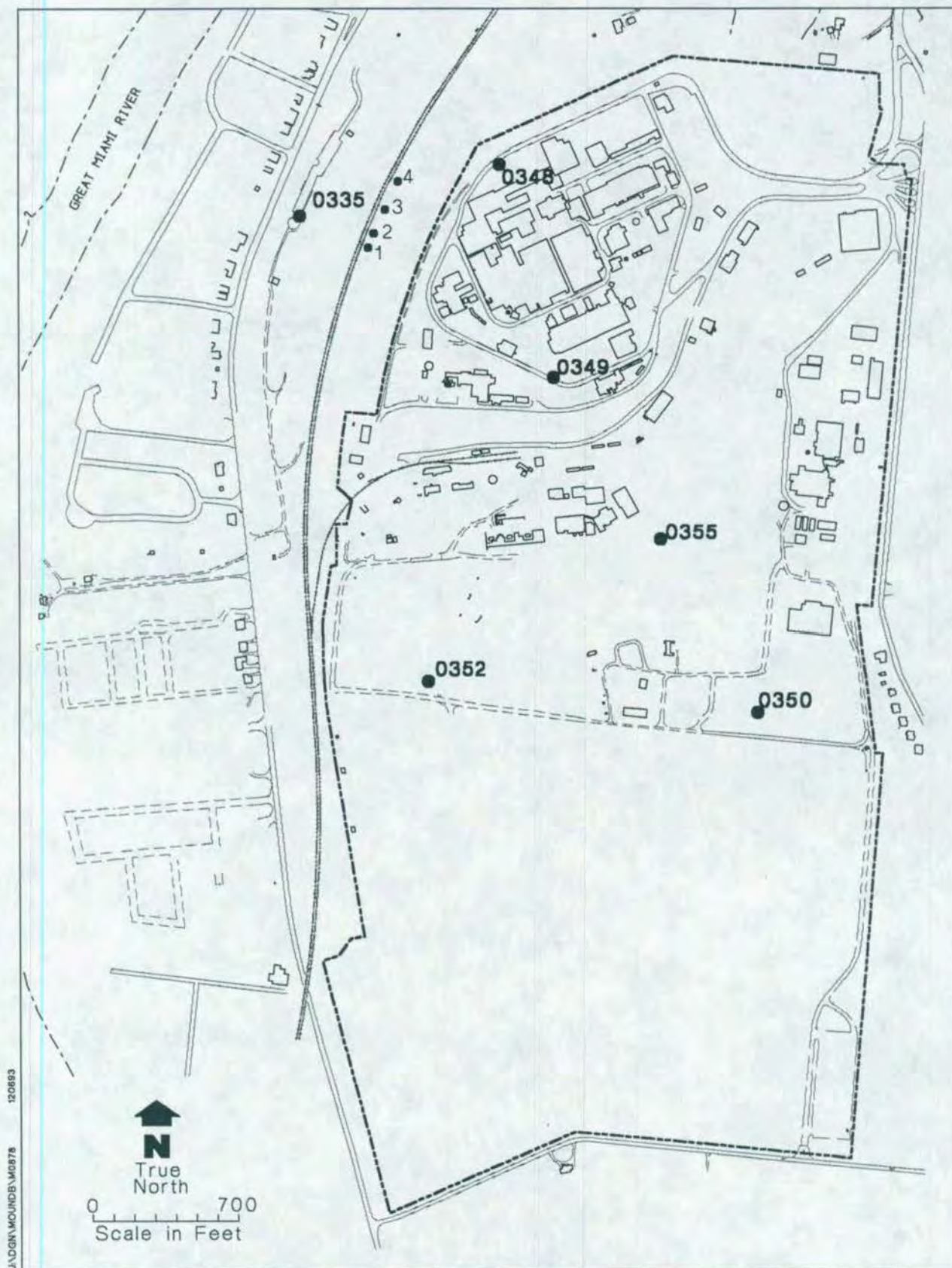


Figure ES. 1. Location of bedrock boreholes and railroad cut survey locations.

ES.2.1. LITHOLOGIC FABRICS

Lithologic fabric refers to the arrangement of the physical components within a rock. Four lithologic fabric types were observed in the bedrock at the Mound Plant: grainstone, packstone, wackestone, and mudstone as follows:

- Grainstones are grain-supported, well-sorted limestones containing less than 10 percent mud. The grainstones observed in the bedrock at the Mound Plant are typically medium gray and are composed of reworked skeletal grains of calcium carbonate and calcium carbonate cements. The grainstones are typically very well sorted with grain sizes varying from very fine (1/16 mm) to fine (1/4 mm).
- Packstones are grain-supported limestones containing some mud matrix. The packstones observed are typically medium gray and are composed of reworked skeletal grains of calcium-carbonate-producing organisms, and calcium carbonate muds. Grain sizes vary from very fine (<1/16 mm) to very coarse (>2 mm); the packstones are poorly sorted. Recrystallization of the sediments after deposition has altered most of the calcium carbonate materials, including the carbonate mud matrix, which causes the packstones to have an apparent wide range of crystallinity.
- Wackestones are limestones that contain more than 10 percent grains and are mud-supported with particles of clay and fine silts. The wackestones observed are dark gray to dark greenish gray and are generally bioclastic, composed of a terrigenous clay and silt matrix with pavements of, or an abundance of, calcium carbonate skeletal grains and fossil fragments.
- Mudstones are defined as shales (non-carbonate rocks) that contain less than 10 percent fossil grains and are mud-supported with particles of clay and fine silts. The mudstones observed are dark gray to dark greenish gray, and are predominantly composed of terrigenous clays and silts with a particle size of <1/16 mm.

Of the four fabric types, mudstone is the dominant fabric observed in the Mound Plant bedrock. Few wackestones are observed in the upper parts of the section, but they are observed to dominate in the lower parts of the section. Likewise, grainstones are rarely observed in the upper parts of the section, but are common in the lower parts.

ES.2.2. LITHOLOGIC FACIES

The sequence of grainstones, packstones, wackestones, and mudstones that comprise the rock fabrics in the cores are grouped into small packages termed lithologic facies. These lithologic facies are defined on the basis of macroscopic characteristics of the core and are simply interpretative packages that aid in correlating packages from core to core and from core to the geophysical logs. The lithologic facies defined in this report have no formal meaning outside of the context of this report. Lithologic

facies are generally defined as the natural variations that occur within time-stratigraphic sequences due to environmental factors. A cross section of Mound Plant lithology is depicted on Figure ES.2. This composite section represents the lithology beneath Mound Plant. Not included in this report are descriptions and discussions of glacial deposits that may mantle the bedrock or that may fill glacial valleys. The lithologic facies discussed in this report are:

- The limestone facies is an interval of rocks that are dominated by limestone fabrics, typically over 90 percent packstones, wackestones, and grainstones by volume.
- The limestone with minor shale facies is an interval of rocks in the Mound Plant core that have between 60 and 90 percent packstones, wackestones, and grainstones by volume. Packstones comprise nearly 60 percent of the fabrics in the rocks in the upper parts of the section, but decrease in frequency in the lower parts of the section where they typically comprise 40 percent.
- The interbedded limestone and shale facies is an interval of rocks in the Mound Plant core that have approximately equal proportions of packstones and mudstones by volume; these typically comprise 80 percent of the rocks.
- The shale minor limestone facies is an interval of rocks in the Mound Plant core that have between 60 and 90 percent mudstones by volume. Limestones include packstones and grainstones. Shales in this facies include some fossil-poor wackestones, especially in the lower parts of the section.
- The fossiliferous shale nodular limestone facies is an interval of rocks in the Mound Plant core that have between 50 and 80 percent wackestones by volume.

ES.2.3. STRATIGRAPHY

The bedrock at Mound Plant is comprised of marine shales and limestones of the Ordovician System. Rocks encountered in the cores drilled during this investigation are grouped within the Cincinnati Series and include rocks from the Richmondian and Mayvillian Stages (Figure ES.2). These units comprise the time-stratigraphic framework within the areas of southwestern Ohio and eastern Indiana. Formations encountered in the cores drilled for this investigation include, from the lowest to the highest, the Corryville Formation, the Mount Auburn Formation, the Oregonia Formation, the Waynesville Formation, the Liberty Formation, and the Whitewater Formation. Historically, the formations within the Cincinnati Series were defined on the basis of fossils and faunal zones, i.e., they were biostratigraphic units. In the strict sense of stratigraphic nomenclature, formations must be defined on the basis of lithologic characteristics. This report generally conforms to the published lithostratigraphic framework. The elevations of the formational contacts shown on Figure ES.2 differ from those published by previously because of the nature of the definitions.

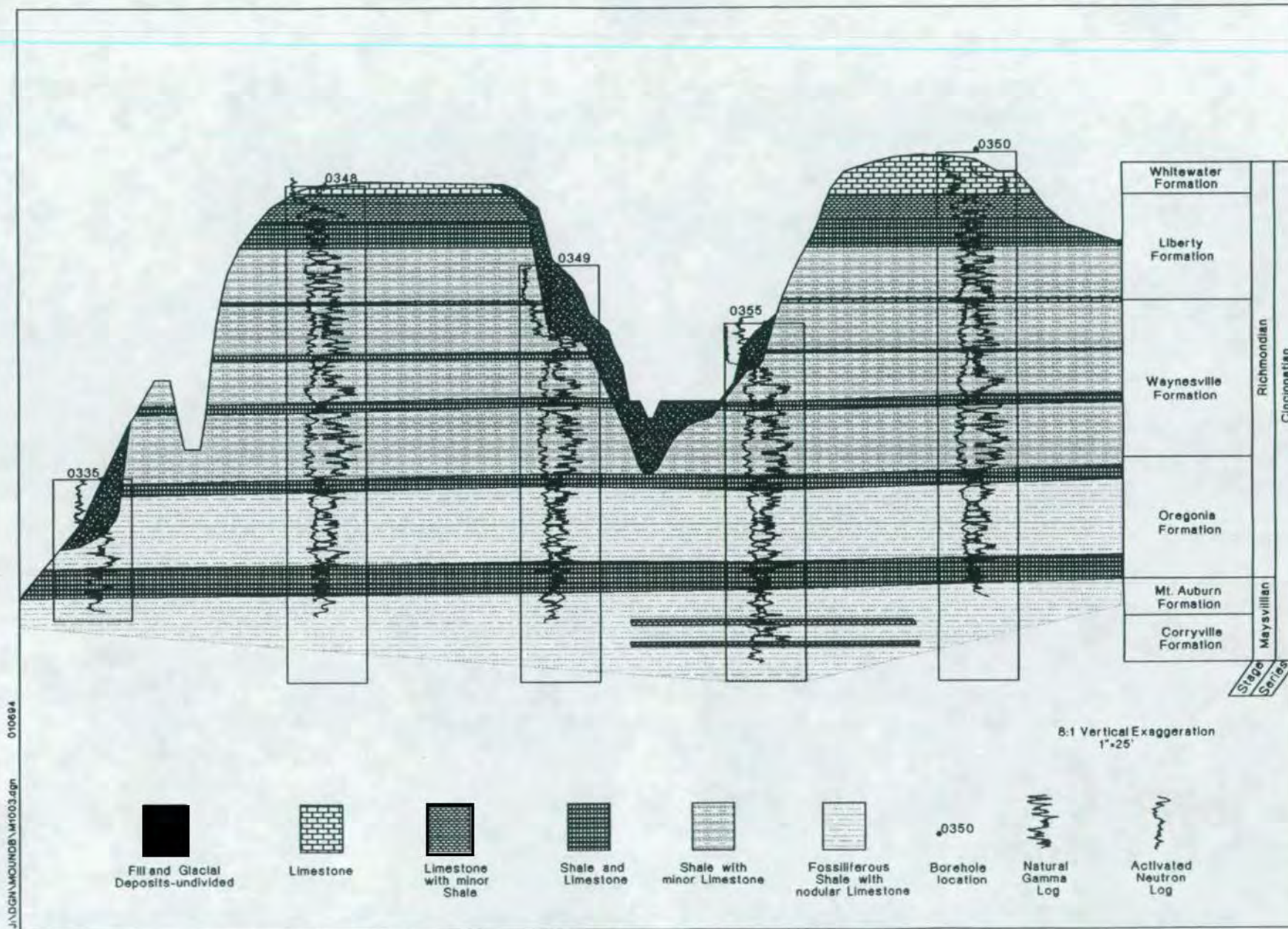


Figure ES 2. Cross-section of Mound Plant Bedrock lithology and stratigraphy.

The Corryville Formation is only encountered in borehole 0355, where it is 31 ft thick and the base is not exposed. It consists dominantly of thickly-bedded shales and interbedded limestones.

The Mount Auburn Formation is approximately 21 ft thick beneath Mound Plant. It consists of fossiliferous shale with nodular limestone and shale with interbedded limestone.

The Oregonia Formation is approximately 69 ft thick beneath Mound Plant. The unit grades from limestone with interbedded shale to fossiliferous shale with nodular limestones. Distinct limestone beds occur near the base of the unit.

The Waynesville Formation is approximately 88 ft thick beneath Mound Plant. It consists of shale and interbedded limestones. Interbedded limestone and shale facies occurs in the middle part of the unit. Bedded grainstones are rare.

The Liberty Formation is approximately 61 ft thick. It is observed only in cores 0348 and 0350, as it has been eroded away at the other locations. It grades from limestones with interbedded shales at the top to shales with interbedded limestones at the base.

The Whitewater Formation is minimally 20 ft thick on the hilltops and has been eroded away at the other locations. It consists of poorly bedded limestones and limestones with interbedded shales. Packstones comprise about 84 percent of the rock in core 0350. Bedded grainstones are absent. Mudstones and wackestones are observed in approximately equal proportions of 8 percent each.

ES.3. FRACTURE STUDIES

The objectives of the fracture studies are to identify the vertical and lateral variations in the frequency and distribution of fractures in the Mound Plant bedrock that may transmit groundwater in the bedrock flow system. The fracture studies provide data on the physical conditions of fractures, including the frequency variations by depth in the boreholes and preferred orientations determined in outcrop.

ES.3.1. CHARACTERISTICS OF FRACTURES IN CORE

Two broad types of fractures are observed in the Mound Plant cores, natural and induced. Natural fractures comprise the fracture carapace and are distinguished from induced fractures by their geometry and morphology. Natural fractures are defined as those fractures that existed in the rock prior to drilling. They exhibit diagnostic characteristics, including irregular, open apertures that typically exhibit evidence of solution dissolution and precipitation of minerals, slickensides, and multiple

breakage. Surface structures and fracture trace characteristics in natural fractures bear no regular geometric relationship to the core.

In this study, rubble zones are considered indirect evidence of the presence of a fracture. In the vicinity of Mound Plant, natural fractures are observed in this and other studies to be largely vertical or high angle. Since the boreholes were vertical, the true frequency of vertical fractures is difficult to estimate. Rubble is believed to represent the evidence that a natural fracture is present, but the fracture itself is not visible in core. The drill stem may have intercepted a vertical fracture, but only rock fragments were recovered. This approach is considered conservative and assumes that natural fractures are present at rubble zones.

Figure ES.3 depicts a summary of the frequency of natural fractures observed in the Mound Plant cores. Natural fractures and rubble zones are abundant in the upper zones of all cores examined and decrease in frequency with depth. Nearly all natural fractures observed are high angle and vertical or subvertical in orientation. Iron-stained fractures, indicative of groundwater precipitation, are observed only in core 0348 on the Main Hill. The Waynesville Formation in borehole 0349 appears almost as intensely fractured as the Liberty Formation in borehole 0348. None of the samples from the SM/PP Hill are as intensely fractured as those from the Main Hill.

The nature and distribution of natural fractures indicates that a fracture carapace is superimposed on the bedrock beneath Mound Plant. This fracture carapace is believed to consist of a network of interconnected vertical and bedding plane fractures that are water saturated in the lower parts and unsaturated in the upper parts. The frequency of fractures and the degree of interconnection decrease with depth to the point where only isolated fractures occur at depths below the fracture carapace (Figure ES.3).

ES.3.2. CHARACTERISTICS OF FRACTURES IN OUTCROP

As part of the fracture studies four vertical profiles at the railroad cut outcrop west of Mound Plant were examined (Figure ES.1). Measurements of azimuthal orientations indicate that four fracture sets are present. The first-formed fracture or primary fracture in each profile is referred to as fracture set 1, followed by secondary fracture sets in consecutive order. The orientation for fracture set 1 trends north 60 degrees west in both shales and limestones; fracture set 2 is observed to trend north 20 degrees east. Figure ES.4 depicts the frequency and distribution of fractures measured at the railroad outcrop projected across the Site. Overall, fracture orientations are generally considered the single most important characteristic of a fracture system. These orientations determine preferred flow directions in groundwater systems dominated by fracture flow. The major orientations of

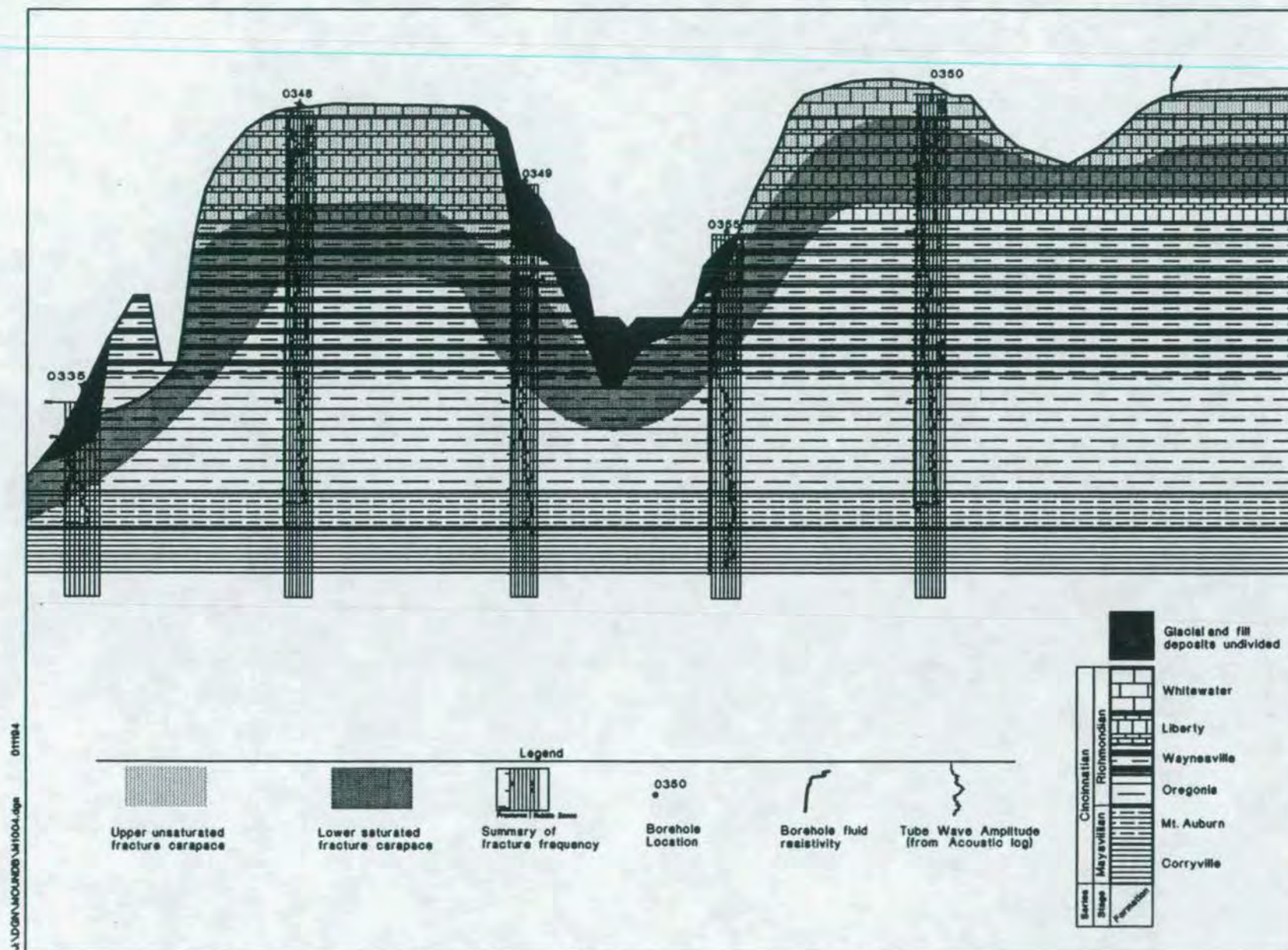


Figure ES 3. Cross-section of fracture carapace.

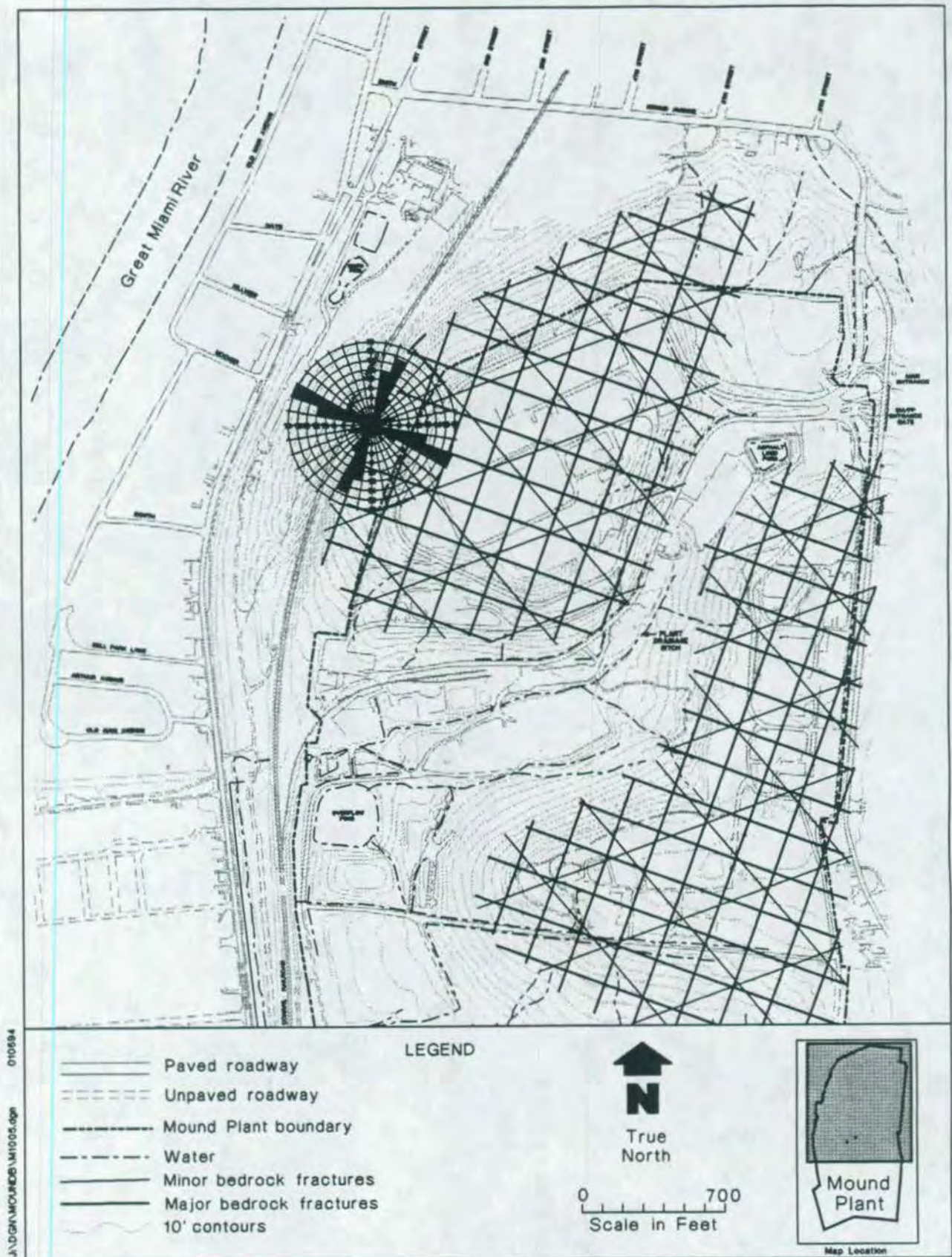


Figure ES 4. Orientations of major and minor bedrock fractures.

fractures observed at Mound Plant are, however, consistent with other studies of regional joint patterns and indicate that fracture orientations are probably inherited from the regional structure of the Cincinnati Arch.

ES.4. BOREHOLE GEOPHYSICS

The borehole geophysics studies identify 1) vertical variations in the properties of the bedrock to determine intervals that may transmit groundwater; and 2) zones of competent rock that may be aquitards. The bedrock flow system is considered to be a complex system dominated by fracture flow. Borehole geophysics provide measurements of the physical properties of rocks and the fluids within them.

Physical fracturing of the rocks in the shallow portions of the boreholes is indicated not only by direct visual observation of fractures, but also by indirect geophysical means. The pattern of the full waveform sonic logs indicate that tube waves have low amplitudes in the upper 100 ft of boreholes on the Main Hill. Tube wave energy is attenuated by fluid interaction between the borehole and adjacent formation as the wave travels between transmitter and receivers. Because permeable fractures or porous media provide a path for this interaction, these conditions reduce the energy of the transmitted wave, resulting in lower tube wave amplitude with more permeable rock. Figure ES.3 displays the relationship between tube wave amplitude and fracture frequency within the fracture carapace. Below the fracture carapace, fractures, indicated by rubble zones, are present but are not interconnected.

The flowmeter measurements and fluid resistivity indicate that groundwater flow is restricted to the fracture carapace. Flow measurements of groundwater in borehole 0348 indicate that at very shallow depths (less than 40 ft) flows are greater than the instrument can measure (greater than 1200 mL/min), decrease to 200 mL/min at depths of 40 to 60 ft, then decrease to zero by 90 ft depth. A sharp decrease in the fluid resistivity measurements occur at depths of 70 to 100 ft correlates with the deepest extent of water flow. These data are interpreted to indicate inflow of groundwater to the borehole and mixing with water standing in the borehole. Fluid resistivities are stable below those depths, indicating that pore water in the formation is relatively rich in salts that yield lower resistivities (Figure ES.5).

The EM conductivity logs also indicate the upper 60 to 80 ft of rock contains relatively fresh, meteoric water that is less conductive and more resistive than the water contained in the rocks below these depths (Figure ES.5). The less conductive zone occurs in the shale with minor limestone facies in the upper part of the Waynesville Formation in boreholes 0349 and 0355, whereas the Waynesville

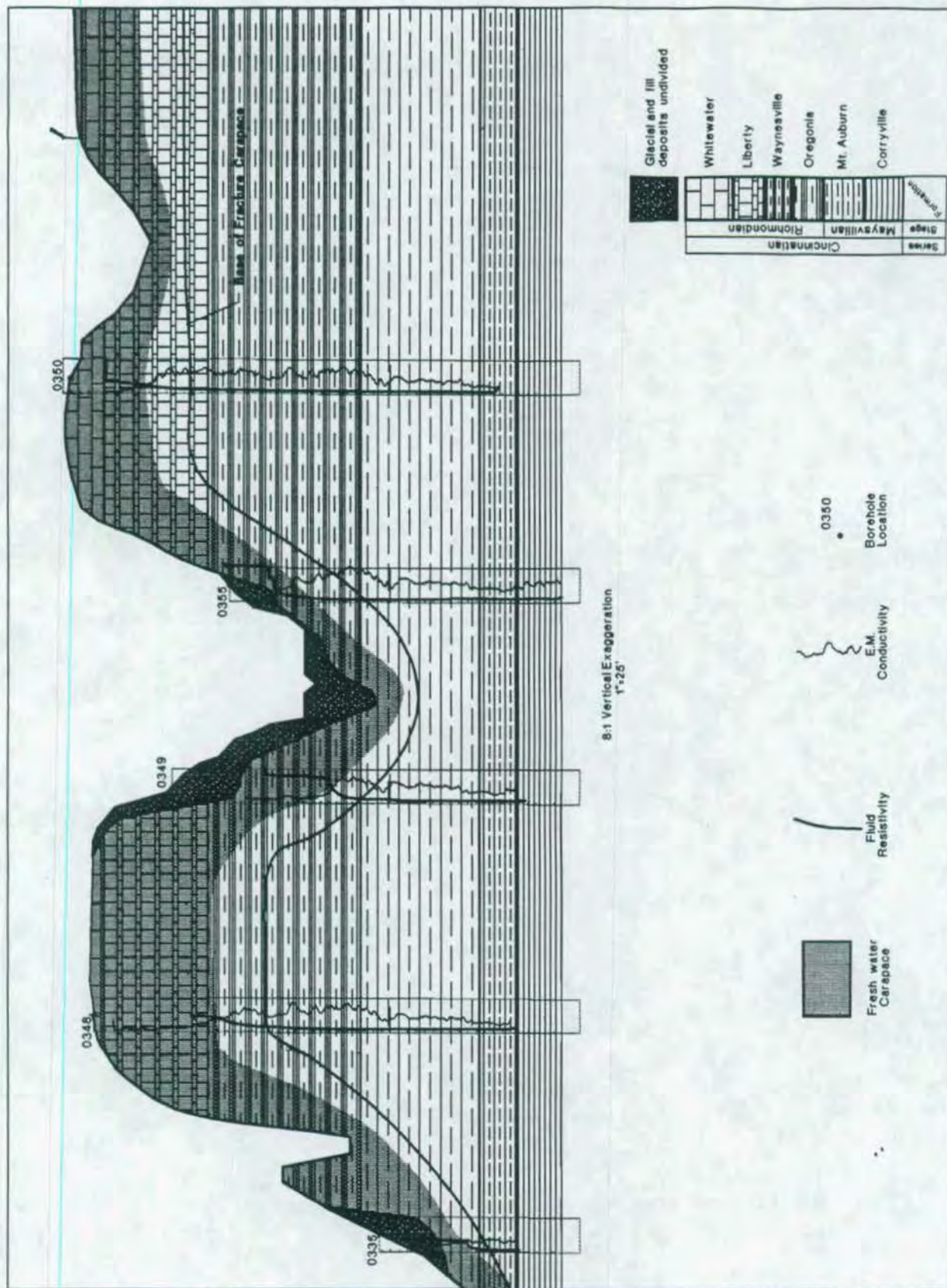


Figure ES 5. Cross-section of freshwater carapace Mound Plant bedrock.

Formation is unaffected in boreholes 0348 and 0350. The less conductive and more resistive nature of the rocks in the shallow parts of the bedrock is attributed to the leaching of salts from the rocks by meteoric groundwater. The shallow zone of fresh water is referred to as the fresh water carapace in this report. Figure ES.5 indicates that the fresh water carapace is entirely contained within the fracture carapace, but does not extend to the base of the fracture carapace.

The correlation of observed fracture frequency and tube wave amplitude with flow meter measurements, and fluid resistivities indicates that fractures control groundwater flow in the upper few tens of ft of bedrock. The fact that the fresh water carapace does not extend to the base of the fracture carapace is attributed to the decreasing groundwater flow rates with depth. Water in fractures near the base of the fracture carapace does not move very efficiently and the very slow movements have allowed little removal of the salts from the rocks. The magnitude of the changes indicate that the fresh water carapace is not as well developed on the SM/PP Hill as it is on the Main Hill.

ES.4.1. POSSIBLE PRESENCE OF A REGIONAL WATER PRESSURE SURFACE

One of the objectives of the OU 9 hydrogeologic investigations of the Mound Plant bedrock is to identify the presence of a regional groundwater surface. If this surface is present, a determination of possible communication between bedrock and the Buried Valley aquifers would be required. The OU 9 Site-Wide Work Plan recognized the unknown aspects of the fracture system and was designed to collect information concerning the possible presence of a deep, through-penetrating fracture system. If present, the postulated penetrating fracture system may have allowed vertical movements of groundwater from the shallow, contaminated zones on the Main Hill into the Buried Valley aquifer. This report presents extensive physical evidence that such a system does not exist at the Mound Plant. On the contrary, the bedrock flow that underlies the Mound Plant is contained within a fracture carapace that mantles topography. There is evidence in the data, however, to support the presence of a deeper, isolated bedrock aquifer that is unconnected to the fracture carapace.

The data from the EM conductivity logs indicates a broad zone of relatively low electrical conductivity below elevations of approximately 660 ft MSL. These lows are interpreted to represent the presence of relatively fresh water that possesses less marine salts than the enclosing rocks. This current study indicates that these rocks are overlain by shale-rich rocks of inherently low permeability; groundwater may be present under confined conditions. It is probable that the zone (660 ft elevation MSL) is not hydraulically connected to the groundwater in the fracture carapace of the upper bedrock. If this zone of groundwater is present, it is not of primary or secondary concern to groundwater pathway description.

ES.5. HYDRAULIC CHARACTERISTICS OF THE FRACTURE CARAPACE AND BEDROCK

The objectives of these studies is to 1) ascertain the degree of interconnection between the fracture carapace and the underlying bedrock; and 2) calculate hydraulic characteristics of the fracture carapace and the underlying bedrock. Techniques used to characterize the bedrock hydraulics included falling head tests, long-term water level monitoring of the fracture and non-fractured zones, and calculation of permeability from data from previous investigations.

Based on the available data, the fracture carapace and underlying bedrock have different hydraulic characteristics. The techniques used to assess the hydraulic characteristics of the bedrock do not differentiate between the upper and lower parts of the fracture carapace. The fracture carapace has permeabilities values up to 0.09 to 0.9 ft/day and the underlying bedrock has permeabilities that range from 1.3×10^{-3} to 2.9×10^{-2} ft/day. In the revised conceptual model of the bedrock flow system, permeability of the fracture carapace is believed to be greatest in the upper parts and decreases to bedrock values through the lower part of the carapace. The lower boundary of the fracture carapace, depicted in Figure ES.3, is interpreted to indicate a no-flow boundary, below which permeability is restricted to primary values of the bedrock.

The permeability of the fracture carapace and bedrock that underlie the Mound Plant is at least three orders of magnitude less than the Buried Valley Aquifer. In sharp contrast, The Buried Valley Aquifer has an average permeability of 500 to 1,500 ft/day as calculated from the 1993 OU-1 aquifer test (DOE 1993c).

ES.6. REVISED CONCEPTUAL MODEL OF THE BEDROCK FLOW SYSTEM

It has long been recognized that water is stored and transmitted principally in the shallow portions through fractures and weathered bedding planes. In the revised model (Figure ES.6), infiltration of surface water migrates vertically until it reaches the water table. Bedding plane fractures may intersect flow to divert groundwater horizontally, but the dominant migration is believed to be downward to the water table. Within the saturated fractures, the decreasing interconnection acts to reduce vertical permeability. Groundwater flow is diverted laterally through the shallower, more hydraulically conductive portions of the rock until it emerges as a hillside seep. Horizontal flow is controlled largely by open vertical fractures and bedding plane fractures that create an interconnected network. In the lower part of the fractured carapace, fractures are assumed to be present, but are poorly interconnected, so that permeability is reduced and capillary forces are probably dominant. Groundwater seeps may be present at any elevation in which saturated fractures occur, but flow at lower elevations is likely to be so low as to be imperceptible. Since the water table, i.e., the elevation

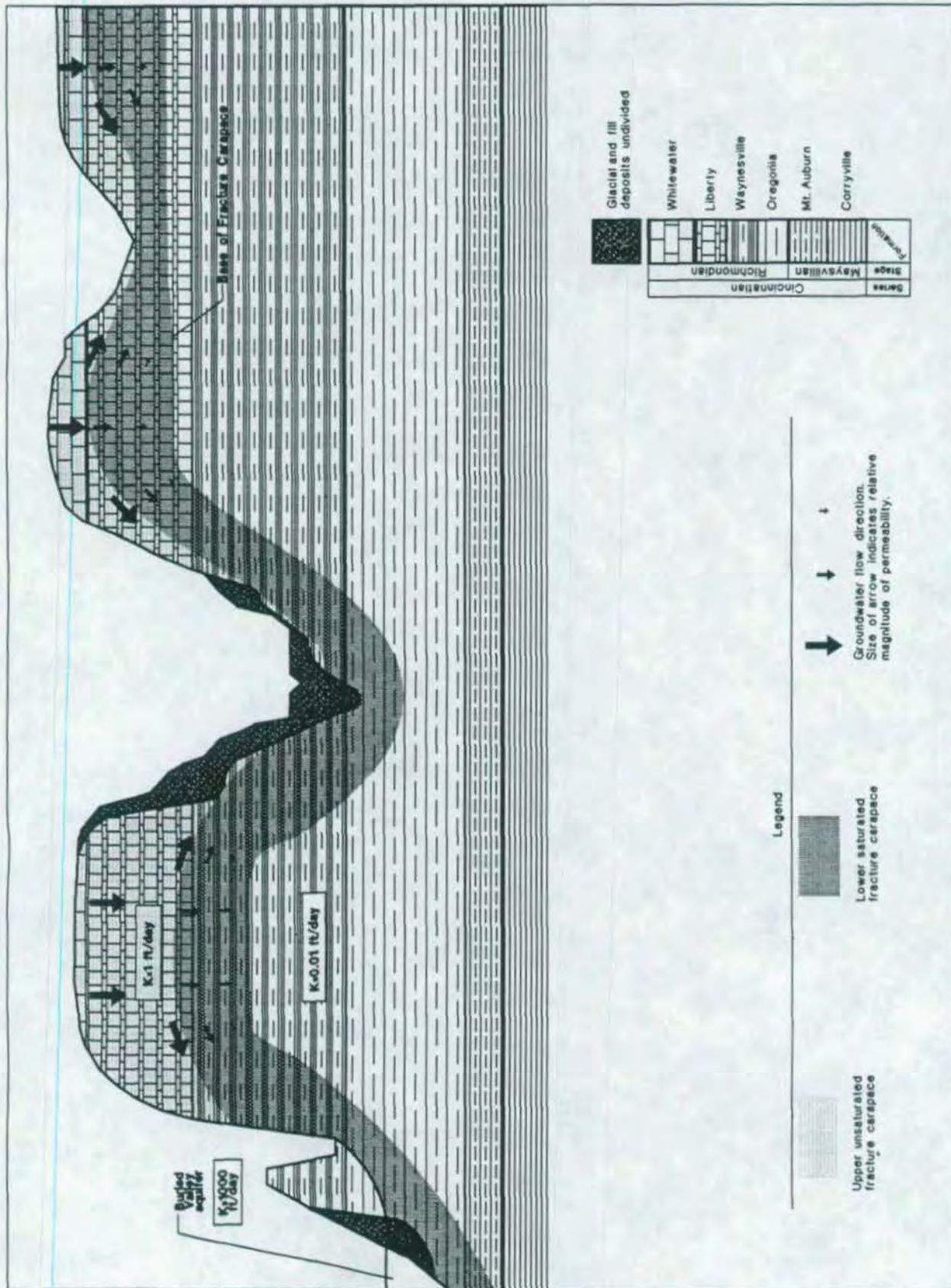


Figure ES 6. Cross-section of conceptual model of bedrock flow system.

at which fractures are saturated may change with time, individual seeps may change flow rates. Below the fracture carapace, fractures are present, but are not interconnected.

In the revised model, the Main Hill is interpreted to have different hydrogeologic characteristics than the SM/PP Hill. The Main Hill is viewed as much more intensely fractured than the SM/PP Hill, the fracture carapace extends to greater depths and measured absolute groundwater flow rates within the fracture carapace are greater. Likewise, the fresh water carapace extends to greater depths, approximately 100 ft, on the Main Hill and about half that on the SM/PP Hill.

ES.7. SUMMARY OF RECOMMENDATIONS

Lithologic and stratigraphic studies indicate that sufficient information exists about the bedrock beneath the Mound Plant. No additional lithologic investigations for the OU 9 hydrogeologic studies are warranted.

The strong correlations between fracture frequency, water flow measurements, and the alteration characteristics of the marine bedrock indicate that the objectives of the OU 9 bedrock studies have largely been obtained. Two outstanding issues remain. First, there is little data to indicate that the fracture orientations of the SM/PP Hill are indeed the same as the Main Hill. Additional limited investigations should be conducted on smaller outcrops on the SM/PP Hill complex and perhaps the surrounding community to ascertain the dominant orientations of fractures. Second, continuous bedrock cores are stored at Miami University in Oxford, Ohio. The examination of these cores was not made in time to include data in this report. It is recommended that the logs be examined for fracture characteristics. These cores may provide an important auxiliary data point for the fracture studies.

The results of the extensive suite of borehole geophysics performed indicate that sufficient information exists on the characteristics of the bedrock flow system beneath Mound Plant to satisfy the objectives of OU 9. No additional borehole investigations are recommended under OU 9. However, site-specific investigations concerning hydraulic characteristics of the fracture carapace may be warranted by other OUs as source term investigations proceed.

The suggestion that a regional ground water surface may be present indicates that additional water level measurements are appropriate in the deep boreholes. It is recommended that water from the lower portion of the boreholes be removed to the extent possible and allowed to recharge under natural conditions. Instrumentation to continuously monitor the recharge will be installed to supply data for calculation of hydraulic conductivity. Recharge of the continued, regional aquifer, if it exists at 660 ft MSL, will be measured.

The final disposition of the boreholes requires considerable thought. The amount and detail of lithologic, hydraulic, and geophysical data for these bedrock locations are unsurpassed anywhere else on the Mound site. It is recommended that the closure plan for these boreholes evaluate options which allow the installation of specialized instrumentation for obtaining additional hydrogeologic data in lieu of simply sealing with grout.

Consideration will be given to additional hydraulic testing in the five remaining open bedrock boreholes at the Mound Facility. Both active and passive testing techniques will be contemplated. An example of active testing techniques will include straddle packer tests in selected zones to better determine permeability. Another active test to consider will be a single-well tracer test to determine the effective porosity of the bedrock unit.

Passive monitoring is suggested to observe recharge rates and possible piezometric surfaces below the fracture carapace. Once the lower portion of the borehole has been isolated and evacuated of standing water, long-term water level recovery will be documented. This data will be analyzed in concert with other meteorological information to quantify ground water movement. Passive monitoring of ground water temperature in the upper bedrock is suggested to determine zones of greatest groundwater movement under natural flow conditions.

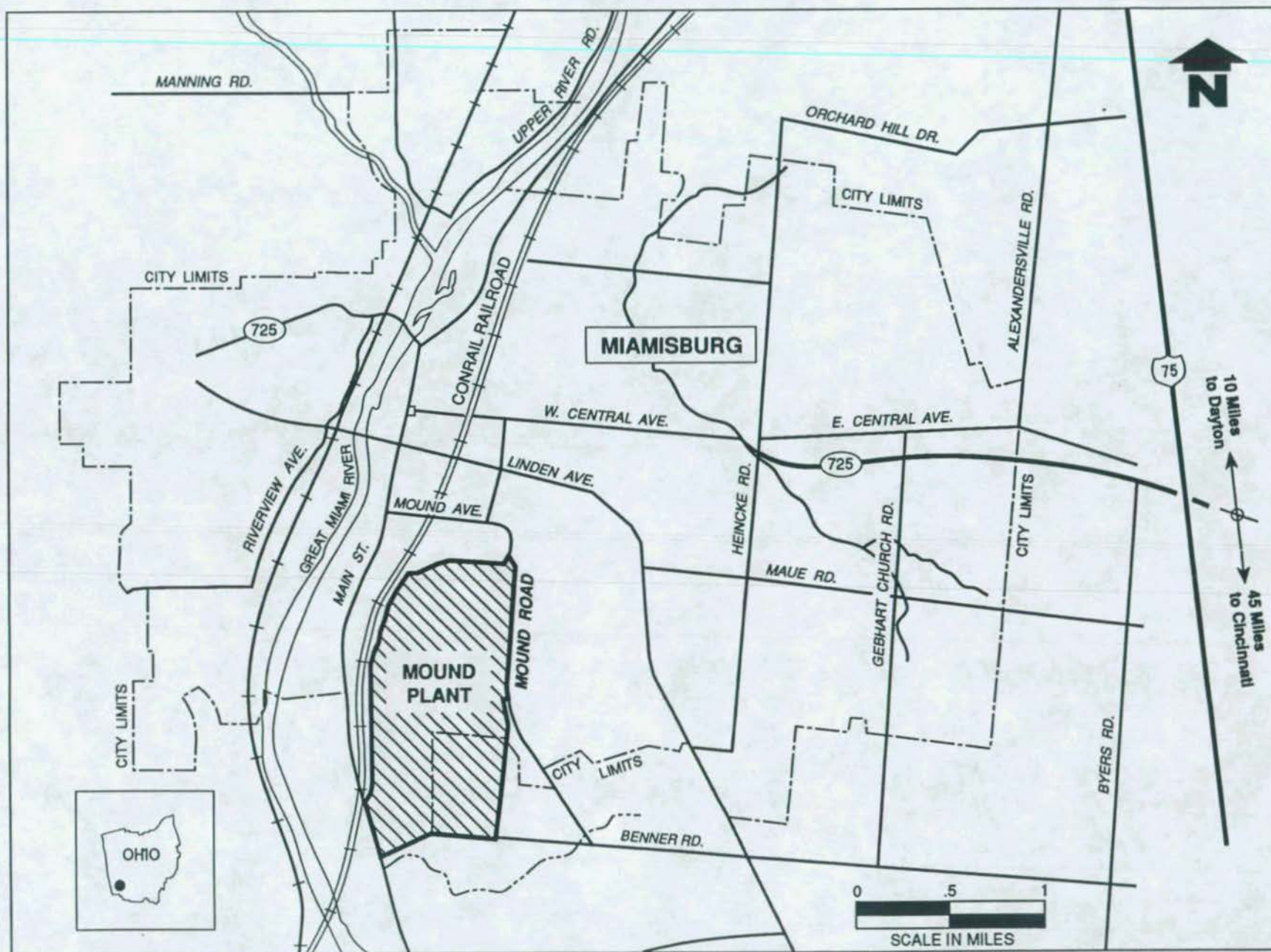
1. INTRODUCTION

The Mound Plant in Miamisburg, Ohio (Figure 1.1) is operated for the U.S. Department of Energy (DOE) by EG&G Mound Applied Technologies. The plant started operation in 1949 and is an integrated research, development, and production facility that operates in support of the DOE weapons and energy programs (DOE 1993a).

The Mound Plant was placed on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, also known as Superfund) National Priorities List (NPL) on November 21, 1989, (54 Federal Register 48184). The facility was added to the NPL as a consequence of historic disposal practices and releases of contaminants to the environment. Pursuant to its NPL status, the DOE signed a CERCLA Section 120 Federal Facility Agreement (FFA) with the U.S. Environmental Protection Agency (EPA) that became effective October 11, 1990, (Administrative Docket #VW-'90-C-075). The Ohio EPA (OEPA) became a signatory to the agreement in July 1993. The terms of the FFA require that the DOE develop and implement remedial investigations (RIs) and feasibility studies (FSs) and conduct interim remedial actions to ensure that environmental impacts associated with past and present activities at the site are thoroughly investigated and appropriate action is taken to protect the public health, welfare, and the environment.

Due to the number of potential release sites (more than 300) and the overall complexity of the RI/FS, the site is divided into nine operable units (OUs) to facilitate program management (DOE 1992a). Currently, six OUs remain; the others have been closed. Operable Unit 9 is designated for site-wide studies that provide the framework for the RI/FS. Investigations that are best conducted for the entire Mound Plant and its regional setting are included in OU 9. As described in the OU 9 Site-Wide Work Plan (DOE 1992a), the hydrogeologic investigations address the hydrogeologic environment of Mound Plant and the nature and extent of groundwater contamination outside the plant boundaries. The characterization of potential source terms within the plant is generally deferred to other OU investigations. Because of the scope of the OU 9 hydrogeologic investigations, the work required to fulfill the objectives is phased. Technical memoranda that describe methods and results of the OU 9 hydrogeologic investigations is subdivided into the following technical memoranda:

- Well Information Report
- Bedrock Report
- Glacial Report
- Soil Chemistry Report
- Groundwater Sweeps Report



Mound location map/7-26-93

Figure 1.1. Location of Mound Plant, Miamisburg, Ohio.

1.1. SCOPE OF REPORT

This report technical memorandum of investigative work was developed as part of the OU 9 hydrogeologic investigations in accordance with the OU 9 Site-Wide Work Plan (DOE 1992a). It focuses on the groundwater flow system in the bedrock that underlies Mound Plant. This system was considered in the OU 9 Site-Wide Work Plan to be dominated by fracture flow, an assumption confirmed in this report. This report provides descriptions of the methodologies and results of work conducted to refine knowledge of the physical characteristics of the bedrock flow system, including lithology, stratigraphy, and alteration profile of the rocks, as well as frequency and orientations of fractures. Investigations of the bedrock include the collection and description of continuous core from six boreholes, a complete suite of geophysical logs in the boreholes and physical measurements of lithology and fractures at an exposed outcrop in a railroad cut west of Mound Plant.

Each of the major sections are subdivided into objectives, methods, results, and discussions. Since this investigation reveals many striking similarities as well as differences between the bedrock characteristics that underlie Main and SM/PP Hills, major discussions center on these two physiographic features.

Section 2 establishes the lithology and stratigraphy of the rocks that comprise the bedrock immediately beneath the plant. Plate 1 provides a general lithologic cross section of the Mound Plant. Detailed lithologic logs of the continuous core and the railroad cut outcrop are provided in Appendix A.

The fracture profile superimposed on the bedrock is established in Section 2. The profile consists of a system of interconnected fractures that generally mimic topography; it is referred to as the fracture carapace in this report. Plate 2 provides a cross section and profile of the fracture carapace. Plate 3 is a map of the general orientations of fractures in the Mound Plant bedrock. Detailed fracture logs of the continuous core and the railroad cut outcrop are provided in Appendix B.

Detailed descriptions of the borehole geophysical measurements conducted in the six boreholes are included in Section 4. These measurements were designed to establish the weathering profile and the extent of groundwater movements within the bedrock. The weathering profile consists of a relative shallow zone in which meteoric water has removed much of the original salts from the marine rocks. In this report, this alteration profile is referred to as the fresh water carapace as it resides in the fracture carapace. Plate 4 provides a cross section of the Mound Plant bedrock and the freshwater carapace. Data sheets of the complete suite of borehole geophysical measurements are included in Appendix C.

Section 5 provides quantitative estimates of the hydraulic properties of the bedrock flow system. Estimates are provided for the primary permeability of the bedrock and the secondary fracture permeability of the fracture carapace.

Descriptions of the revised conceptual model of the bedrock flow system are in Section 6. Plate 5 is a cross section of the conceptual model.

Summaries of the recommendations for additional work are given in Section 7. These recommendations are discussed in the preceding sections as appropriate and are summarized in Section 7 for ease of reference.

1.2. OVERVIEW OF PLANT PHYSICAL CHARACTERISTICS

The plant boundaries include the developed areas containing the Main Hill and SM/PP Hill on the north or old property and the undeveloped area on the south or new property. The plant comprises 306 acres with approximately 182 acres on the north property and 124 acres on the south property. The U.S. Geological Survey (USGS) 7.5-minute quadrangle for Miamisburg, Ohio, maps this area at 80° 17' 20" north latitude and 39° 37' 30" west longitude included in the Site Scoping Report: Volume 5, Topographic Map Series (DOE 1992b).

The dominant physical features of the Mound Plant are the two adjoining hills (Main and SM/PP) that are underlain by Ordovician Age bedrock and a thin veneer of glacial till. A plant drainage ditch flows through the center of the plant site, dividing the Main Hill and the SM/PP Hill (Figure 1.2). The crests of these hills average 880 ft above mean sea level (MSL); the plant drainage ditch begins at an elevation of 770 ft MSL and discharges into the retention basins at 706 ft MSL. Most of the north property drains into the plant drainage ditch, which discharges into the southern portion of the Miami-Erie Canal.

The topography of the south property is gradually sloping from a high point of 890 ft MSL in the northeastern corner to a low point of 700 ft MSL at and along the western boundary. The general surface water flow on the south property is from east to west toward the Miami-Erie Canal.

1.3. OVERVIEW OF OPERABLE UNIT 9 BEDROCK FIELD PROGRAM

The OU 9 hydrogeologic investigation characterization of the bedrock flow system was accomplished by 1) the collection of continuous bedrock core from six boreholes (Figure 1.3) for descriptions of fractures and lithology; 2) geophysical measurements performed in the boreholes; 3) four vertical



Figure 1.2. General topography of Mound Plant.

profiles mapped on the face of an outcrop along the railroad cut located along the western boundary of the Mound Plant (Figure 1.3); and 4) calculations of permeability of the fracture carapace and underlying bedrock.

The bedrock boreholes required the services of three drill rigs. A roto-sonic device was used to obtain the initial core to bedrock, and a cable-tool rig enlarged the hole so a 10-inch casing could be installed to stabilize the surface construction. Figure 1.4 depicts the general surface construction of the boreholes. An air rotary drill was used to advance an NQ-size core barrel. Compressed air was used to encounter groundwater and a water mist kept the cuttings from clogging the drill. The boreholes varied in depth from approximately 81 to 250 feet (ft) below ground surface to a common elevation of about 625 ft above mean sea level, which is about 50 ft below the normal stage of the Great Miami River. Table 1.1 summarizes the borehole specifications. Overall, core recovery was approximately 95 percent.

After coring, the boreholes were flushed with potable water from the plant supply until the waste stream ran clear. The boreholes were allowed to stabilize about one week before the borehole geophysics were conducted. The borehole video camera was the first instrument in the borehole, because the system required clear, sediment-free water to perform. The boreholes stabilized for 48 hours before the borehole fluid resistivity and temperature measurements were made. To perform some measurements, the boreholes were stemmed or filled with potable water. For the borehole flowmeter tests under stressed conditions, a supply of water was metered into the borehole so that a constant water level was maintained at the top of the casing. Conditions of separate tests are detailed in Section 4 of this report.

After the borehole geophysics were complete, borehole 0335, located offsite, was reamed to an 8-inch diameter and completed as a monitoring well. Specifications of the well are included in the OU 9 Hydrogeologic Investigations: Well Information report (DOE 1994). The other five boreholes have not been completed as wells. Packers were installed in the five boreholes immediately after the geophysics were complete and water levels monitored for a 90-day period. Currently, the boreholes remain open with the packers in place.

The outcrop mapping at the railroad cut originally called for 10 traverses. The high percent of core recovery and detailed lithologic correlations across the site indicates that more than four traverses would not provide additional data. The limited vertical extent of the outcrop does not provide the coverage of the cores. The truly important contribution of the outcrop investigation is to provide detailed data concerning fracture azimuthal orientation, not available in the cores.

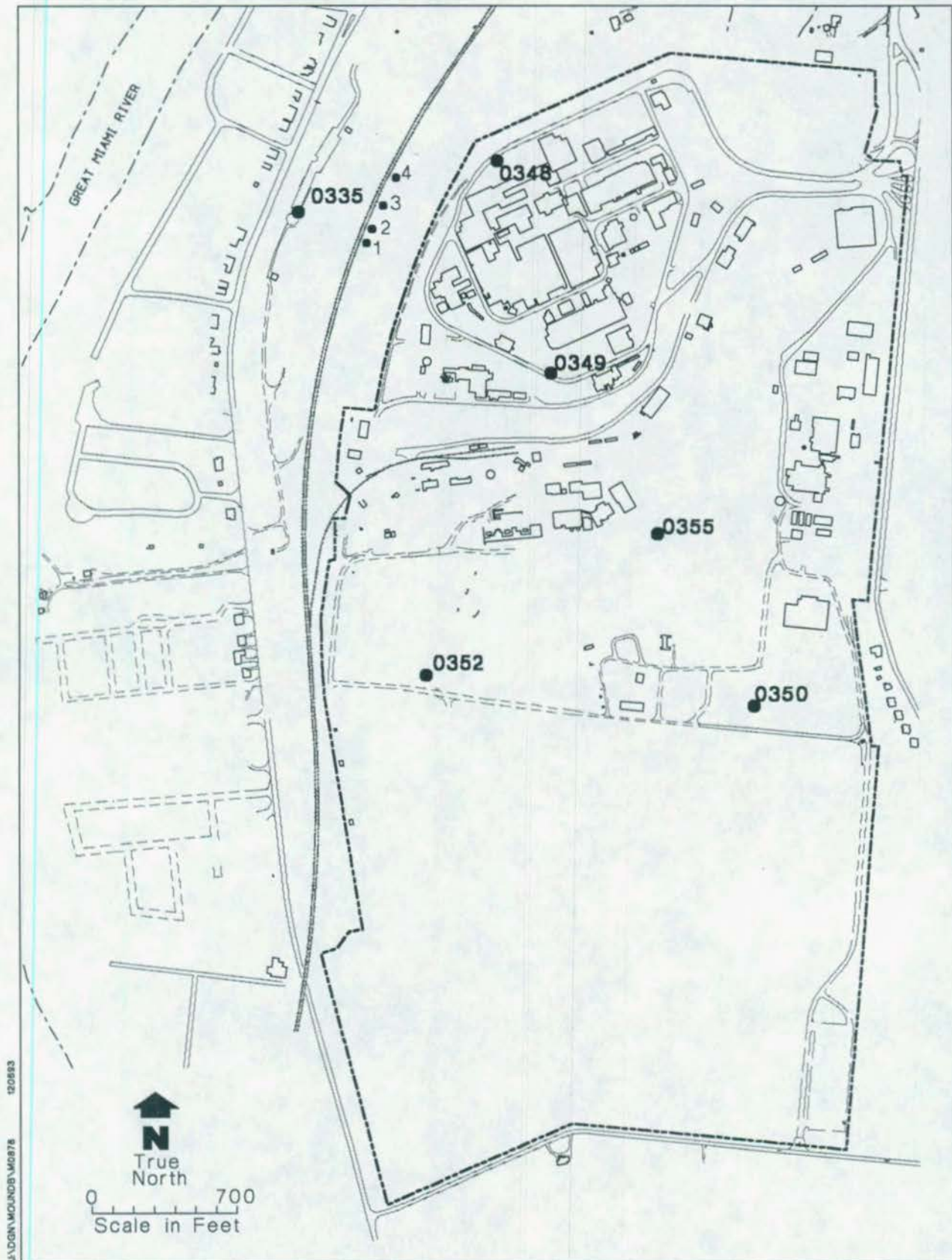
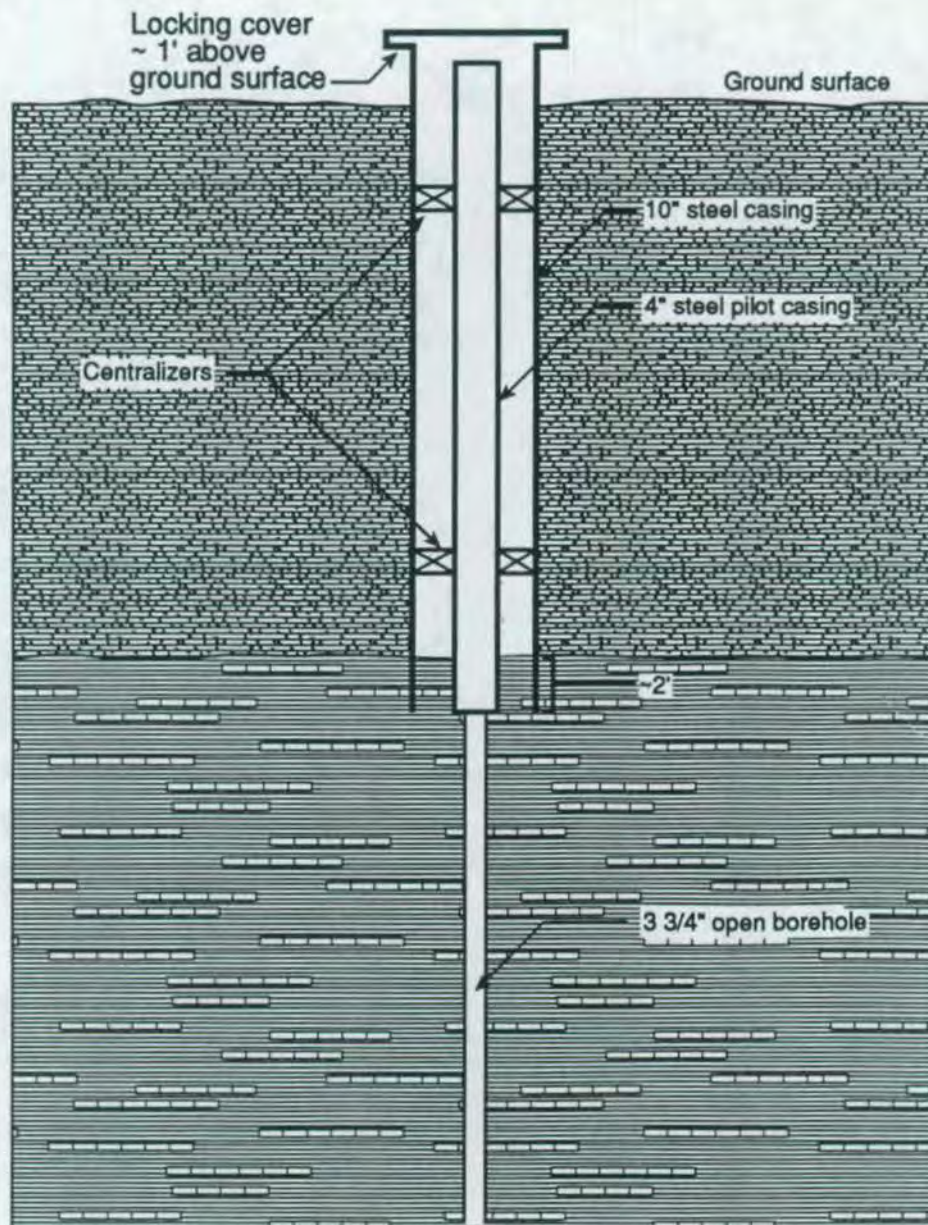


Figure 1.3. Location of bedrock boreholes and railroad cut survey locations.

NOT TO SCALE



LEGEND

- Low permeability  Glacial till: clay containing variable proportions of gravel, sand, and silt
- Variable fracture permeability  Bedrock: interbedded shale and minor limestone

MND/FFA/PR-RPT#4-01/4-93

Figure 1.4. Typical surface construction of bedrock boreholes.

Table I.1. Borehole Specifications

Borehole Location	Water Level (ft ^a)	Bit Size (in)	From (ft)	To (ft)	Casing Size (in)	From (ft)	To (ft)
0335	14.5	10 3 7/8	0 27	27 80.7	10 4	0 0	27 28.5
0348	19	10 3 7/8	0 10	10 249.7	10 4	0 0	10.5 15.5
0349	51	10 3 7/8	0 ND	38 203.6	10 4	0 0	38 40
0350	22	10 3 7/8	0 8	8 251	10 4	0 0	8 12
0352	5	10 3 7/8	0 20	20 101.4	10 4	0 0	20 21.8
0355	1	10 3 7/8	0 26	26 197.4	10 4	0 0	26 27

^aFt below ground surface.

2. LITHOLOGY AND STRATIGRAPHY

A detailed investigation of the bedrock that underlies the Mound Plant has been conducted as part of the Operable Unit 9 hydrogeologic investigations. The lithologic studies will refine the lithologic database to assist in establishing the hydraulic properties of the bedrock flow system. The bedrock flow system is considered to be a complex system in which weak groundwater flow along the interface of limestone and shale beds is enhanced by local fractures. The studies provide data that identify preferential pathways of groundwater movement along probable permeable beds and bedding planes. Initial descriptions of the bedrock lithology were provided in the OU 9 Site-Wide Work Plan (DOE 1992a) and the Site Description and Safety Assessment Report (Dames and Moore 1973). These previous studies did not provide sufficient detail to resolve specific questions concerning the characteristics of the bedrock flow system. Previous qualitative models of the bedrock flow system required the presence of thick beds of impermeable shale that restricted the flow of shallow groundwater. The actual presence and possible extent of the beds on a site-wide basis were unknown in any detail and have not been substantiated by this investigation.

The subsections that follow provide descriptions and results of the investigations of the lithology and stratigraphy of the bedrock beneath Mound Plant and places it within regional context. Since the bedrock consists of relatively thinly interbedded shales and limestones, descriptions of bed fabrics are provided in detail. Since each fabric element cannot be evaluated, the fabrics that compose the physical components of the rocks are grouped into packages called facies. These facies are grouped into larger packages called formations. The facies have no meaning outside the context of this report. The formations are regionally recognized rocks that have been given formal names.

2.1. METHODS OF STUDY

As part of the Operable Unit 9 hydrogeologic investigations, six continuous cores were obtained from the boreholes (Figure 1.3). The cores were visually examined for percent shale, fossil assemblage, bedding, sorting, color, texture, structure, and fabric. These types of descriptions are often made using thin-sections or other polished slabs. The descriptions of the Mound Plant bedrock cores and outcrop were made entirely by hand-specimen observations in a nondestructive manner; cores were not broken or damaged during observation. Information was recorded on prepared logging forms in general accordance with the Handbook for Logging Carbonate Rocks (Bebout and Loucks 1984). Information was gathered in detail in 0.1-ft intervals and recorded on prepared forms. Copies of the logs are in Appendix A. Data from each core for percent shale and fabric were digitized to allow graphic comparisons with the geophysical data.

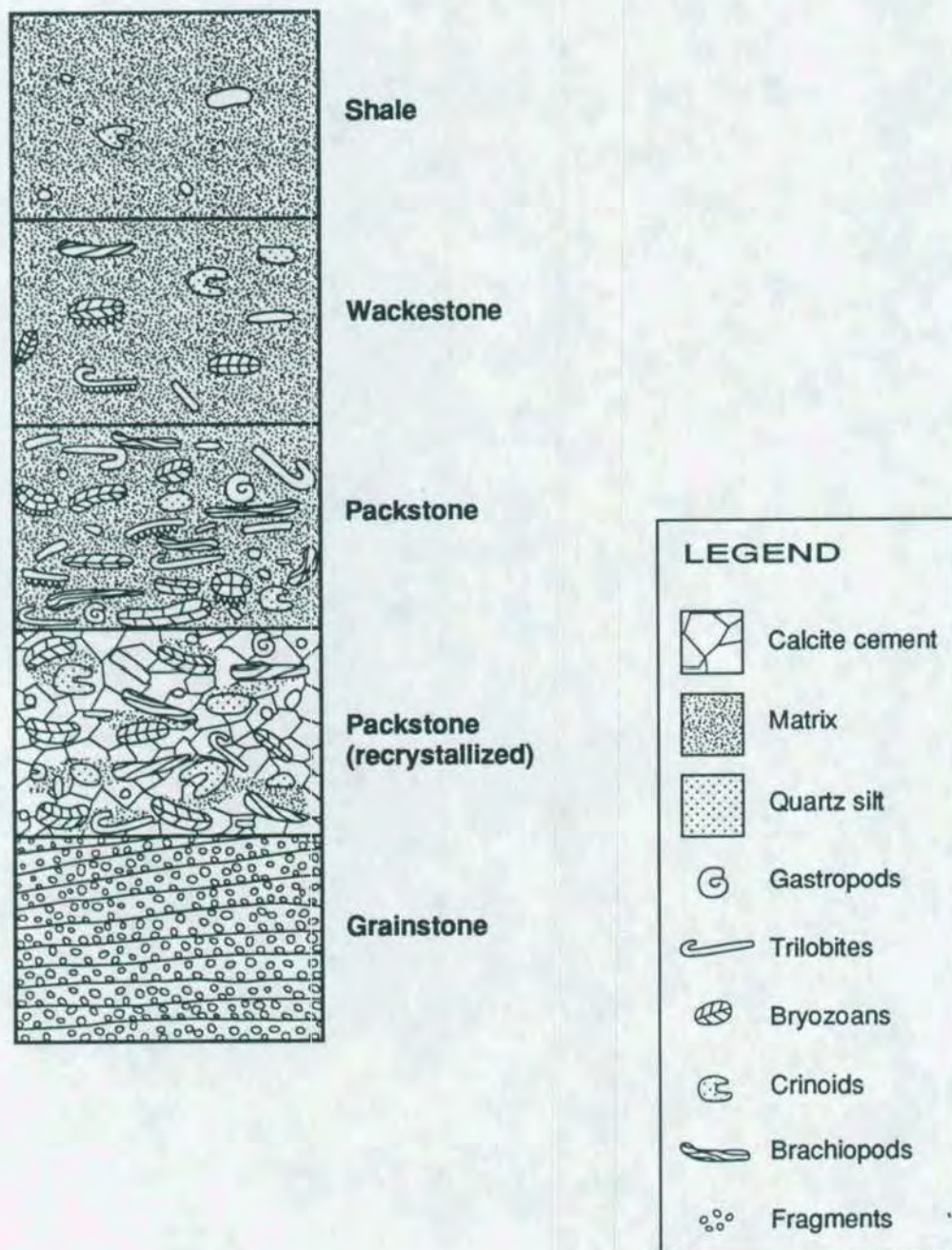
In addition to the cores, four vertical profiles of the bedrock exposed on a railroad cut west of the plant were examined. The mapping exercise included parameters similar to those examined in the core. Since the outcrop does not possess a truly vertical cliff, the data was collected by distance down the slope and the slope angle. For comparisons with the other data, the slope distance has to be recalculated to true stratigraphic thickness. The OU 9 Site-Wide Work Plan (DOE 1992a) originally called for 10 vertical profiles, but this was deemed unnecessary when the high quality of the core was determined. The outcrop at the railroad cut is interpreted to expose only the rocks of the Waynesville Formation (described below). Additional vertical profiles would not provide additional usable information.

2.2. DESCRIPTION OF LITHOLOGIC FABRICS

Lithologic fabric refers to the arrangement of the physical components within a rock. Four lithologic fabric types were observed in the bedrock at the Mound Plant: mudstone, packstone, wackestone, and grainstone. The definitions are after Dunham (1962). These classifications are descriptive in order and indicative of the relative amounts of mud, particles smaller than 20 microns, and grains, particles greater than 20 microns. Grain support refers to sufficient abundance of grains in a fabric so that the grains support one another. Mud-supported is the condition in which grains are not so abundant as to support one another, but are observed to be "floating" in a mud matrix (Figure 2.1). In the sense of carbonate petrology, these classifications allow distinctions to be made between those sediments deposited in calm water as opposed to those sediments deposited in agitated water, inasmuch as calm waters allow the settling of mud. From the hydrogeologic viewpoint, rocks such as packstones tend to be porous and may possess higher natural permeabilities. Rocks such as mudstones tend to have very low natural permeabilities. The natural permeabilities of packstones may be quite low also, as the interstitial mud tends to seal all pores. Secondary porosity may be imparted on the rocks by leaching of mud from pores. A few layers of pure clay were observed and are referred to as claystones in the descriptions that follow.

Grainstones

For the purposes of this report, grainstones are defined as grain-supported, well-sorted limestones containing less than 10 percent mud (Dunham 1962). The grainstones observed in the bedrock at the Mound Plant are typically medium gray and are composed of reworked skeletal grains of calcium carbonate and calcium carbonate cements. The grainstones are typically very well sorted with grain sizes varying from very fine (1/16 mm) to fine (1/4mm). Although the presence or absence of mud within the grainstone was not obvious in hand specimens due to the crystalline nature of the sediments and the secondary recrystallization of the calcium carbonate muds within the sediments, it is



MND09 Bedrock-01/12-20-93

Figure 2.1. Schematic diagram of lithologic fabrics observed at Mound Plant.

interpreted that the physical actions which created these well-sorted conditions would remove the fine clay and silt-sized mud particles. Therefore, the rock fabric classification of grainstone is based upon the well-sorted nature of the limestones. Few grainstones are observed in the bedrock at Mound Plant. No primary porosity is observed in any of the grainstones; however, secondary porosity is observed as fractures.

Structurally, the grainstones are found to be thinly bedded (0.2- to 0.5-ft thick). Some very thin (<2mm) laminations of grainstone are observed in the mudstones as horizontal or streaky laminations. Traces of nodular grainstones are also observed in the core. Bedding features within individual beds of grainstone are not evident in either the core or in the grainstones exposed in the outcrop. Contacts between individual beds of grainstones and mudstones are generally described as sharp irregular; however, some gradational contacts with packstones are observed.

Internal structures and paleofauna are not features observed within the grainstones. Because of the well-sorted nature of the grainstones, there is an absence of clay laminations, stylolites, and other diagenetic features. Additionally, bioturbation and burrows are not observed in the grainstones. Because of the fine grain sizes associated with the grainstones, individual bioclastic fragments of fossils large enough to determine species are not present.

The well-sorted nature of the grainstones and the thorough decimation of bioclastic grains within the grainstones indicate that the grainstone sediments were deposited in a shallow marine, near shore, moderate-to-high energy environment. The mechanism of sorting within the grainstone sediments can be attributed to either wave action and/or tidal influences suggesting such a near shore environment. However, sediments deposited in such an environment are usually extensively bioturbated (Holland 1993), indicating that the unbioturbated grainstones observed at the Mound Plant may be somewhat unusual.

Packstones

For this report, packstones are defined as grain-supported limestones containing some mud matrix (Dunham, 1962). The packstones observed are typically medium gray and are composed of reworked skeletal grains of calcium carbonate-producing organisms and calcium carbonate muds. Grain sizes and crystallinity vary from very fine (<1/16mm) to very coarse (>2mm), and the packstones are typically poorly sorted. Recrystallization of the sediments after deposition has altered most of the calcium carbonate materials, including the carbonate mud matrix, which causes the packstones to have an apparent wide range of crystallinity. Because of secondary recrystallization of the carbonate mud matrix, the mud matrix is often difficult to distinguish in hand specimens from the primary crystallized

sedimentary features. Therefore, the rock fabric classification of packstone was determined from the degree of sorting and the varying crystallinity within each limestone (i.e., poorly sorted limestones with a fine-to-coarsely-crystalline appearance were interpreted to be packstones). Generally, the packstones observed below an elevation of 667 ft MSL were more coarsely crystalline than the packstones observed upsection. No primary porosity, with the exception of a few isolated and noninterconnected vugs, is observed in the packstones; however, secondary porosity is observed as fractures.

Structurally, the packstones are found to be very thin to medium bedded (.05- to 1.0-ft thick). Some very thin (<2mm) laminations of packstone are observed in the mudstones as horizontal or streaky laminations. Bedding features within individual packstones are more evident in the exposed weathered outcrops due to differential weathering of the beds, than in the freshly exposed packstones observed in the core. Individual packstones observed in the core are massive with very thin (generally <2mm) laminations or varves of clay material. These very thin clay laminations have been weathered away in the exposed packstones found in the outcrop giving some of the outcropping packstones a bedded appearance. In addition to the bedded packstones, nodular packstones are observed in the core. These nodular packstones varied in size and were generally found in a mudstone matrix. Contacts between interbeds of packstones and mudstones are generally described as sharp-irregular; however, some gradational and visibly-scoured contacts are present. Burrowed and bioturbated contacts are frequently observed, but are more easily distinguished in the core samples than in the exposed outcrop. Sharp conformable and sharp disconformable contacts are often difficult to distinguish.

Internal structures within the packstones consist of stylolites, intraclasts, burrows, clasts, fining upward sequences, and crossbedding. Often, burrows and bioturbation are common giving the packstones a highly disturbed appearance. Fining upward sequences are observed infrequently and are generally gradational with the overlying mudstone beds. Cross bedding is observed in very few instances. Intraclasts are frequently observed in the packstones.

The paleofauna observed in the packstones consisted primarily of thin-walled brachiopods and, to a lesser extent, branching bryozoa. Rugose corals are present in the uppermost limestone unit, but are not observed below an elevation of 850 ft MSL. Pelecipods and gastropods are present in the packstones interbedded in the limestone/shale facies and in the shale minor limestone facies (subsection 2.3). Very few trilobites or trilobite parts are observed in the packstones logged in the core, but are somewhat more evident in the packstones logged in the outcrop. Thin-walled brachiopods are dominant throughout most of the bedrock section; however, the occurrence of thick-walled brachiopods increases with depth and, eventually, thick-walled brachiopods become dominant below an elevation of 629 ft MSL.

Generally, the packstones observed at the Mound Plant appear to be very similar in composition and subsequently were probably deposited in similar environments. The paleofauna and composition of the packstones suggest that they are moderately shallow marine in origin, possibly deposited in a moderate-to-low-energy environment such as a subtidal or restricted shelf, bay, or lagoon. The relatively low to medium faunal diversity yet large volume of individual fossil fragments (i.e., predominantly thin-walled brachiopods and branching bryozoa found as pavements) and the abundance of burrows and bioturbation are indicative of a subtidal or restricted, moderately shallow marine, low energy environment (Enos 1983). Additionally, the dominance of thin-walled brachiopods and thin delicate bryozoa, poorly sorted nature of bioclasts, and lack of structural features formed by water current and/or wave action (ripple marks, oolites, and other peloid carbonate structures) suggest the majority of the packstones were deposited in a moderately low energy environment. Occasional fossil assemblages of thick-walled brachiopods and thick-stemmed bryozoa found in some packstones may indicate that these packstones were deposited in a higher energy, possibly intertidal environment. However, these morphologies are not uncommon to a mid-shelf habitat which is consistent with the depositional environment of packstones containing thin-walled brachiopods (Holland, 1993).

Wackestones

For the purposes of this report, wackestones are defined as limestones that contain more than 10 percent grains and are mud-supported with particles of clay and fine silts (Dunham 1962). The wackestones observed are dark gray to dark greenish gray and are generally bioclastic, composed of a terrigenous clay and silt matrix with pavements or an abundance of calcium carbonate skeletal grains and fossil fragments. Some wackestones containing intraclasts of calcium carbonate nodules and streaky laminae are observed. Grain size varies from the $<1/16$ mm matrix to >2 mm fossil and nodular grains. No primary porosity is observed in the wackestones and very few fractures yielding secondary porosity are observed. What few fractures that are observed in the wackestones tend to be healed.

Structurally, the wackestones are found to be thinly bedded (0.1- to 0.8-ft thick). The beds of wackestones are usually gradational within the silt and clay mudstones and are associated with bioclastic accumulations of paleofauna. Wackestones, which are easily observed in the freshly exposed core, are difficult to identify in the exposed outcrop to the effect of differential weathering removing the more resistant calcium carbonate bioclasts from the easily weathered clay and silt matrix. Because weathering has removed much of the bioclastic material, washing the bioclastic material down the face of the outcrop, many of the wackestones identified in the bedrock core may be logged as mudstones in the outcrop. Correlations of fabric from core to core and core to outcrop were deemed nearly hopeless, so groups of fabric types were created as facies.

Internal structures within the wackestones are difficult to distinguish. Some streaky laminations and nodules of carbonate materials are observed. Evidence of bioturbation is also observed, giving the wackestones a highly disturbed appearance.

The paleofauna observed in the wackestones primarily consists of well-preserved thin-walled brachiopods and branching bryozoa, found in pavements or abundant accumulations. Other fossil types, (pelecipods, gastropods, and trilobites) are present in only trace quantities. These pavements of bioclasts are usually observed to have one dominant fossil type with only one or two minor fossil type constituents.

The abundance of terrigenous clays and silts associated with most of the wackestones and the well preserved nature of the fossil fragments found in most of the wackestones suggests that these sediments were deposited in low energy offshore, deeper water environment (Holland 1993). Some wackestones were observed to have a highly disturbed appearance containing abundant packstone intraclasts within a mudstone matrix indicating that these wackestones may have been deposited in water shallow enough to permit wave base disturbance during storm events.

Mudstones

For the purposes of this report, mudstones are defined as shales (non-carbonate rocks) that contain less than 10 percent fossil grains and are mud-supported with particles of clay and fine silts (Dunham 1962). The mudstones observed are dark gray to dark greenish gray, and are predominantly composed of terrigenous clays and silts with a particle size of $< 1/16$ mm. The mudstones are non- to very calcareous, grading at times to a true carbonate mudstone. True carbonate mudstones, known as micrites, are observed primarily in the uppermost limestone-dominant facies in core 0350, and very rarely observed in the lower portions in the other five cores. The silt content in the mudstones varies from slightly silty to very silty, with some gradation to a silt-dominant mudstone. The mudstones contain no visible primary porosity and very few fractures yielding secondary porosity. What few fractures that are observed in the mudstones tend to be healed.

Structurally, the mudstones are found to be very thinly laminated (< 2 mm) to medium bedded units of 2 to 3 ft in thickness. Due to weathering, bedding features within individual mudstone units are much more apparent in the outcrop than in the core. The mudstones tend to be platy in texture and, occasionally, blocky in texture. The clay dominant mudstones tend to be brittle and somewhat splintery when observed as fresh in the core samples and are occasionally somewhat fissile. The silt-dominant mudstones tend to be more massive and less platy than the clay-dominant mudstones, and are more resistive to weathering in the exposed outcrop.

Internal structures within the mudstones are difficult to distinguish. Burrows and bioturbation are observed usually at or near the contacts with packstones. Some mudstones contain streaky laminations of carbonate materials and nodules of packstone material. These nodular packstones are present in only a few of the mudstone dominated sequences.

The paleofauna observed in the mudstones primarily consists of thin-walled brachiopods, thin branching bryozoa, and trilobites. Generally, the biomass of paleofauna in the mudstones is considerably less than the biomass of paleofauna noted in the packstones and wackestones. Although occasional pavements of thin-walled brachiopods and/or branching bryozoa are observed, a majority of the mudstones logged at the Mound Plant contain only fragments of trilobites.

The majority of mudstones observed are composed of terrigenous silts and clays deposited in an offshore, deeper water environment. Offshore deposition is suggested by the abundance and thickness of the mudstone units and the occurrence of predominantly thin-shelled, well preserved brachiopods, thin bryozoa, and trilobites. The presence of mudstones is accepted to indicate the apparent inhibition of grain-producing organisms (Dunham 1962). Micritic mudstones, observed primarily in the uppermost limestone dominant unit, are generally deposited in a low energy, shallow water environment (Holland, 1993).

Claystones

A few unique lithologic units are observed in the rock core at the Mound Plant. These units, described in this report as claystones, are observed as medium dark gray, very thinly bedded (<0.5-ft thick), soft, poor to non-indurated beds of clay-sized material. These claystone beds appear to be hydrophilic in nature in that they become very soft and amorphous immediately after coring and being in contact with the drilling water. The individual claystone beds have no internal bedding features or structures. Additionally, no paleofauna or traces of bioturbation are observed in association with these claystone beds. The origin of these claystones is uncertain. The clays may represent the final stages of setting of graded beds, but beds of bentonitic clays have been documented in the Ordovician-Aged sediments in southwest Ohio. The hydrophilic nature of the claystone beds observed suggest that these clays may be bentonitic clays.

Discussion

Of the four fabric types, mudstone is the dominant fabric observed in the Mound Plant bedrock. Within the entire section and comparing core-to-core descriptions, mudstones comprise 45 to 52 percent of the rock fabrics, wackestones are 24 to 36 percent, packstones from 17 to 29 percent, and

grainstones and clays less than or equal to 1 percent each. Few wackestones are observed in the upper parts of the section, but they are observed to dominate in the lower parts of the section. Likewise, grainstones are rare in the upper parts of the section, but are present in the lower parts.

The results of the fabric descriptions in the Mound Plant cores in digital format are displayed in Figure 2.2. The data has been smoothed using a three-point smoothing routine that removes some of the sharp variations inherent in thin alternating beds. No attempt has been made to correlate individual beds or fabric elements, as individual thin beds are rarely correlative across the plant. In the subsection that follows, fabrics are grouped into larger packages of rocks called facies. These facies allow broad correlations between lithology observed in cores and between geophysical measurements.

Figures 2.3 and 2.4 depict the correlation between percent shale, natural gamma and neutron, and fabric logs for boreholes 0348 and 0350, respectively. Data from these boreholes are depicted to represent the Main and SM/PP Hills at Mound Plant. These data indicate a strong correlation between all log patterns and reinforce the interpretation that the geophysical measurements of natural gamma and neutron attenuation represent lithology. The graphs for percent shale and natural gamma increase with increasing percent of shale. The natural gamma are interpreted to measure the relative amounts of naturally occurring isotopes of uranium, thorium, and potassium in the mudstones. The graphs of neutron and fabric logs increase with increasing percent of limestone. The neutron log is interpreted to measure the relative porosity of the rocks (assuming the pores are water saturated) and the amounts of bound water typically greater in a poorly sorted rock such as a packstone.

The lithologic fabrics described are generally consistent with the definitions published by Dunham (1962) and Bebout and Loucks (1984). As previously stated, however, detailed studies of carbonate petrology require polished and thin sections to properly identify fine-grained and recrystallized materials. The identification of a grainstone for instance requires specific knowledge of the amount of fine-grained matrix present. For this investigation, grainstones are defined as limestones that are well-sorted, the sorting interpreted as the mechanism that controlled the grain-size distribution within the rock and prevented matrix support. If the rock appears well sorted, then the environmental factors precluded much muddy matrix, i.e., the fines could not settle. Most of the fabrics observed in the Mound Plant cores appear to be poorly sorted with varying amounts of fine-grained matrix. Virtually all of the packstones are those deemed poorly sorted. The environment of deposition appears to have been one of extremely muddy character. Tobin (1982 and 1986) also distinguishes between packstones and grainstones on the basis of sorting, but has the advantage of knowing the composition of the fine-grained matrix, so he identifies many more grainstones throughout the section than are identified here.

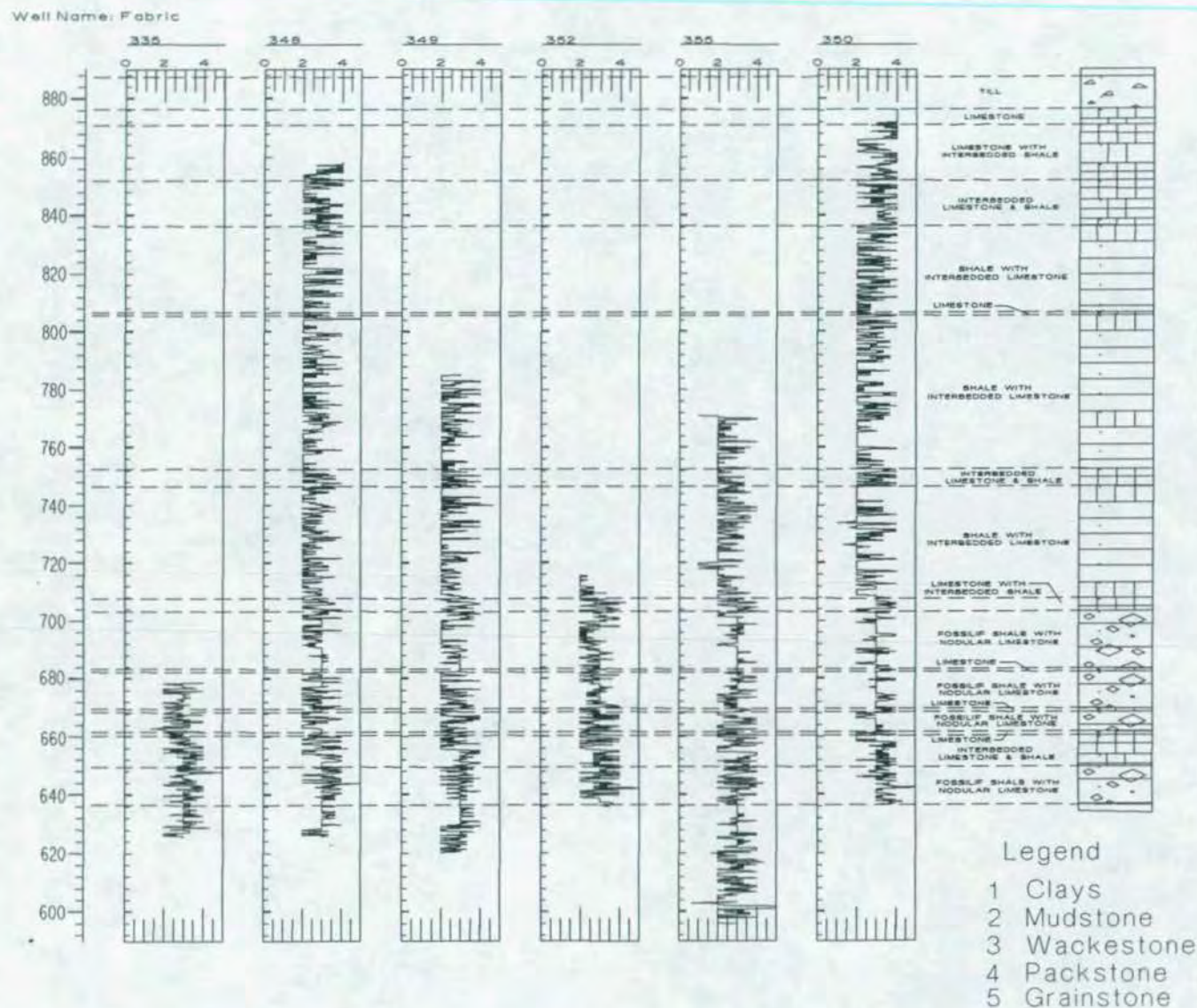
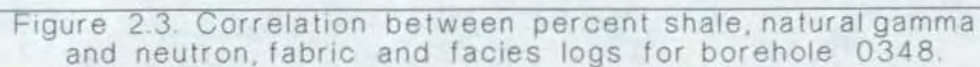


Figure 2.2. Correlation of fabrics observed in Mound Plant cores.
Data has been smoothed using a three point smoothing routine.



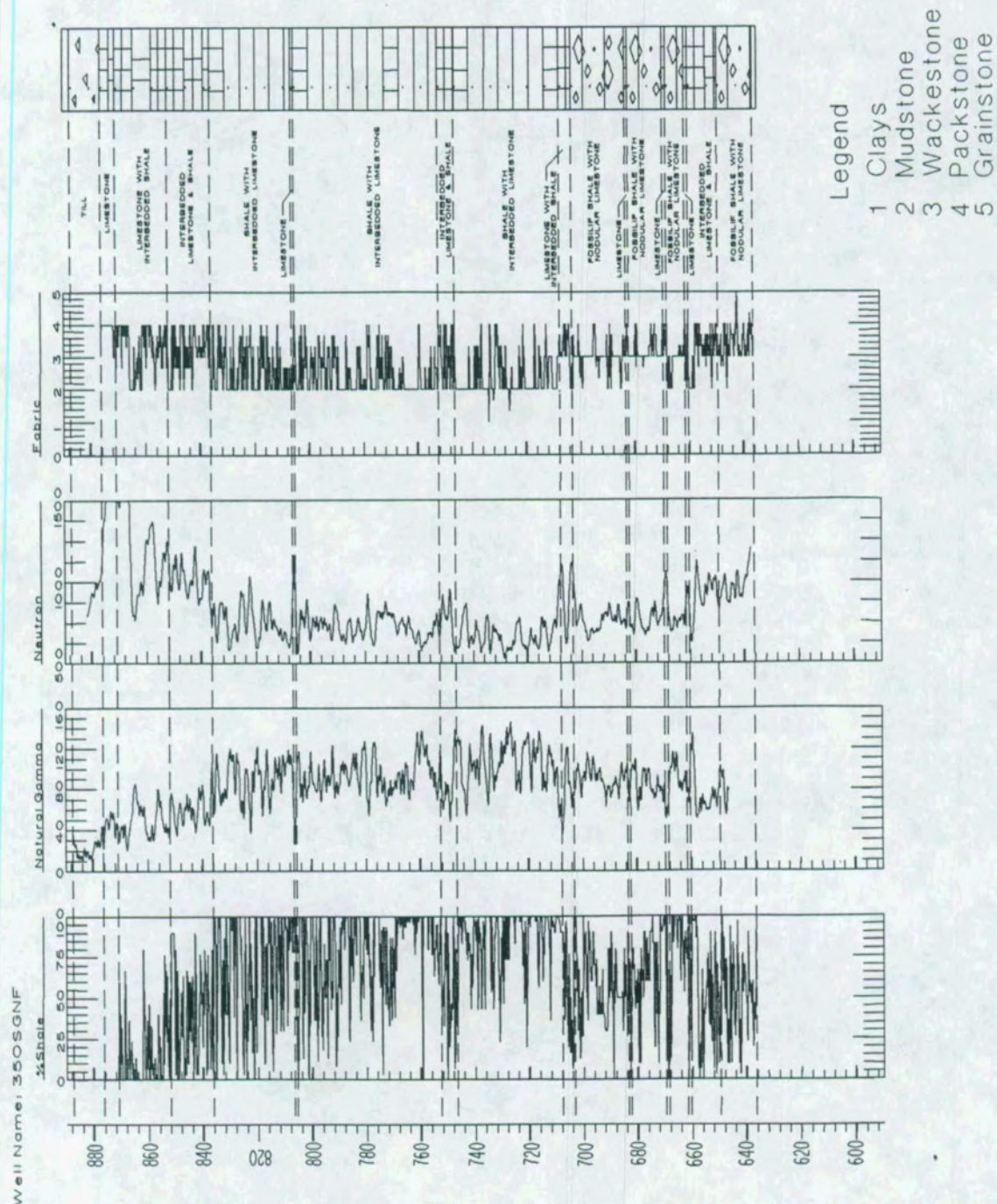


Figure 2.4. Correlation between percent shale, natural gamma and neutron, fabric and facies logs for borehole 0350.

Wackestones are generally considered carbonate rocks (Dunham 1962), but they are observed to grade from very fossil-rich shales, i.e., a very muddy packstone, to fine shales. The distinction between wackestone and shale being the presence of 10 percent fossil content in the wackestone (Dunham 1962). A wackestone, by definition then, may have as few as 10 percent grains and the remainder consist of mud. The low end member then can be more a fossiliferous shale than a carbonate rock. Since the cores were examined at 0.1-ft intervals, gradational contacts are placed where the percentage of fossil fragments drops below 10 percent, so the interpretation and accounting of wackestones may vary by the observer. The weathering of poorly lithified wackestones may result in a small pile of fragments in outcrop. Relatively fresh exposures may display more wackestones than heavily weathered ones. In the facies descriptions that follow, wackestones are placed within facies groups based on their macroscopic appearance and not necessarily whether they are or are not defined as carbonate rocks.

2.3. DESCRIPTION OF LITHOLOGIC FACIES

The sequence of mudstones, packstones, wackestones, and grainstones that comprise the rock fabrics in the cores were grouped into small packages termed lithologic facies in this report. These lithologic facies are defined on the basis of macroscopic characteristics of the core and are simply interpretative packages that aid in correlating packages from core to core and from core to the geophysical logs.

The lithologic facies defined in this report have no formal meaning outside of the context of this report. Lithologic facies are generally defined as the natural variations that occur within time-stratigraphic sequences due to environmental factors. For example, within the same period of time, a marine shale will be forming at the same time, but in a different environment than a contiguous marine limestone. Over relatively small distances encompassed by the boreholes drilled during this investigation, lithologic characteristics are unlikely to cross time lines, i.e., the lithologic facies are assumed to represent the same period of time over the Mound Plant area. Over broader areas of the Cincinnati Series rocks, lithologic facies may change characteristics. Such variations are discussed by Holland (1993) in his description of sequences of stratigraphic units within the Cincinnati Series rocks.

In a dissertation study conducted by H.B. Hay (1981), lithologic facies were determined in systematic fashion for rocks of the Cincinnati series. The study required systematic investigations at outcrops to determine detailed textural and bedding characteristics. Excerpts of the study were published as part of the Field Guidebook to the Biostratigraphy and Paleoenvironments of the Cincinnati Series of Southeastern Indiana (Pope and Martin 1986). A composite section of the cores drilled by Dames and Moore as part of the 1973 investigations was included in the dissertation study. However, the facies and the formational units described by Hay (1981) are not widely recognized and are not utilized

in this report. The methods are difficult to apply during investigations of core as the weathering and lateral bedding characteristics cannot be examined. The dissertation study adds no pertinent information to the understanding of the hydrogeologic characteristics of the bedrock at Mound Plant.

The following subsection provide description of the lithologic facies described in this report. It is emphasized that lithologic facies are convenient interpretive packages and should not be confused with descriptive rock fabrics.

Limestone Facies

For this report, limestone facies is defined as an interval of rocks that are dominated by limestone fabrics, typically over 90 percent packstones, wackestones, and grainstones by volume. Estimates are made by visual inspection. In core 0350, a thick limestone facies is present in the uppermost part of the section. Thin limestone facies are also identified in the cores where a prominent packstone bed is observed to extend across all or many of the cores. These thin facies act as good marker beds for correlation and cross checks of the geophysical data.

Limestone With Minor Shale Facies

Limestone with minor shale facies is an interval of rocks in the Mound Plant core that have between 60 and 90 percent packstones, wackestones, and grainstones by volume. Packstones comprise nearly 60 percent of the fabrics in the rocks in the upper parts of the section, but decrease in frequency in the lower parts of the section where they typically comprise 40 percent. Estimates are made by visual inspection. In core 0350 the limestone minor shale facies is present throughout the section in approximately 10-ft thick zones.

Interbedded Limestone and Shale Facies

The interbedded limestone and shale facies is an interval of rocks in the Mound Plant core that have approximately equal proportions of packstones and mudstones by volume and these exceed 80 percent of the rocks. Estimates made by visual inspection. In core 0350, the interbedded limestone and shale facies is present throughout the section.

Shale Minor Limestone Facies

The shale minor limestone facies is an interval of rocks in the Mound Plant core that have between 60 and 90 percent mudstones by volume. Limestones include packstones and grainstones. Shales in this

facies include some fossil-poor wackestones, especially in the lower parts of the section. Estimates are made by visual inspection. The shale minor limestone facies dominates in the central parts of the section.

Fossiliferous Shale Nodular Limestone Facies

The fossiliferous shale nodular limestone facies is an interval of rocks in the Mound Plant core that have between 50 and 80 percent wackestones by volume. Estimates are made by visual inspection. Because of the wide definition of wackestone, the fossil contents may vary down to just 11 percent and these rocks may grade to fossil-poor mudstones. The fossiliferous shale nodular limestone facies is dominate in the lower part of the section.

Shale Facies

The shale facies is defined as a interval of rocks that are dominated by shale fabrics, typically over 85 percent mudstone by volume. Estimates are made by visual inspection. The shale facies is exceedingly rare in the section and is only observed through an interval in the upper part of core 0352.

Discussion

The facies types described above allow correlations between cores and correlations between cores and geophysical logs. A cross section of Mound Plant lithology is depicted on Plate 1. For the purposes of correlation only, cores 0335 and 0352 are projected into the section line depicted. This lithologic cross section establishes the rock types beneath the plant. Contacts in Plate 1 are determined from the natural gamma and neutron logs depicted and are shown to have a strong correlation with lithology (Figures 2.3 and 2.4) but have a greater control of depth and elevation than the cores. Boxing, handling, and examination of cores naturally distorts the true lengths. In this facies depiction, relative good correlation is evident between all cores.

A composite lithologic section for the Mound Plant bedrock is depicted in Figure 2.5. This composite section represents the lithology likely to be encountered at any point beneath Mound Plant depending on topography. Descriptions and discussions are not included here which address any glacial deposits that may mantle the bedrock or that may fill glacial valleys. Plate 1 depicts the fill and glacial deposits as undivided units. Another of the OU 9 hydrogeologic investigation reports will address glacial geology.

2.4. STRATIGRAPHY

The bedrock at Mound Plant is comprised of marine shales and limestones of the Ordovician System. A regional bedrock geologic map is shown in Figure 2.6. Rocks encountered in the cores drilled during this investigation are grouped within the Cincinnati Series and include rocks from the Richmondian and Mayvillian Stages. These units comprise the time-stratigraphic framework within the areas of southwestern Ohio and eastern Indiana. The Cincinnati Series rocks have been studied for well over a century for their spectacular exposures and fossil assemblages. Summaries and bibliographies have been published by Tobin (1986), Pope and Martin (1986), Holland (1993) and Gutstadt (1958).

The basic rock-stratigraphic unit is the formation. Formations are rock bodies distinguished on lithologic character and large enough to be mapped in the field. They generally represent distinct depositional environments or related environments. Since deposition may begin in some areas at different times than other areas, rock-stratigraphic units may not exactly correspond to time-stratigraphic units. Criteria for establishing rock-stratigraphic, i.e., lithostratigraphic units, are outlined in the 1983 North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature 1983). Formations encountered in the cores drilled for this investigation include, from the lowest to the highest, the Corryville Formation, the Mount Auburn Formation, the Oregonia Formation, the Waynesville Formation, the Liberty Formation, and the Whitewater Formation. These units have only recently been recognized as true lithostratigraphic units.

This subsection discusses the stratigraphy of the bedrock units encountered by the six borings and their regional context. Detailed descriptions of the rock formations are complex and beyond the scope of this report. Figure 2.7 displays selected examples of the nomenclature applied to rocks of the Cincinnati Series. Figure 2.8 depicts a generalized cross section of the Mound Plant bedrock stratigraphy. The following subsections describe the rock formations encountered in the Mound Plant cores. Sufficient information is provided to place the Mound bedrock within its regional setting for purposes of context only. Additional references are provided as appropriate.

Formational contacts discussed are defined at Mound Plant in cores 0350 and 0355. Core 0350 represents the rocks highest in the section and core 0355 represents rocks lowest in the section. It is emphasized that formational units are convenient, regional interpretive packages that may be composed of several lithologic facies. Contacts are typically gradational indicating that most lithologies are part of a genetically related suite of facies.

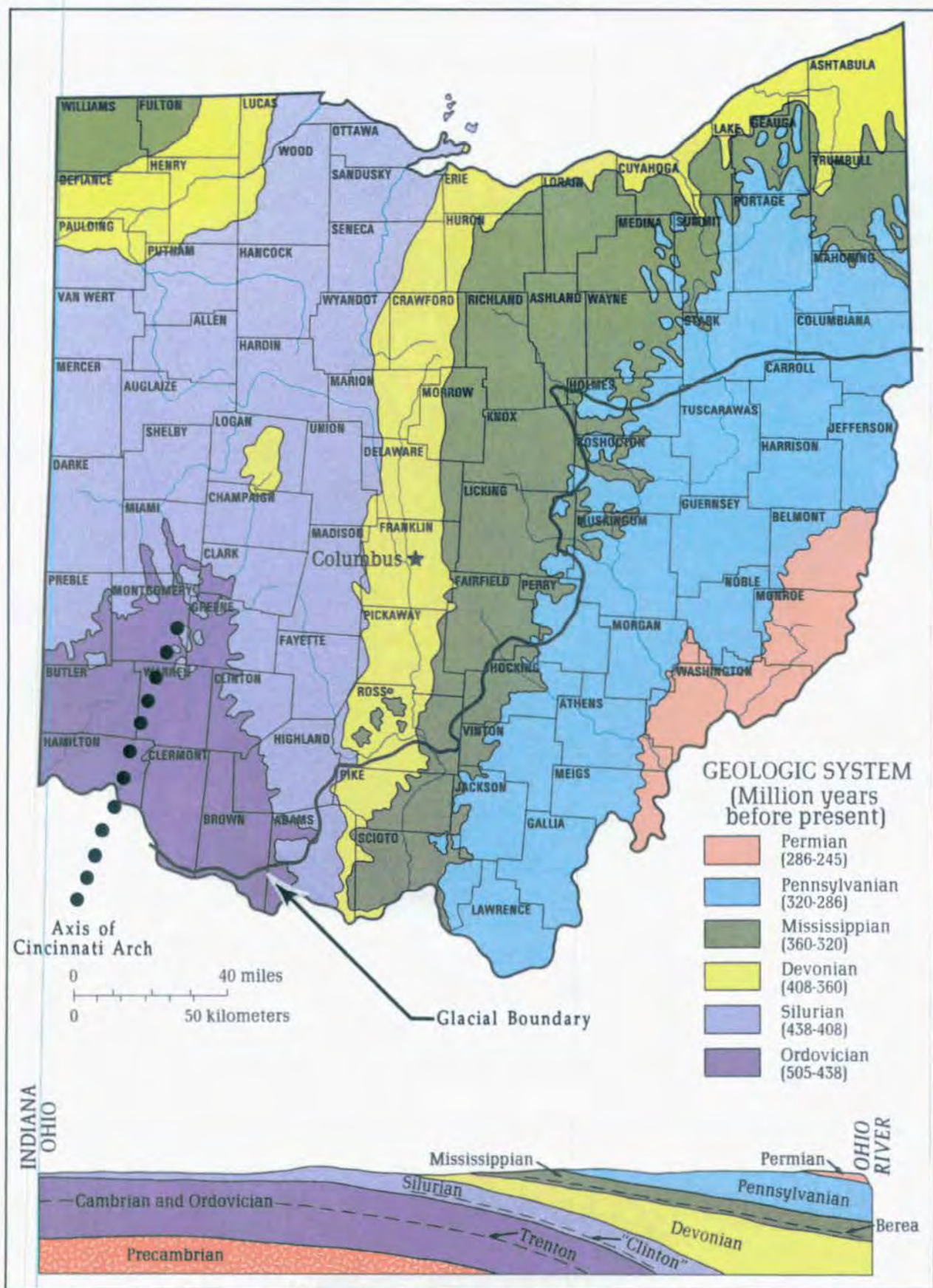


Figure 2.6. Bedrock geologic map and cross section of Ohio (adapted from State of Ohio, Department of Natural Resources, March 1992).

Series	Stage	Davls (1992)		Hay (1981)		Tobln (1986)	This Report
		Formation	Member	Formation	Member	Formation	Formation
Cincinnatian (upper Ordovician)	Richmondian	Whitewater	Upper Whitewater	Whitewater		Saluda Whitewater	Whitewater
			Saluda	Saluda			
			Lower Whitewater	Whitewater			
		Liberty		Brookville	Liberty	Liberty	Liberty
		Waynesville			Waynesville	Waynesville	Waynesville
	Maysvillian	Arnheim	Oregonia	Excello		Oregonia	Oregonia
			Sunset			Sunset	
		McMillan	Mt. Auburn			Mt. Auburn	Mt. Auburn
			Corryville			Corryville	Corryville
			Bellevue			Bellevue	
				Station Hollow			
				Bellevue	Bellevue	Bellevue	

Figure 2.7. Selected examples of stratigraphic nomenclature for Cincinnatian Series rocks in the vicinity of Mound Plant.

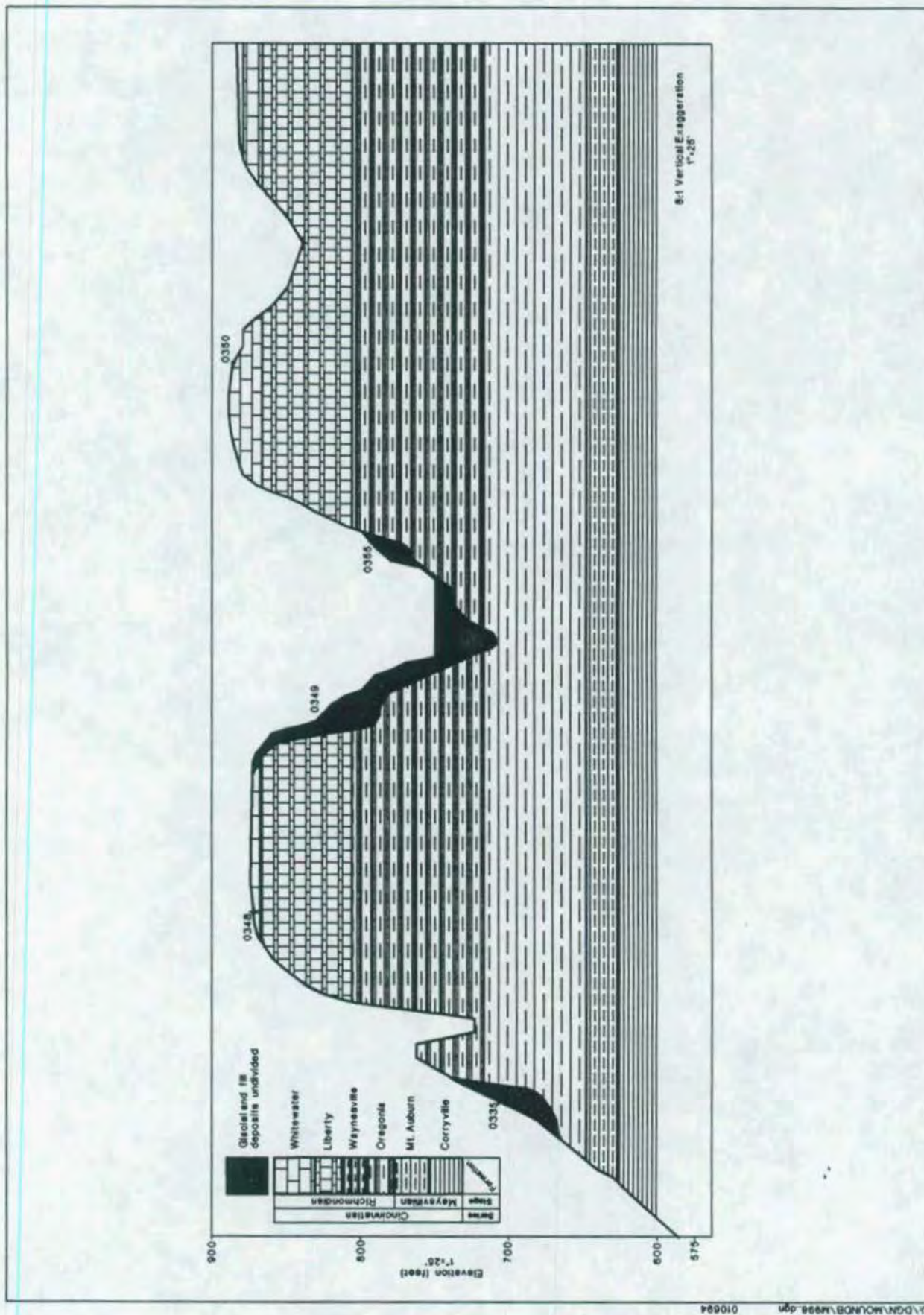


Figure 2.8 Generalized cross-section of Mound Plant bedrock (See Figure 1.3 for borehole locations).

CORRYVILLE FORMATION

The Corryville Formation is locally exposed throughout the southwesternmost parts of Ohio (Tobin 1986). It generally consists of relatively thickly bedded limestones and very thick beds of shale. The shale content is typically 64 percent in the region (Tobin 1986). Bedding is typically continuous. Fossils are abundant and varied. According to Tobin (1986), it is over 100-ft thick in the region.

In the core obtained for this investigation, the Corryville Formation is only encountered in borehole 0355, where it is 31-ft thick and the base is not exposed. It is interpreted to be found at an elevation of 627 to 596 ft MSL in core 0355. It consists dominantly of thickly-bedded shales and interbedded limestones. Mudstones comprise approximately 50 percent of the rocks with wackestones and packstones in approximately equal proportions, 20 to 24 percent, respectively. Grainstones comprise about 5 percent of the fabrics observed on core 0355, but overall appear in slightly less abundance than in the overlying Mount Auburn Formation. Both the Corryville and Mount Auburn Formations show greater concentrations of grainstones than rocks higher in the section.

MOUNT AUBURN FORMATION

The Mount Auburn Formation is locally known in the region of Cincinnati and southwestern parts of Ohio (Tobin 1986). It generally consists of limestones and lesser amounts of shale. The shale content is typically 37 percent in the region (Tobin 1986). Bedding is variable and discontinuous. Fossils are abundant and varied, but the presence of the brachiopod *sp. Platystrophia ponderosa* is characteristic of the formation. According to Tobin (1986), it is generally only about 17-ft thick in the region.

In the cores obtained for this investigation, the Mount Auburn Formation is approximately 21-ft thick. It is interpreted to be found at an elevation of 627 to 648 ft MSL in borehole 0350. It consists of fossiliferous shale with nodular limestone and shale with interbedded limestone. Mudstones are observed to comprise only about 9 percent of the rocks, wackestones 55 percent, packstones 30 percent. Bedded grainstones are generally correlative across all of the boreholes drilled and comprise approximately 6 percent. Bedded, well-sorted grainstones are more common in the Mount Auburn Formation than in either the overlying or underlying units. Several specimens of the brachiopod *sp. Platystrophia ponderosa* are observed in boreholes 0350 and 0355. The base is only observed in borehole 0355. For the purposes of this report, the lower contact is placed at the top of a coarse-grained bedded limestone. The Mount Auburn Formation was not encountered in the boreholes drilled by Dames and Moore (1973).

The Mount Auburn Formation observed in the cores obtained for this investigation is not intensely fractured. Rubble zones observed in core 0355 indicate fractures are present. The unit appears to lie at a sufficient depth to that it has not been susceptible to the pressures of glaciation and surficial weathering processes. Fracturing and jointing associated with the Cincinnati Arch structure probably induced light fracturing that does not appear sufficient to support measurable groundwater flow.

SUNSET FORMATION

The Sunset Formation is locally exposed in the region of Cincinnati, southwestern parts of Ohio, and eastern Indiana (Tobin 1986). It and the Oregonia Formation have been historically grouped into the Arnheim Formation (Figure 2.7). Tobin (1986) differentiated the Oregonia Formation from the Sunset Formation on the basis of bedding characteristics. The Oregonia Formation was described as shales and nodular limestones and the Sunset Formation as shales and planar bedded limestones. According to Tobin (1986), the Sunset is about 44-ft thick in the region.

The Sunset Formation is not identified in the cores obtained in this investigation.

OREGONIA FORMATION

The Oregonia Formation is locally exposed in the region of Cincinnati, southwestern parts of Ohio, and eastern Indiana (Tobin 1986). It is the uppermost formation in the Maysvillian Stage. It and the Sunset Formation have been historically grouped into the Arnheim Formation (Figure 2.7). The Arnheim Formation is apparently an archaic term that is still used locally. Tobin (1986) differentiated the Oregonia Formation from the Sunset Formation on the basis of bedding characteristics. The Oregonia Formation was described as shales and nodular limestones and the Sunset Formation as shales and planar bedded limestones. The shale content of the Oregonia Formation is typically 44 percent in the region and the Sunset is 52 percent (Tobin 1986). According to Tobin (1986), the Oregonia Formation is generally only about 24-ft thick in the region.

In the report by Dames and Moore (1973), the Arnheim Formation is described by Dr. John Pope of Miami University as irregularly bedded, nodular limestone and poorly bedded shale. Bedding was apparently observed to be more even toward the base of the unit. The base of the unit was not encountered in the borings drilled for that investigation. The Arnheim Formation was interpreted to be a minimum of 85-ft thick beneath Mound Plant, which was much greater than expected in the area, even considering the combined thicknesses of the Oregonia and Sunset Members. The formation identification was based largely on faunal contents, the convention at that time.

In the cores obtained for this investigation, the Oregonia Formation is approximately 69-ft thick. It is interpreted to be found at an elevation of 717 to 648 ft MSL in borehole 0350. The unit grades from limestone with interbedded shale to fossiliferous shale with nodular limestones. Distinct limestone beds occur near the base of the unit. Mudstones are observed to comprise approximately 29 percent of the rocks, wackestones 50 percent, and packstones 21 percent. Bedded grainstones are observed to comprise less than 1 percent. A prominent limestone zone approximately 700 ft MSL in the cores possesses a distinct signature on the geophysical logs and is recognizable in outcrops in the region. The zone has a bed of distinct phosphatic micro-fossils that serves as a regional marker bed. It appears to have an erosional top suggesting that a disconformity exists near the top of the Oregonia Formation. No obvious planar beds were observed in the cores obtained for this investigation, so the Sunset Formation is not recognized. For this report, the lower contact of the Oregonia Formation is placed at the top of a prominent grainstone in borehole 0350.

The Oregonia Formation observed in the cores for this investigation is locally intensely fractured. Rubble zones observed in core 0355 indicate fractures are present at depth. In core 0352, which lies at a surface elevation of 716 ft MSL, the unit apparently lies at a sufficiently shallow topographic elevation to have been susceptible to surficial weathering processes to the degree that measurable groundwater flow is present. Relatively low values of conductivity in boreholes 0348 and 0350 suggest that structural fractures within the limestone beds at elevations near 700 ft MSL may exhibit small volumes of water.

WAYNESVILLE FORMATION

The Waynesville Formation is widely exposed in Montgomery County, southwestern parts of Ohio, and eastern Indiana (Tobin 1986). It is the lowermost formation in the Richmondian Stage. It generally consists of sparsely fossiliferous thick shale beds with relatively evenly spaced limestones. The shale content of the Waynesville Formation is typically 67 percent in the region (Tobin 1986). The limestone beds generally decrease in frequency with depth. Bedding is relatively continuous. A prominent limestone zone is recognized in the middle portion that exhibits abundant, large brachiopods *sp. Rafinesquina* (Davis 1992), but the common fossil within the formation is the brachiopod *sp. Omniella*. According to Tobin (1986), it is generally over 100-ft thick in the region. Dames and Moore (1973) reported a thickness of 90 to 100 ft beneath Mound Plant.

In the cores obtained for this investigation, the Waynesville Formation is approximately 88-ft thick. It is interpreted to be found at an elevation of 717 to 805 ft MSL in borehole 0350. It consists of shale with interbedded limestones; interbedded limestone and shale facies occur in the middle of the unit. Mudstones are observed to comprise 69 percent of the rocks; wackestones and packstones are

in approximately equal proportions, about 15 percent each. Bedded grainstones are rare and are observed to comprise less than one percent. The limestone and interbedded shale facies has a distinct bed of abundant, very large brachiopod *sp. Rafinesquina*. Whole fossils of the brachiopod *sp. Omniella* are found throughout the unit. For this report, the lower contact is placed at the top of a nodular limestone bed that lies below a planar shale bed (Tobin 1986). This basal contact actually appears within the shale with minor limestone facies (Plate 1). Neither the upper nor lower contacts are exposed in the railroad cut outcrop west of Mound Plant (Figure 2.9).

For this investigation, the Waynesville Formation is observed in the cores and outcrop and is locally intensely fractured. Fractures and rubble zones in core 0348 indicate fractures are present at depth, probably due to prolonged periods of surficial weathering and loading and unloading during glaciation. Fractures and rubble zones are much rarer in core 0350, probably indicating much greater competence of the bedrock mass of that area compared to the topographically isolated Main Hill.

LIBERTY FORMATION

The Liberty Formation is widely exposed in Montgomery County, southwestern parts of Ohio, and eastern Indiana (Tobin 1986). It consists of fossiliferous thick limestone interbedded with relatively thick shales. The limestone beds are generally thicker than those in the underlying Waynesville Formation and the shale is thinner. The shale content of the Liberty Formation is typically 45 percent in the region (Tobin 1986); bedding is relatively continuous. An unpublished stratigraphic description of the Brookville, Indiana, outcrop describes a gray, finely crystalline, poorly fossiliferous burrowed limestone at the top of the unit (Pope, unpublished). A prominent indicator fossil is the brachiopod *sp. Thaerodonta* (Davis 1992). According to Tobin (1986), the unit is generally 60-ft thick in the region.

Dames and Moore (1973) reported a thickness of 26 to 29 ft beneath Mound Plant, but an apparent discrepancy exists between the text and the logs published. Although the text states that the Liberty Formation was encountered from 849 to 821 ft MSL, the logs (Plates 7.1-3 and 7.1-4) indicate elevations from about 809 to 835 ft MSL. In either case, the approximate thickness is 26 ft.

In the cores obtained for this investigation, the Liberty Formation is approximately 61-ft thick. It is interpreted to be found at an elevation of 805 to 866 ft MSL in borehole 0350. It is observed only in cores 0348 and 0350; it has eroded away at the other locations. It grades from limestones with interbedded shales at the top to shales with interbedded limestones at the base. Mudstones comprise about 57 percent of the rocks and packstones approximately 36 percent. Wackestones and bedded grainstones are observed to be approximately 5 and 2 percent, respectively. The grainstones are

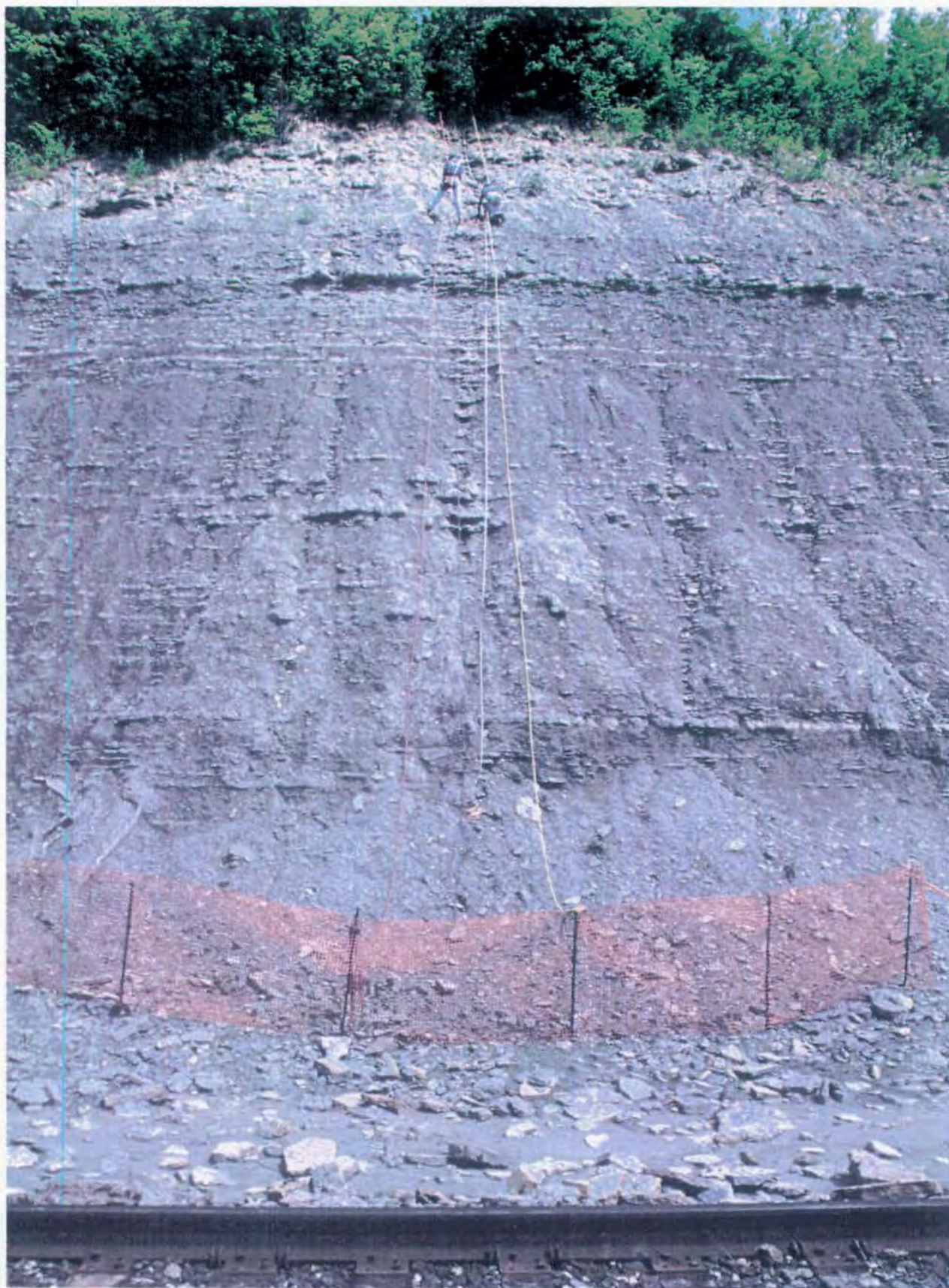


Figure 2.9. Photograph of Waynesville Formation at railroad outcrop west of Mound Plant (see Figure 1.3 for location).

observed only near the bottom of the unit. The brachiopod *sp. Thaerodonta* is observed in core 0350 at an elevation of 824.6 ft MSL. For this report, the lower contact is placed at the base of a limestone bed that overlies a shale bed greater than 0.5 meter thick (Tobin 1986).

In the cores obtained for this investigation, the Liberty Formation is observed to be locally intensely fractured. Fractures on cores 0348 and 0350 indicate decreasing frequency with depth. Observed fractures and rubble zones in 0348 are generally more frequent than in core 0350 indicating that the degree of fracturing of the Main Hill has been more intense than the SM Hill.

WHITEWATER FORMATION

The Whitewater Formation is locally exposed in southwestern Ohio and eastern Indiana (Tobin 1986). It generally consists of irregular thin limestone and fossiliferous shale beds. The shale content of the Whitewater Formation is typically 14 percent in the region (Tobin 1986). Bedding is discontinuous. Bryozoa tend to be more common than brachiopods. According to Tobin (1986), it is generally 35-ft thick in the region. Dames and Moore (1973) reported a thickness of 24 to 35 ft beneath Mound Plant, but the top is obviously eroded and the unit is not fully exposed.

In the cores obtained for this investigation, the Whitewater Formation is minimally 20 ft thick. It is interpreted to extend from an elevation of 866 ft MSL to the surface (887 ft MSL) in borehole 0350. It is observed only in core 0350, as it has been eroded away at the other locations. It consists of poorly bedded limestones and limestones with interbedded shales. Packstones comprise about 84 percent of the rock in core 0350; bedded grainstones are absent. Mudstones and wackestones are observed in approximately equal proportions of 8 percent each. For this report, the lower contact is placed at the top of a gray, finely crystalline, poorly fossiliferous burrowed limestone (Pope and Martin 1986).

The Whitewater Formation is observed in the cores to be locally intensely fractured. Fractures on core 0350 indicate decreasing frequency with depth.

2.5. DISCUSSION OF STRATIGRAPHY OF MOUND PLANT BEDROCK

Historically, the formations within the Cincinnati Series were defined on the basis of fossils and faunal zones, i.e., they were biostratigraphic units. In the strict sense of stratigraphic nomenclature, formations must be defined on the basis of lithologic characteristics, not biological characteristics. The geologic cross-section of the Mound Plant bedrock published by Dames and Moore (1973) defined the formational contacts according to the traditional fossil faunal assemblages. Recent work by

Hay (1981) and Tobin (1982) provide the lithologic framework for identification of lithostratigraphic formations within the Cincinnati Series. The lithostratigraphic descriptions of Tobin (1986) appear to be the only formal presentations of these data and appear to be endorsed by the Ohio Geological Survey. The elevations of the formational contacts shown on Plate 2 differ from those published by Dames and Moore (1973) because of the nature of the definition. This report generally conforms to the lithostratigraphic framework of Tobin (1986).

2.6. DISCUSSION OF ENVIRONMENTAL ORIGINS OF MOUND PLANT BEDROCK

The Cincinnati Series rocks at Mound Plant consist of a complex sequence of marine shales and limestones. These rocks are believed to have formed over 400,000 years ago in an offshore shelf that experienced a series of fluctuations in sea level rise (transgressions) and fall (regressions). Evaluation of the lithologic facies allows interpretations of environment and changes of that area over time.

The most distal of the offshore deposits are represented by relatively deep-water marine shales. For example, rocks of the Waynesville Formation consist largely of mudstones and few interbedded packstones and wackestones. These shales and rare limestones have abundant thin-shelled fossil assemblages that indicate a quiet, deep-water environment. Local graded beds and broken fossil assemblages suggest occasional storm beds. The fact the rocks such as the Waynesville Formation directly underlie rocks of the Liberty Formation indicate a major sea level regression.

Nearer shore environments are represented by interbedded shales and limestones. Rocks of the Liberty and Mount Auburn Formations, for example, consist of layers of fossil-rich packstones and grainstones, interbedded with fossil-rich wackestones. The limestones consist of whole and broken fossils that are locally intensely bioturbed and include thick-shelled brachiopods that indicate subtidal conditions. Thick graded beds of fossiliferous shales (wackestones that grade to fossil-poor shales) indicate abundant storm activity. These interbedded facies suggest relative small and rapid sea level fluctuations. Rocks of the Oregonia Formation that contain beds of intensely broken fossil fragments may indicate further sea level decline and an environment of sediment-starved conditions and possible subaerial exposure. The fact that rocks such as the Waynesville Formation directly overlie rocks of the Oregonia Formations indicate a major sea level transgression.

2.7. BEDROCK GEOLOGIC MAP OF MOUND PLANT

A bedrock geologic map of the Mound Plant is depicted in Figure 2.10 and a stratigraphic cross section of Mound Plant is presented in Figure 2.8. The map and cross section were compiled from a topographic map of bedrock topography. The topographic map was compiled from an extensive set of borings conducted by Mound Plant for engineering and foundation studies, as well as parts of the remedial investigations. A preliminary version of the map appeared in the Site Scoping report:



Figure 2.10. Bedrock geologic map of Mound Plant and vicinity
(Glacial deposits not shown).

Volume 2 Addendum - Stratigraphic and Lithologic Logs (DOE 1993b). Stratigraphic contacts are depicted from the descriptions presented above. All of the stratigraphic units within the Cincinnati Series are relatively underformed, essentially flat-lying marine shales and limestones. Figure 2.8 and Plate 2 differ from the map and cross section presented by Dames and Moore (1973) because theirs were compiled on the topographic surface map. Not shown are the glacial deposits that may mantle the bedrock topography as thin tills or that fill the valleys as thick outwash deposits. Descriptions of the glacial deposits are provided in the OU 9 Hydrogeologic Investigation Report: Glacial Hydrogeology (DOE in preparation).

2.8. DISCUSSION OF LITHOLOGIC CONTROL OF BEDROCK FLOW SYSTEM

This report presents a revised conceptual model of the bedrock flow system. The preliminary model, presented in the OU 9 Site-Wide Work Plan (DOE 1992a), was one in which shallow groundwater on either of the two hilltops percolated through the weathered bedrock until it hit an impermeable shale layer at an elevation of approximately 820 ft. At the boundary of the shale, the perched water migrated along the bedding surface until it emerged at the surface as a groundwater seep.

The revised conceptual model is one of combined structural and stratigraphic control of groundwater flow. The bedrock flow system is viewed as a mass of marine shales and limestones in which fracturing and weathering has established a fracture carapace occupied by fresh water that mantles and mimics the surface topography. Below the fracture carapace, pore waters retain much of the characteristics of connate brine fluids.

In the revised model, infiltration migrates vertically rather rapidly through the fractured bedrock carapace until the frequency and density of fractures decrease to the extent that vertical flow is not possible. At depths of 40 to 50 ft, infiltration reaches a zone where capillary forces increase and further vertical migration is inhibited. Water flow is then diverted laterally through the shallow, more hydraulically conductive portions of the fracture carapace until it emerges as a hillside seep. Horizontal flow is controlled largely by open vertical fractures and bedding plane fractures that create an interconnected network. In the lower part of the fracture carapace, fewer fractures and fewer interconnections combine to retard permeability. Since few fractures are observed in shales, either in the core or in outcrop, the interbedded limestones are proposed to contain the dominant pathways, although with the relatively high percent of shales observed throughout the section, the shale beds must be fractured to permit vertical flow. Open vertical fractures in the uppermost portions of the hills undoubtedly penetrate the shales to produce the rates of flows observed. Local shale bedding planes may act as aquacludes to water flow as specific seeps may be observed to occur at the tops of thin shale beds.

Considering the regional and local stratigraphy, the nature and extent of development of fractures may be controlled by lithology. The upper formations in the area, the Whitewater and Liberty Formations, consist of high percentages of limestones and relatively small proportions of shales. The limestones, because of their brittle nature, are naturally more susceptible to fracturing. The shales, with high proportions of clay and silt materials, tend to deform by strain rather than break by brittle failure. The depth of fracturing on the Main Hill approximately coincides with the contact of the Waynesville Formation. The change in lithology from about 57 to 69 percent shale in the Liberty and Waynesville Formations may be sufficient to reduce the frequency and degree of fractures.

2.9. RECOMMENDATIONS

Lithologic and stratigraphic studies indicate that sufficient information exists for the bedrock beneath the Mound Plant to adequately characterize the lithology and its effects on the bedrock flow system. Lithology is described in detail at 0.1 ft increments and a composite lithologic section is compiled for the upper 300 ft of bedrock immediately beneath the plant (from elevation of 888 ft MSL in borehole 0350 to elevation 595 ft MSL in borehole 0355). This coverage is sufficient to encompass the bedrock flow system.

Stratigraphy of the Mound Plant bedrock is known within the regional context. Academic discussions of the nature and locations of contacts between formations may be ongoing due to the complexity of the problem (Tobin 1986; Holland 1993). However, stratigraphic nomenclature itself is an unimportant attribute of the rocks. Certainly the lithology described will not change regardless of where the contacts are placed between formations.

Additional continuous bedrock cores are identified to be stored at Miami University in Oxford, Ohio. The identification of these cores was not made in time to include data in this report. It is not believed that any additional lithologic data from these cores will add to the knowledge base of the Mound Plant bedrock. No additional lithologic investigations for the OU 9 hydrogeologic studies are warranted.

3. FRACTURE STUDIES

A detailed investigation of the fractures in the bedrock that underlies Mound Plant has been conducted as part of the Operable Unit 9 hydrogeologic investigations. The objectives of the fracture studies are to identify the vertical and lateral variations in the frequency and distribution of fractures in the Mound Plant bedrock that may transmit groundwater in the bedrock flow system. The fracture studies provide data on the physical conditions of fractures, including the frequency variations by depth in the boreholes and preferred orientations determined in outcrop.

The bedrock at the Mound Plant consists of a thick sequence of interbedded marine shales and limestones that have been surficially altered by processes of weathering. The bedrock flow system is considered to be a complex system in which weak groundwater flow along the interface of limestone and shale beds is enhanced by local fractures. The infiltration of meteoric water has, through time, created a fresh water carapace by the leaching of the original salts from the marine rocks. The rocks encountered at depth in the boreholes in this investigation retain some of the geophysical signature of the marine salts that were trapped during deposition, but the fresh water carapace is apparent in the upper zones of all boreholes. The distribution of shallow fractures is believed to be the controlling factor in the origin of the fresh water carapace.

The fact that the bedrock flow system is a fracture flow system is well known in the region. Norris (1948) reported that few groundwater wells completed in the bedrock were successful. Sedam and Stein (1970) mapped the base of potable water in bedrock and noted that below this base (approximately 800 ft MSL in the vicinity of Mound Plant) groundwater was too saline for drinking purposes. Limited investigations on fractures were conducted on the Mound Plant bedrock during the Site Description and Safety Assessment (Dames and Moore 1973). These previous studies indicated that fractures in outcrop exhibited preferred orientations of north-northwest and east-northeast. However, no data was included to substantiate the discussion. These previous studies did not provide sufficient detail to resolve specific questions concerning the frequency, distribution and orientation of fractures in the bedrock flow system.

In this report, fracture refers to any break or physical discontinuity in the rock caused by stresses that exceed the rock's physical strength (Kulander et al. 1990). The definition includes the terms fault and joint. Faults are fractures whose opposing faces have experienced demonstrable shear offset, with or without opening. A joint is a fracture whose opposing faces have demonstrable normal opening without shear. By far, the majority of fractures in the Mound Plant bedrock are truly considered joints.

The subsections that follow provide descriptions of the frequency and distribution of fractures observed in the continuous cores and measurements compiled from outcrop adjacent to the plant. These observations strongly correlate with geophysical measurements (see Section 4.0) to establish the geometry of the fracture flow system.

3.1. METHODS OF FRACTURE DESCRIPTION

The fractures studies were accomplished by the collection of continuous bedrock core from six boreholes for descriptions of fractures and lithology; and the examination of fractures on the face of an outcrop along the railroad cut located just west of the Mound Plant. Characterization of fracture flow systems typically involves the physical parameters including orientation, surface roughness, aperture size and shape, and mineral fillings for individual fractures; and density, connectivity, spatial distribution and trace length for fracture networks (Barton and Hsieh 1989). No measurements were made for this investigation concerning aperture size, connectivity or fracture trace lengths. These data are useful in quantifying fracture flow models (Barton and Hsieh 1989), but this is beyond the scope of this investigation. Fracture trace lengths are typically obtained from map scale investigations, but are precluded in the area of Mound Plant because of the cover of glacial till.

The cores were visually examined for presence and character of natural fractures including frequency, dip direction, fracture length, rubble zones, and presence of secondary iron-staining that is indicative of water movement. Induced fractures were also observed, but are attributed to breakage during drilling. The descriptions of the Mound Plant bedrock cores and outcrop were made entirely by hand-specimen observations in a nondestructive manner, i.e., cores were not broken or damaged during observation. Information was recorded on prepared logging forms in general accordance with Fractured Core Analysis - Interpretation, Logging and Use of Natural and Induced Fractures in Core (Kulander et al. 1990). Information was recorded in detail in 0.1-ft intervals and recorded on prepared forms. Copies of the logs are included in Appendix B.

Examination of fractures in outcrop was conducted on the large railroad cut west of Mound Plant. Four vertical profiles were examined for orientation, frequency, shape, roughness and mineral fillings of fractures. The vertical profiles ranged from approximately 68 to 75 ft in length (Figure 3.1). The close proximity of the outcrop to the railroad tracks and the steep slope required the use of standard rock climbing-rapelling equipment. Fracture sets were identified on the basis of common orientation and cross-cutting relationships. Once fracture sets were identified, fracture orientation and frequency were measured and recorded on prepared forms. For the purposes of the fracture logging at the outcrop, lithology was recorded as simply limestone or shale according to the weathering characteristics. Limestones include grainstones, packstones and resistant wackestone. Shales may include

nonresistant wackestones, mudstones and clay layers. Completed fracture logging forms are included in Appendix B.

At the outcrop, fracture frequency for a given fracture set within a bed or layer of rock was counted in a direction perpendicular to the average trend of the set. Generally, it was possible to measure frequency only for fractures within the set at high angle to the face of the outcrop. In many layers, exposed for only a short distance, it was impossible to obtain a meaningful figure for frequency.

Qualitative inspections of the fracture aperture surfaces were performed for each set within a given layer of limestone or shale. Aperture surface textures include smooth and planar, smooth and curvilinear, rough and planar, and rough and curvilinear. No quantitative measurements of physical aperture openings were conducted as part of this investigation. As discussed below, aperture openings undoubtedly influence the magnitude of flow, but at present there is no general agreement concerning the most appropriate manner in which to characterize the hydraulic properties of an individual fracture.

3.2. CHARACTERISTICS OF FRACTURES IN CORE

Detailed examination of fracture was conducted on the bedrock core collected at six borehole locations. Two general types of fractures are observed in the Mound Plant cores, natural and induced. Natural fractures comprise the fracture carapace and are distinguished from induced fractures by their geometry and morphology. Drilling-induced fractures do not contribute to the fracture flow system, but are described to establish the criteria for their recognition in order to distinguish them from fractures that do contribute. The characteristics and distribution of each in the Mound Plant cores is described below.

3.2.1. Natural Fractures

Natural fractures are defined as those fractures that existed in the rock prior to drilling. They exhibit diagnostic characteristics, including irregular, open apertures that typically exhibit evidence of solution dissolution and precipitation of minerals, slickensides and multiple breakage. Surface structures and fracture trace characteristics in natural fractures bear no regular geometric relationship to the core. Natural fractures may exhibit slickensides and cataclastic materials. Fracture propagation paths, if visible, may be oblique to core axis. Slickensides are typically polished or smooth surfaces that indicate shear movement along the plane of the fracture. They may contain fibrous minerals that grow parallel to the displacement. Cataclastic zones are areas of very fine-grained, granulated rock produced along fractures by shear forces. Secondary minerals, such as calcite and iron oxide, may coat the fracture surface indicating precipitation from solutions and groundwater. In some cases, such

secondary mineralization may close the fracture entirely. A mineralized fracture is one in which mineral growth or an amorphous material fills the fracture void. A fracture may be healed either by secondary mineralization or simple closing of the fracture aperture.

In this study, rubble zones are considered indirect evidence of the presence of a fracture. In the vicinity of Mound Plant, natural fractures are observed in this and other studies to be largely vertical or high angle. Since the boreholes were vertical, the true frequency of vertical fractures is difficult to observe. Rubble is believed to represent the evidence that a natural fracture is present, but the fracture itself is not visible in core. The drill stem may have intercepted a nearby vertical fracture, but only rock fragments were recovered. This approach is considered conservative and assumes that natural fractures are present at rubble zones.

3.2.1.1. Observations of Natural Fractures in Cores

Figure 3.2 depicts a summary of the frequency of natural fractures observed in the Mound Plant cores. Natural fractures and rubble zones are abundant in the upper zones of all cores examined and decrease in frequency with depth. Nearly all natural fractures observed are high angle and vertical or subvertical in orientation. Iron-stained fractures, indicative of groundwater precipitation, are observed only in core 0348. Four of the six cores examined exhibited evidence of healed or mineralized natural fractures that suggest that some natural fractures may exist that are poor conduits of fluid or groundwater flow. The following subsections summarize the observations of natural fractures in each of the Mound Plant cores.

Core 0335

At borehole 0335 (surface elevation 705.92 ft MSL), located offsite, no fractures were observed below 648 ft MSL and rubble zones were not observed below 651 ft MSL. The dip direction of the natural fractures ranged from 50 to 90 degrees. Measured fracture length varied from 0.3 to 0.5 ft. No stains are observed. Core 0335 has two healed fractures at 41 ft and 57 ft below ground surface; no secondary mineralization observed in the healed fractures.

Core 0348

Fractures and rubble zones were observed in borehole 0348 (surface elevation 876.69 ft MSL) to an elevation of approximately 768 ft MSL and 645 ft MSL, respectively. Iron-stained fractures and bedding plane solution cavities observed in the core at borehole location 0348 to an approximate depth of 66.5 ft below ground surface (Figure 3.3). The dip direction of the natural fractures at borehole

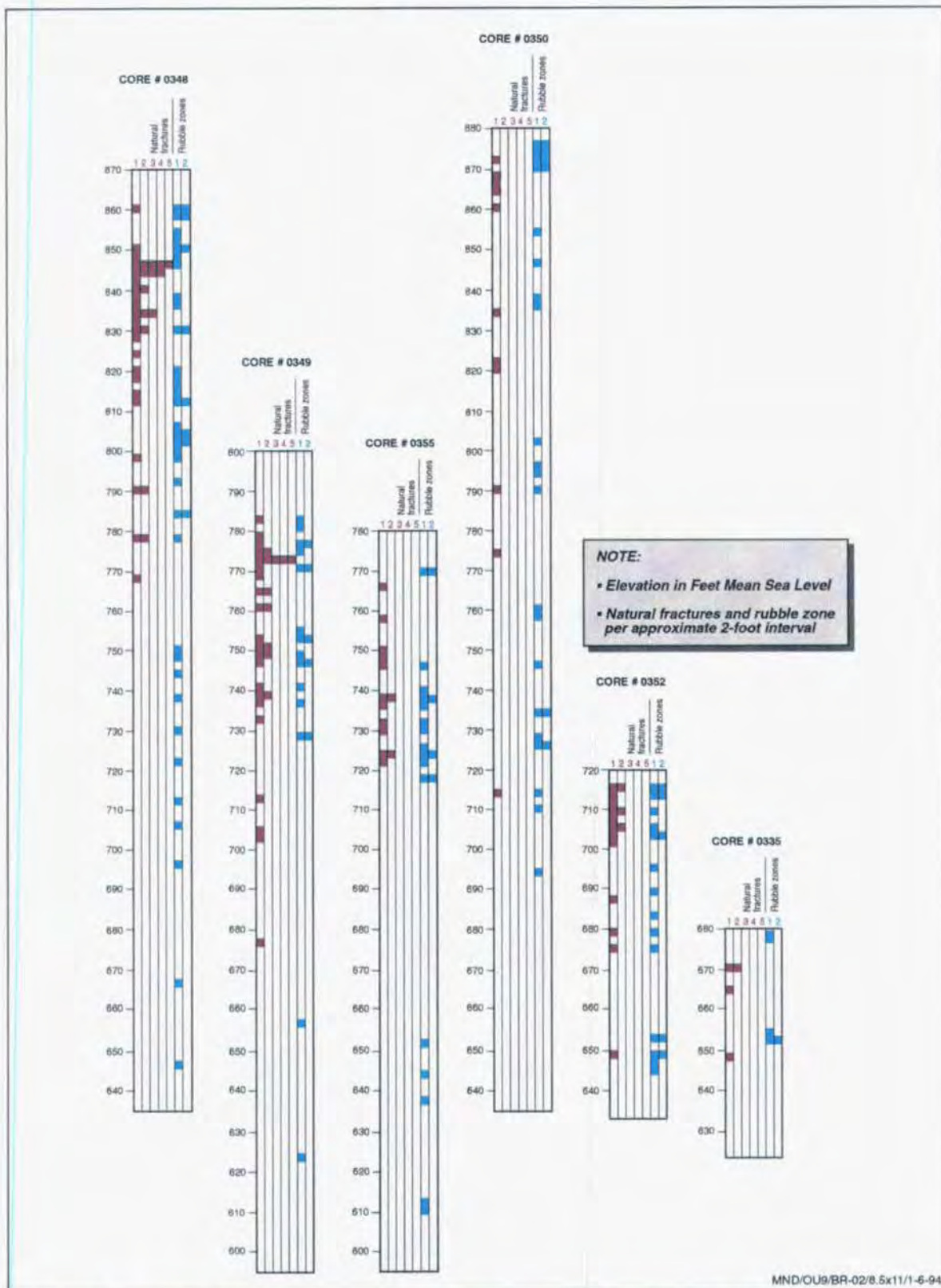


Figure 3.2. Summary of frequency of natural fractures and rubble zones in the Mound Plant cores.



Figure 3.3. Photograph of natural fractures in core 0348 at 42-ft depth (elevation 834 ft MSL)
(splice of Mound photographs #932459 and #932460).

0348 ranged from 40 to 90 degrees. Core 0348 had the broadest range in measured fracture length from 0.1 to 0.9 ft. No healed fractures were observed in core 0348.

Core 0349

In core 0349 (surface elevation 825.03 ft MSL), no fractures were observed below 678 ft MSL and no rubble zones were observed below 623 ft MSL. The dip direction of the natural fractures ranged from 70 to 90 degrees. Measured fracture length varied from 0.3 to 0.5 ft. No stains were observed. Core 0349 has at least 4 recognizable healed fractures at depths of approximately 88.5, 92.5, 112.5, and 120 ft below ground surface; no secondary mineralization observed in the healed fractures.

Core 0350

At borehole 0350 (surface elevation 887.40 ft MSL), no fractures were observed below 714 ft MSL and no rubble zones were observed below 693 ft MSL. The dip direction of the natural fractures ranged from 85 to 90 degrees. Measured fracture length varied from 0.3 to 0.5 ft. No stains and no healed fractures were observed in core 0350.

Core 0352

At bore hole 0352 (surface elevation 738.16 ft MSL), no fractures were observed below 649 ft MSL and no rubble zones were observed below 645 ft MSL. The dip direction of the natural fractures ranged from 45 to 90 degrees. Measured fracture length varied from 0.3 to 0.5 ft. No stains are observed. Core 0352 has three healed fractures at 24-, 36.5-, and 58.5-ft depth below ground surface.

Core 0355

At borehole 0355 (surface elevation 796.99 ft MSL), no fractures were observed below 723 ft MSL and no rubble zones were present below 610 ft MSL. The dip direction of the natural fractures ranged from 85 to 90 degrees. Measured fracture length varied from 0.3 to 0.5 ft. No secondary mineralization or stains were observed. One healed fracture was observed at core 0355 at a depth of approximately 51 ft below ground surface.

3.2.2. Induced Fractures

Fractures that have developed during drilling, coring, or subsequent handling are referred to as induced or mechanical fractures. The induced fractures do not contribute to the understanding of the bedrock flow system, but are common in the cores recovered as part of this investigation. This subsection provides the criteria by which induced fractures are described in the Mound Plant cores.

Three types of induced fractures were observed in the cores; disc fractures, torsion fractures and petal-centerline fractures. Disc fractures were the most abundant fractures observed, followed by torsion fractures and last, petal-centerline fractures. These induced fractures typically exhibit regular geometric relationships to the core. Drilling induced fractures propagate in the rock ahead of the bit during drilling. Because they may extend beyond the rock yet to be drilled, they may be present in the borehole wall. Coring induced fractures may develop anywhere along the core barrel, but typically form near the drill bit where pressures are the greatest. Handling-induced fractures are attributed to stresses caused by bending, impact during boxing and shipping. General handling during core examination may cause shales and poorly consolidated rocks to break along bedding planes or previously existing zones of weakness (Kulander et al. 1990).

Disc fractures are coring-induced fractures that are most prevalent in fine-grained and fissile rocks. They form primarily in response to a vertically acting principle tension and generally are horizontal to subhorizontal in vertical or subvertical core. Orientation of disc fractures can be influenced by inclined bedding, cross-bedding or large origin flaws (Kulander et al. 1990). Completely developed discs cut entirely across the core or abut previously developed natural or drilling-induced fractures, as shown in core log 0352 at approximately 28.5 ft below ground surface. Disc fracture frequency can vary throughout the core. Frequency variations may correlate with changes in rock mechanical properties. Sections of high disc frequency in shale cores may correlate directly with high organic contents and/or fissility (Kulander et al. 1990).

On the average, the frequency of disc fractures decreases slightly with depth. The frequency of disc fractures in borehole 0348 ranged from 1 to 9 fractures per ft. In boreholes 0350 and 0355, the range of disc fractures slightly increased to a range of 1 to 11 fractures per ft. In boreholes 0349 and 0352, the range was 1 to greater than 15 fractures per ft. Offsite, at borehole 0335, the frequency of disc fractures is 1 to 8 fractures per ft. Overall, disc fracture frequency was quite variable with depth in all the cores.

The second most abundant induced fractures observed in the cores were torsion fractures. Torsion fractures commonly are found at the bottom of a core run and develop when the driller twists off the

core prior to extracting it from the borehole. However, torsion fractures can form anywhere within the core barrel and generally can be attributed to loose core fragments that cause jamming. In most cases, torsion fractures were found at the bottom of a core run in all the cores with exception of borehole 0350 in which torsion fractures were not associated with the bottom of the core run.

Petal-centerline fractures are coring-induced fractures that possess distinct morphologies that relate to the core axis. They are observed to be fractures that have origination points near the core boundary and propagation paths vertically down and parallel to the core axis. They are generally smooth, curvilinear to planar and curve in a downcore direction. The surface morphology resembles a petal in the area of origin with thin, fine ridges that may curve to meet the core boundary or a pre-existing fracture. These fine ridges are generally referred to as hackle plumes. Arrest lines may form closely spaced, concentric, convex downcore arcs (Figure 3.4). Arrest lines, sometimes called rib marks, in almost every case indicates the direction of fracture propagation, as the curvature is convex in the direction of propagation (Kulander et al. 1979). Petal-centerline fractures are interpreted to originate below the cutting edge of the drill bit, even slightly out of the drill column (Kulander et al. 1990). Petal-centerline fractures were observed in core 0348 at depths of 145.5 and 196 ft below ground surface.

3.3. CHARACTERISTICS OF FRACTURES IN OUTCROP

As part of the fracture studies, four vertical profiles at the railroad cut outcrop west of Mound Plant were examined (Figure 3.1). A photograph of one of the profiles is shown in Figure 2.9. Tables B.1 to B.4 (Appendix B) present the fracture set data for each vertical profile. These measurements provide azimuthal orientations, frequency, and general surface roughness and shape of fractures on the Main Hill.

Measurements of azimuthal orientations indicate that four fracture sets are present with the exception of profile #4, the northernmost profile, where only three fracture sets are recognized (Table III.1). The first-formed fracture or primary fracture in each profile is referred to as fracture set 1, followed by secondary fracture sets in consecutive order. The orientation for fracture set 1 trends north 60 degrees west in both shales and limestones; fracture set 2 is observed to trend north 20 degrees east. Figure 3.5 depicts the frequency and distribution of fractures in shales at the railroad outcrop. Figure 3.6 depicts the same data for limestones. Again, no major differences in orientation are observed between shales and limestones. When all the data are considered (Figure 3.7), limestones are observed to have a minor set of fractures that trend north 40 degrees west that are absent in shales.

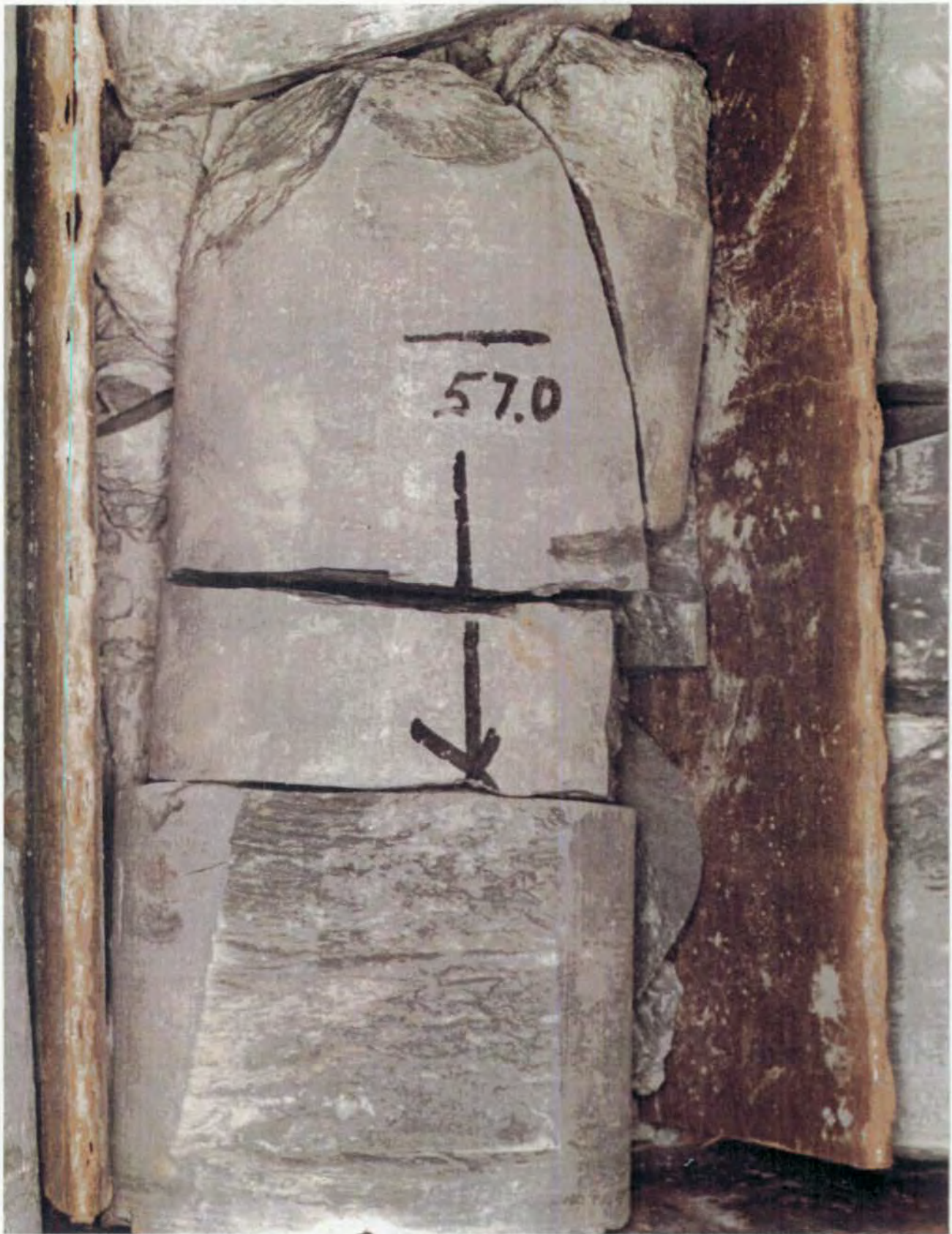


Figure 3.4. Photograph of a petal-centerline fracture in Mound Plant core 0350 (Mound photograph #932479).

Table III.1. Summary of Fracture Orientations at Railroad Cut

DATA SETS	PROFILE #1	PROFILE #2	PROFILE #3	PROFILE #4
Fracture Set 1 (limestones & shales)	N60–N70 W	N70–N80 W	N60–N70 W	N60–N70 W
Fracture Set 2 (limestones & shales)	N10–N20 E	N10–N20 E	N20–N30 E	N20–N30 E
Fracture Set 3 (limestones & shales)	N70–N80 E	N10–N20 E	N70–N80 E	N50–N60 E
Fracture Set 4 (limestones & shales)	N30 W	N10–N70 E/N35 W	N20 W / N20 E	–
All data (limestones & shales)	N60–N70 W	N70–N80 W	N60–N70 W	N60–N70 W
All shales (fracture set 1–4)	N10–N20 E	N70–N80 W	N60–N70 W	N20–N30 E
All limestones (fracture set 1–4)	N60–N70 W	N60–N80 W	N60–N70 W	N60–N70 W
Fracture set 1 (Shales only)	N60–N70 W	N70–N80 W	N60–N70 W	N60–N70 W
Fracture set 1 (limestones only)	N60–N70 W	N60–N70 W	N60–N70 W	N60–N70 W
Fracture set 2 (Shales only)	N10–N20 E	N10–N20 E	N20–N30 E	N20–N30 E
Fracture set 2 (limestones only)	N10–N20 E	N20–N30 E	N20–N30 E	N20–N40 E
All shales data	N60–N70 W = dominant trend			
All limestone data	N60–N70 W = dominant trend			
All data	N60–N70 W = dominant trend			

ftable.wk1



Figure 3.5 Frequency and orientation of fractures in shales at railroad cut outcrop.



Figure 3.6. Frequency and orientation of fractures in limestones at railroad cut outcrop.

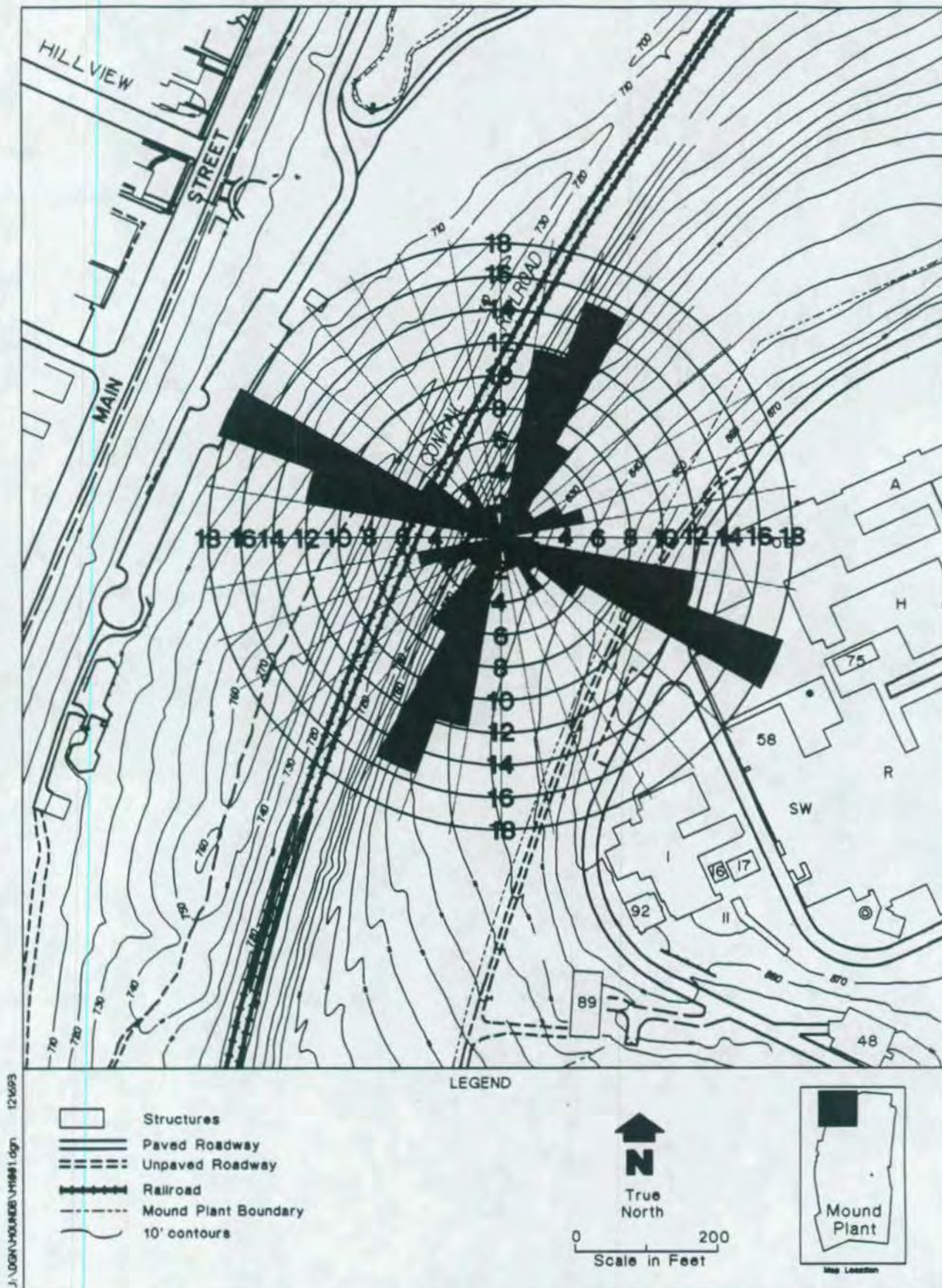


Figure 3.7. Frequency and orientation of all fractures at railroad cut outcrop.

The measured frequency of fractures in the shale beds showed a broad range in any given bed and could be as high as 24 fractures per ft, averaging about 12 fractures per ft. The measured frequency of fractures in the limestone was more consistent and averaged about 3 fractures per ft. Figure 3.8 illustrates the relationship between bedding thickness and fracture frequency for the primary fractures in limestones. These data indicate that frequencies in limestone beds of given thicknesses vary widely, but fracture frequency is greater in thinner beds. Figure 3.9 illustrates bedding thickness versus fracture frequency for primary fractures in shales. The fracture frequency in shales does not favor thin or thick beds.

No measurements of vertical orientation was performed; all fractures observed in outcrop are assumed to be vertical. Horizontal bedding plane fractures were not observed. The extremely irregular bedding characteristics of the Cincinnati Series rocks makes the positive identification of horizontal fractures extremely difficult.

Fractures observed in the outcrop are generally stratabound. In the limestones fractures generally penetrated the entire bed or layer of limestone. In the shale beds, however, fractures rarely penetrated the entire bed. No fractures were observed that penetrate through a limestone-shale-limestone sequence. Fractures in shales are rarely larger than 4 square centimeters and generally only one square centimeter.

Surface textures of fractures are observed qualitatively. Fracture set 1 tends to have surfaces that are smooth and planar; rough surfaces are common, but not dominant. Fracture set 2 tends to be mostly rough and curvilinear; smooth and curvilinear are very common, but not dominant. The remaining fracture sets tend to have rough surfaces in both planar and curvilinear morphologies.

No secondary mineralization was observed on any fracture surfaces in outcrop.

3.4. DISCUSSION OF OBSERVATIONS OF NATURAL FRACTURES

Fracture studies are classically designed to provide data on the stress events that existed during specific periods of geologic time. Such an analysis is generally beyond the scope of this investigation. The strong differences in fracture frequency between the Main Hill and SM/PP Hill suggest that the abundant shallow fractures resulted from glacial forces rather than structural deformation related to the Cincinnati Arch. In the Mound Plant cores, fractures are examined to provide specific data on the distribution and geometry of bedrock groundwater flow system. These data are used in conjunction with geophysical measurements to quantify the nature and extent of the fracture carapace.

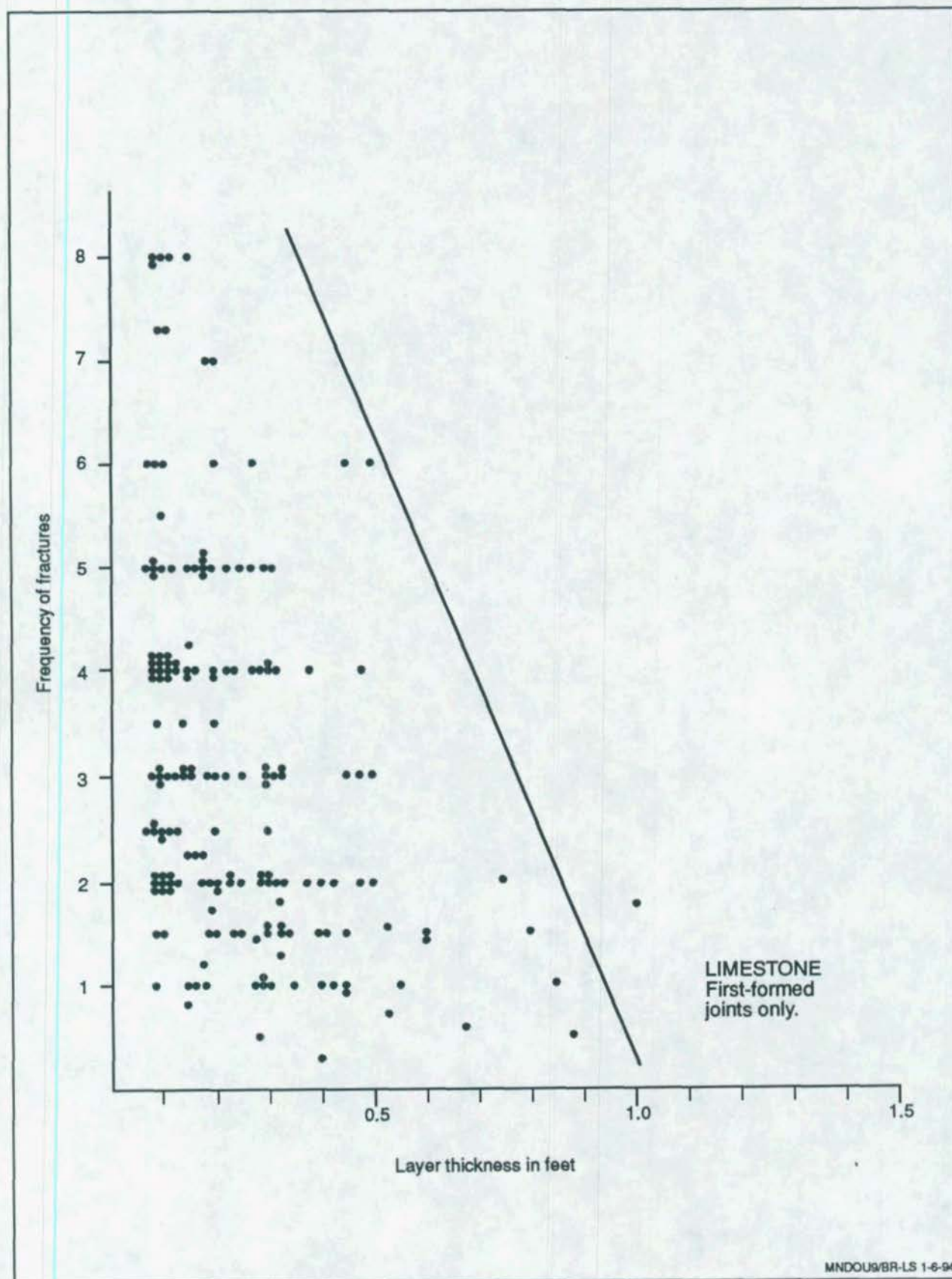
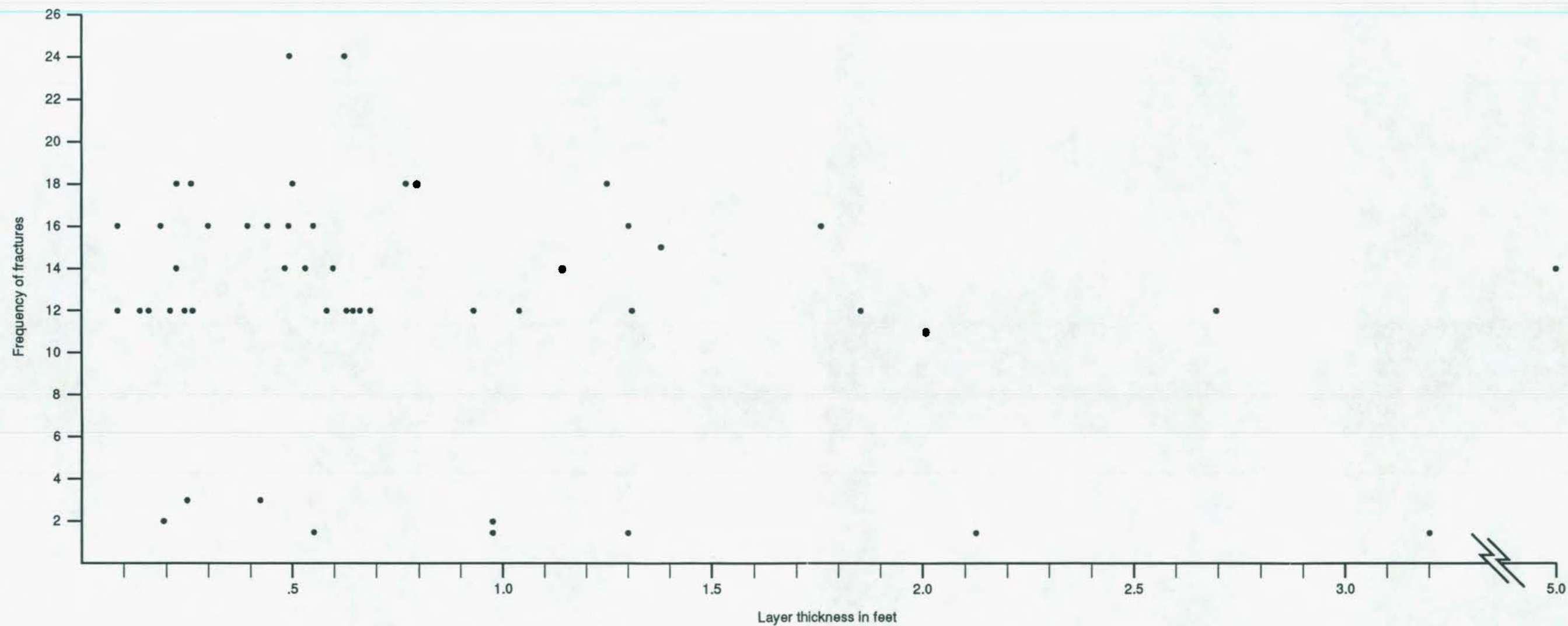


Figure 3.8. Summary of frequency of fractures versus layer thickness in limestones at railroad cut outcrop.



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Figure 3.9. Summary of frequency of fractures versus layer thickness in shales at railroad cut outcrop.

The fracture carapace is interpreted to consist of the shallow, interconnected fracture network that possesses sufficient enhanced permeability such that the magnitude of groundwater flow is significantly elevated above that in the underlying rocks. Estimates of permeability, described in Section 5, suggest the unfractured bedrock has permeability of approximately 0.01 ft/day, whereas the fracture carapace has permeability, due to fracture, of approximately 1 ft/day.

The following paragraphs, discuss general results of fracture frequency, orientations, and morphologies of fractures observed in this investigation. Detailed discussions of individual characteristics of the Main and SM/PP Hills, and the origin and evolution of the fracture carapace then follows.

The trends of fracture frequency is similar in all cores examined. Fracture density is greatest in the upper few tens of ft and decreases with depth. Rubble zones are also observed to be present throughout the cores and are interpreted to indicate the presence of fractures, even though the fracture itself is not observed. Rubble zones are also observed to decrease in frequency with depth indicating that even if the true frequency of vertical fractures are not observed in the vertical cores, their distribution is evident.

The rubble zones may also indicate the presence of horizontal bedding plane fractures. However, the extremely irregular bedding characteristics of the Cincinnati Series rocks render the positive identification of bedding plane fractures extremely difficult to nearly impossible. The striking iron stains on the bedding surfaces in core 0348 indicates that bedding plane fractures are important shallow conduits for groundwater flow. The iron stains are prevalent to a depth of about 63 ft, so if bedding plane fractures are an important factor in the bedrock flow system, it is assumed to possess a similar vertical distribution as the prominent vertical fractures.

Overall, fracture orientations are generally considered the single most important characteristic of a fracture system. These orientations determine preferred flow directions in groundwater systems dominated by fracture flow. In the Mound Plant bedrock, the fracture trends at the railroad cut outcrop are shown in Figure 3.7. Two major directions are evident: north 60 degrees west and north 20 degrees east. These data are consistent with joint measurements performed by Dames and Moore (1973). Forty-eight joint measurements indicated at least two major joint sets were present, striking in a west-northwest to east-southeast direction and in a north-northeast to south-southwest direction. No data were reported however. These directions are interpreted to represent the major trends of fractures not only on the Main Hill where the measurements were taken, but also on the SM/PP Hill. No major outcrops are known on the SM/PP Hill.

The major orientations of fractures observed at Mound Plant are, however, consistent with other studies of regional joint patterns and indicate that fracture orientations are probably inherited from the regional structure of the Cincinnati Arch (see subsection 3.7 for discussion). Hofmann (1966) reviewed unpublished studies that measured over 2000 joints in southwest Ohio and found three predominant joint sets: west-northwest, northwest, and northeast. Ver Steeg (1944) compiled a structural map for southwestern Ohio based on USGS data that indicated joint sets with northwest and north-northeast trends. Hofmann (1966) studied deformational structures visible in outcrop in the immediate area of Cincinnati. In decreasing abundance, vertical fractures were observed to have formed along four main directions: northwest, north-northwest, north-northeast, and east-northeast. A recent study by Ritzi and Andolsek (1992) involved a azimuthal electrical resistivity survey and anisotropic pumping test in a fractured carbonate flow system west of Dayton, Ohio. The results of the resistivity survey were used to design a pumping test. The results indicated the principal axis of transmissivity extended in the north 25 degrees east to north 45 degrees east direction. This is in the range for the second fracture set observed near the Mound Plant in the railroad cut. Ritzi and Andolsek (1992) correlated this fracture set to the axis of the Cincinnati Arch that strikes approximately north 30 degrees east. They interpreted the fracture set to have formed normal to the direction of least principal stress during the time of arch formation. Ritzi and Andolsek (1992) noted that other tests in the Ohio region have observed similar trends.

No quantitative measurements were obtained in physical aperture openings. Since we are not currently attempting to model fracture flow, physical data may not be useful and the physical openings of the fractures exposed at the surface are probably affected by weathering processes. Aperture texture may also determine flow properties through control of aperture variation, but at present there is no general agreement concerning the most appropriate manner in which to characterize the hydraulic properties of an individual fracture. Fracture apertures undoubtedly influence fracture flow in that the solution to the Navier-Stokes equation leads to a cubic function. Flow through a smooth-walled fracture may be proportional to the cubic law, but rough-walled fractures require empirical correction factors. It appears generally accepted that hydraulic aperture may be different from measured mechanical apertures. These two may, in turn, be different from the transport aperture. The transport aperture is used to calculate the velocity at which a dissolved chemical is transported through the rocks (Barton and Hsieh 1989).

3.5. DISCUSSION OF FRACTURE CHARACTERISTICS OF THE MAIN HILL (CORES 0348 AND 0349)

All data including water levels, fracture distribution, and iron staining indicate that the bedrock flow system on the Main Hill is strongly developed. The physical characteristics of the Main Hill are exemplified in cores from boreholes 0348 and 0349. The top of borehole 0348 is located on the top

of the Main Hill in the Liberty Formation at an elevation of 876 ft MSL. The top of borehole 0349 is located on the south flank of the Main Hill in the Waynesville Formation; the Liberty Formation has eroded away. The borehole lithologies are well correlated between them in the core descriptions and lithologic logs. Lithologic bedding is horizontal and undeformed except for joints, i.e., fractures.

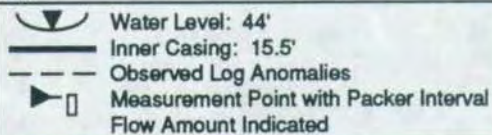
Physical fracturing of the rocks in the shallow portions of the boreholes is indicated by direct visual observation of fractures. Fracture frequency is observed to be greatest in the upper 50 ft, above an elevation of approximately 810 ft MSL in core 0348 and 730 ft MSL in core 0349. Intermittent fractures are observed down to an approximate depth of 90 ft at elevation 768 ft MSL in 0348 and 675 ft MSL in 0349. Rubble zones, interpreted to represent the presence of unobserved fractures, indicate isolated fractures are present throughout the bedrock section. Core 0348 had the broadest range in measured fracture lengths from 0.1 to 0.9 ft and abundant iron stains on fractures and bedding plane surfaces. The cores from these locations indicate that fracturing is relatively frequent at the surface and decreases in frequency and degree with depth. The Waynesville Formation in Core 0349 appears almost as intensely fractured as the Liberty Formation in Core 0348. These data indicate that fracturing is a function of depth from the ground surface. The fact that the two boreholes are located at elevations 60 ft apart indicates that the shallow fracture system mimics surface topography on the Main Hill. This mantle of fractured rock is referred to as the fracture carapace in this report.

On the Main Hill, measured groundwater flows exhibit strong correlations with fracture frequency. Figure 3.10 depicts a summary of fracture frequency and results of the borehole flowmeter measurements. In borehole 0348, groundwater flow direction is downward and measured flow is greater than 1200 mL/min at depth less than 35 ft; below 35 ft, flow decreases to 214 mL/min; and by 90-ft depth, measured flow decreases to zero. The data depicted in Figure 3.10 was obtained under stressed conditions, as detailed in Section 4.11. Under ambient conditions, no vertical flow was measured at or below 68-ft depth. Figure 3.11 depicts similar relationships for borehole 0349. In all cases, flow was from the water-filled borehole into the formation. These data indicate that vertical groundwater flow and the greatest degree of fracturing occurs in the upper 50 ft and decreases over the same depth interval. This correlation indicates that groundwater flow in the shallow bedrock is controlled by fracture frequency. But fracture frequency may not be the only control of groundwater movements. The actual interconnection of fractures probably controls permeability, but interconnection is certainly related to frequency by an unknown function. The amount of interconnection is interpreted to decrease with depth.

Plate 3 depicts a general cross section of the fracture carapace on the Main Hill. The bedrock flow system is subdivided into three zones; the upper, shallow part of the fracture carapace; the lower,

Well Name: 348
STRESSED CONDITIONS

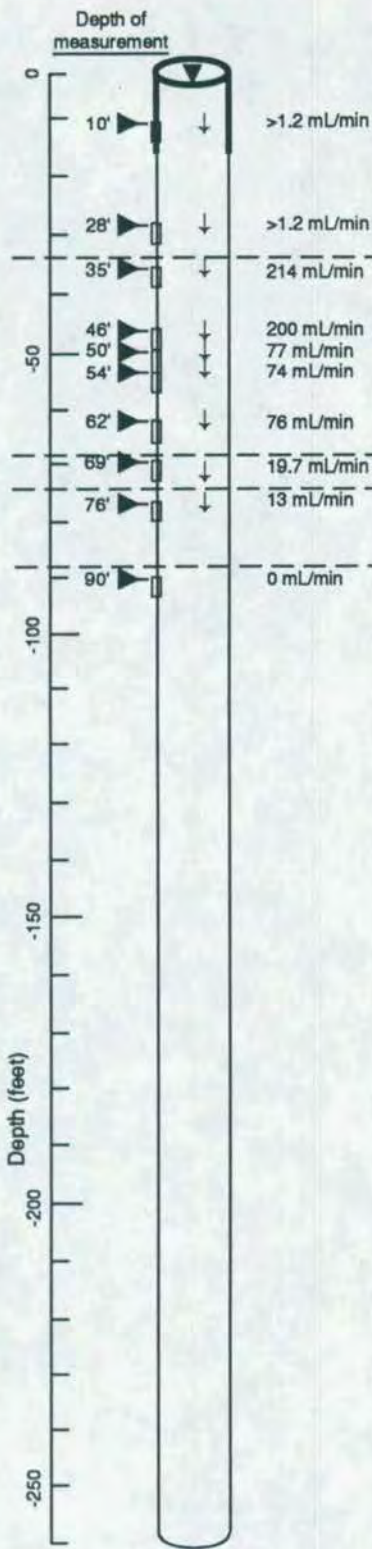
KEY:



FRACTURE FREQUENCY



FLOWMETER DATA



FLUID RESISTIVITY (ohm-meters)

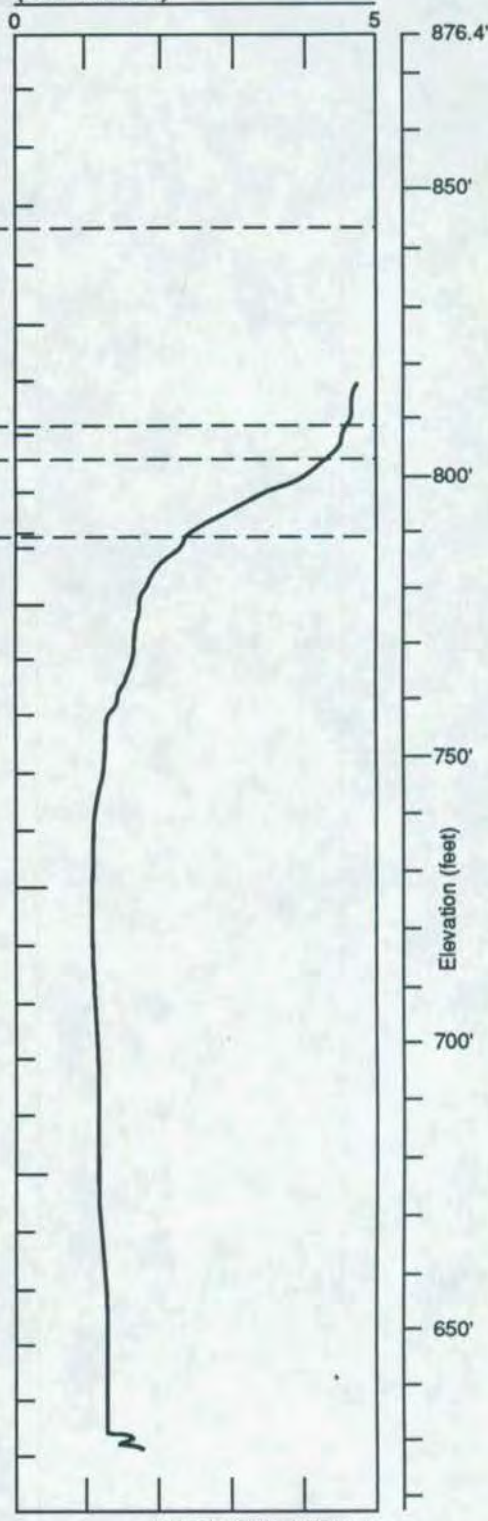
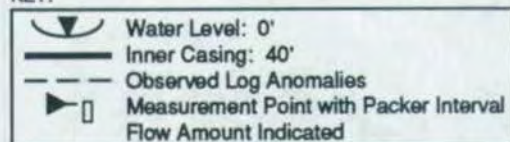


Figure 3.10. Correlation of flowmeter measurements and fracture frequency at borehole 0348.

Well Name: 349
STRESSED CONDITIONS

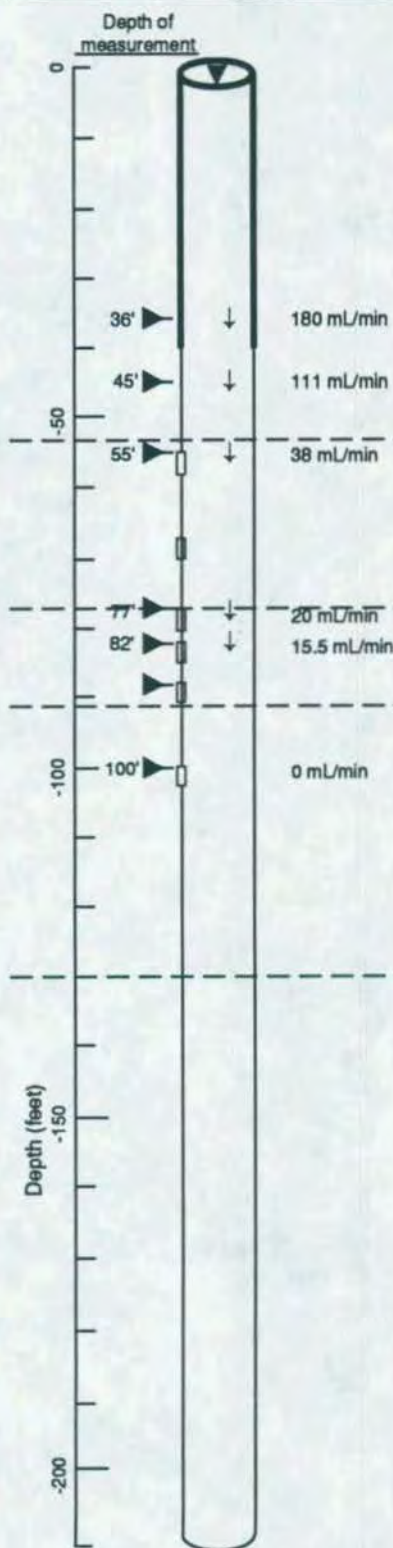
KEY:



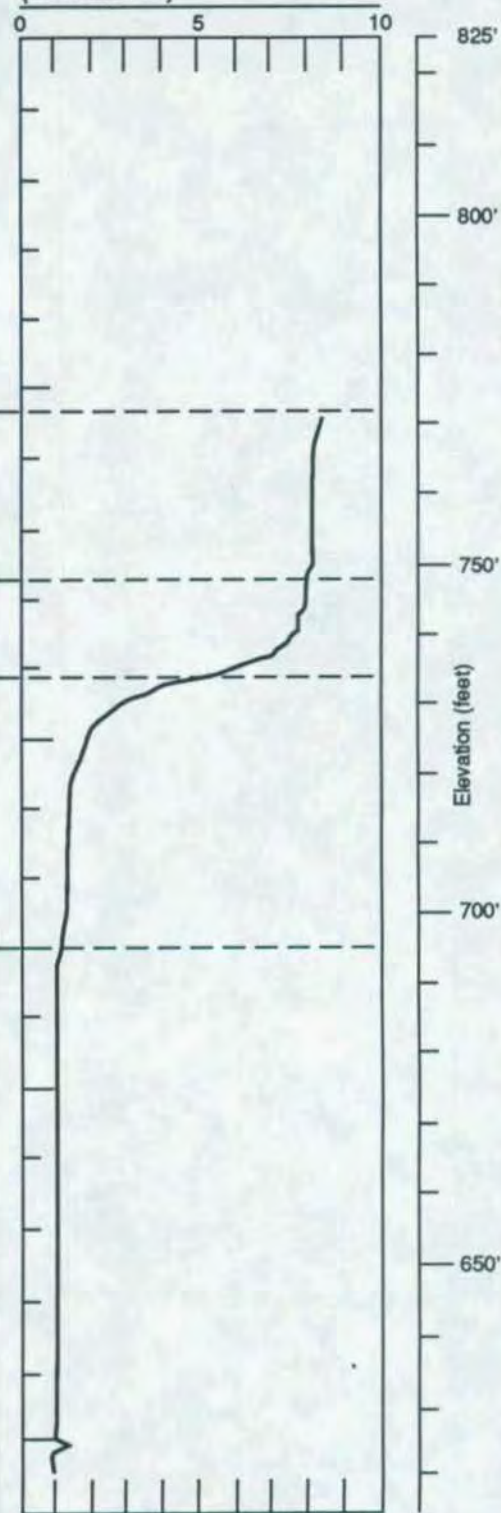
FRACTURE FREQUENCY



FLOWMETER DATA



FLUID RESISTIVITY (ohm-meters)



MND09/BR-349FM/FF 1-5-94

Figure 3.11. Correlation of flowmeter measurements and fracture frequency at borehole 0349.

deeper part of the fracture carapace; and the bedrock beneath the fracture carapace. The upper part of the fracture carapace is interpreted to extend from the surface to a depth of about 50 ft on the Main Hill. This zone exhibits evidence of frequent, interconnected fractures that are partially saturated with groundwater. The lower part of the fracture carapace is interpreted to extend from a depth of approximately 50 ft to a maximum depth of approximately 100 ft on the Main Hill. This zone exhibits evidence of less frequent, poorly interconnected fractures that are probably water saturated. The degree of interconnection is interpreted to decrease with depth through the lower zone until the magnitude of groundwater flow is unable to be measured by modern instrumentation. Beneath the fracture carapace is probably a zone of no flow in which isolated fractures are not interconnected. Subsection 5.2 provides additional description and discussion of the fracture carapace on the Main Hill.

3.6. DISCUSSION OF FRACTURE CHARACTERISTICS OF THE SM/PP HILL (CORES 0350 AND 0355)

In contrast to the Main Hill, all data including water levels, fracture distribution and the lack of iron staining indicate that the bedrock flow system on the SM/PP Hill is poorly developed. Cores 0350 and 0355 exhibit many similar physical characteristics and exemplify conditions on the SM/PP Hill. The top of borehole 0350 is located on the top of the SM/PP Hill in the Whitewater Formation at an elevation of 887 ft MSL. The top of borehole 0355 is located on the northwest flank of the SM/PP Hill in the Waynesville Formation; the Whitewater and Liberty Formations have been eroded away (Figure 2.9). The borehole lithologies are well correlated between the two in the core descriptions, neutron and natural gamma logs. Lithologic bedding is horizontal and undeformed except for joints, i.e., fractures.

Physical fracturing of the rocks in the shallow portions of the boreholes is indicated by direct visual observation of fractures. In core 0350, fracture frequency is observed to be greatest in the upper 20 ft, above an elevation of approximately 860 ft MSL. In core 0355, fractures are observed to occur intermittently from the surface to a depth of 50 ft at elevation 720 ft MSL. Rubble zones indicate that isolated fractures are probably present throughout the bedrock. No iron staining or other secondary mineralization is observed in fractures from boreholes on the SM/PP Hill. The Waynesville Formation in Core 0355 appears as intensely fractured as the Liberty Formation in Core 0350. These data indicate that fracturing is a function of depth from the ground surface and that it is not generally related to lithology or stratigraphy. The fact that the two boreholes are located at elevations 80 ft apart indicates that the fracture carapace mimics surface topography on the SM/PP Hill.

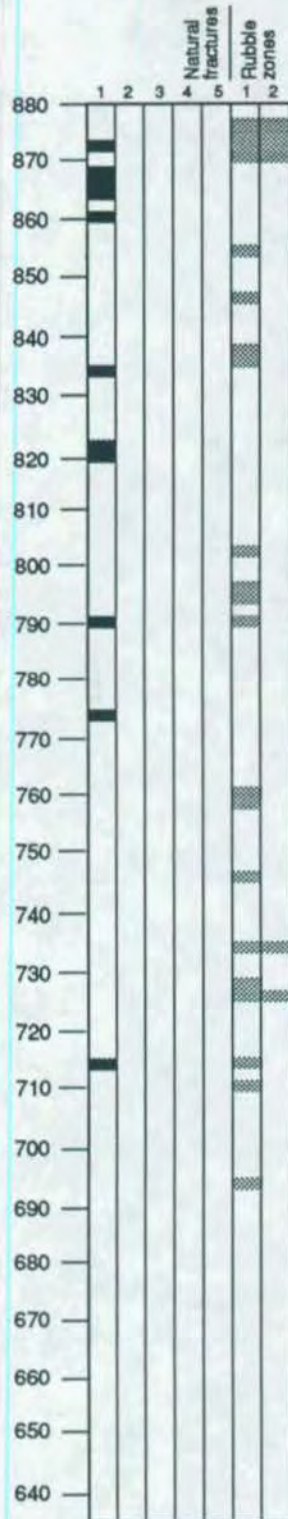
On the SM/PP Hill, measured groundwater flows exhibit strong correlations with the fracture carapace. Figure 3.12 depicts a summary of fracture frequency and results of the borehole flowmeter measurements in borehole 0350; vertical groundwater flow and frequency of fractures are restricted

Well Name: 350

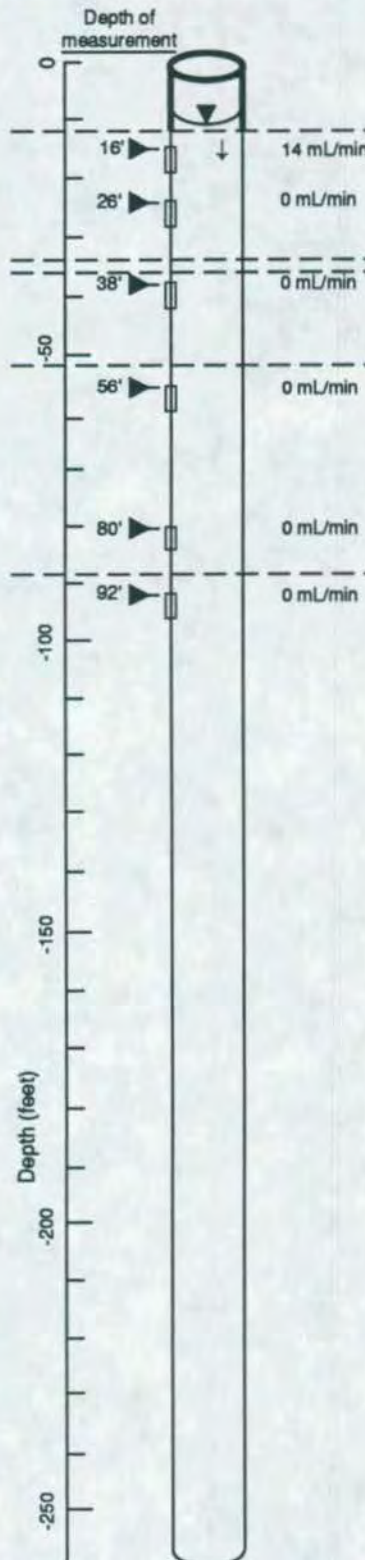
KEY:

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-  Inner Casing: 12'
-  Observed Log Anomalies
-  Measurement Point with Packer Interval
Flow Amount Indicated

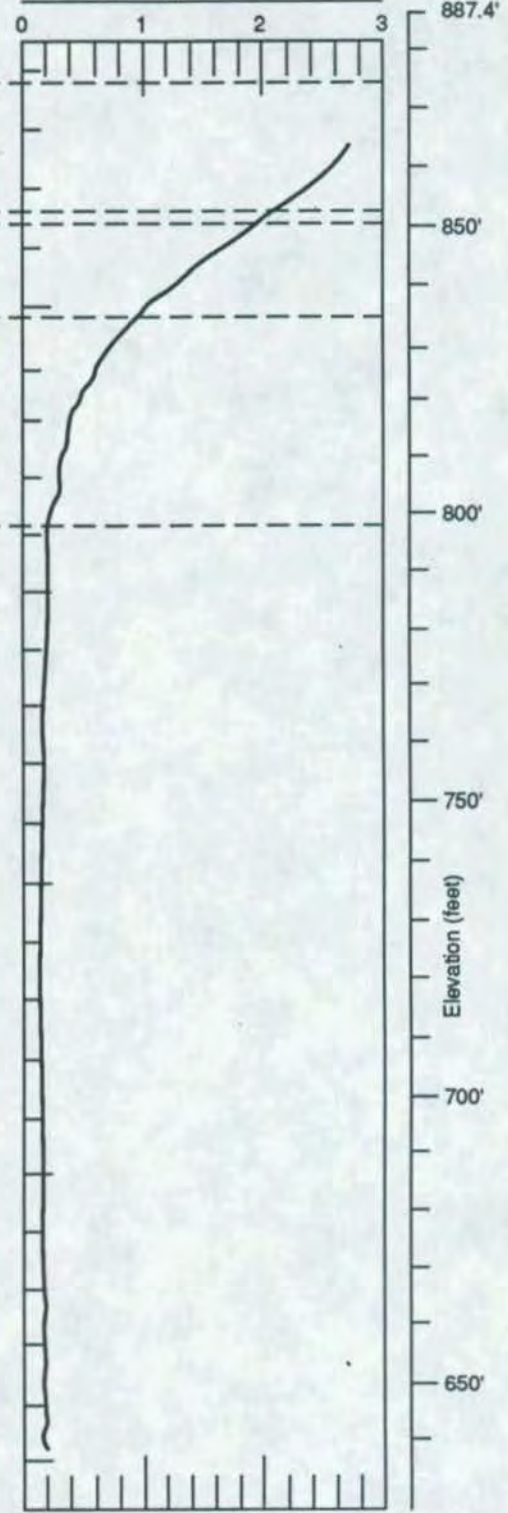
FRACTURE FREQUENCY



FLOWMETER DATA



FLUID RESISTIVITY (ohm-meters)



MND09/BR-350FM/FF 1-5-94

Figure 3.12. Correlation of flowmeter measurements and fracture frequency at borehole 0350.

to very shallow depths. Neither the fractures nor the measured groundwater flow are as deep as the Main Hill. The only interval in which vertical flow was detected is at 16-ft depth (elevation 871.4 ft MSL) at a rate of 14 mL/min flow. The other intervals that were measured showed no measurable flow. No vertical flow was measured whatsoever in borehole 0355. Neither of these boreholes could be measured under stressed conditions because of the very shallow water levels. These data strongly correlate with the observed distribution of fractures, as the greatest degree of fracturing occurs in the upper 20 ft at core 0350. Core 0355 does not exhibit the upper zone of intensely fractured rock evident in the other cores. These data indicate that vertical groundwater flow and the greatest degree of fracturing occurs in the upper 20 ft and decreases over the same depth interval. This correlation indicates that groundwater flow in the shallow bedrock is controlled by fracture frequency and the interconnected fracture network. On the SM/PP Hill the amount of interconnection is interpreted to decrease rapidly with depth.

Plate 3 depicts a general cross section of the fracture carapace on the SM/PP Hill. As with the Main Hill, the bedrock flow system is subdivided into three zones; the upper, shallow part of the fracture carapace; the lower deeper part of the fracture carapace; and the bedrock beneath the fracture carapace. On the SM/PP Hill, the upper part of the fracture carapace is interpreted to extend from the surface to a depth of about 25 ft and the lower part is interpreted to extend from a depth of approximately 25 to a maximum depth of approximately 60 ft. The degree of fracture interconnection is interpreted to decrease with depth through the lower zone until the magnitude of groundwater flow is unable to be measured by modern instrumentation. Subsection 5.2 provides additional description and discussion of the subdivision of the fracture carapace on the SM/ PP Hill.

3.7. DISCUSSION OF THE ORIGIN AND EVOLUTION OF THE FRACTURE CARAPACE

This report describes a system of interconnected fractures superimposed on the Mound Plant bedrock. This mantle of fractured rock is referred to as the fracture carapace in this report. The fracture carapace is interpreted to consist of the shallow, interconnected fracture network that possesses sufficient enhanced permeability such that the magnitude of groundwater flow is significantly elevated above that in the underlying rocks. The frequency of fractures and their degree of interconnection are interpreted to decrease with depth until groundwater flow is completely attenuated at the base of the carapace. Plate 3 depicts a cross section of the fracture carapace. It exhibits a greater degree of development on the Main Hill than the SM/PP Hill. The differential is attributed to the greater surface area exposed on the Main Hill as detailed below.

The fracture carapace is interpreted to have formed by processes of combined physical and chemical weathering. The fracture system itself probably predates the formation of the current bedrock surface.

Fracture orientations suggest that they were inherited from the regional structure of the Cincinnati Arch. The striking differences in fracture frequency between the Main Hill and SM/PP Hill, however, indicate that glacial processes dominate fracture evolution. Mechanical stresses imposed by glaciers against the valley walls could have promoted additional fracturing or could have deformed the rocks along pre-existing fractures. During periods of glacial unloading and release of overburden stress, existing fractures would have dilated and increased their effective apertures. Since the Main Hill is more exposed than the SM/PP Hill, it would expose more fractures to the dilational effects. The SM/PP Hill is only exposed on the western sides that face the glacially incised Buried Valley aquifer. Dilation from glacial rebound is expected to have the greatest effects on bedding plane fractures. These are difficult to recognize in the very irregular bedded rocks at Mound Plant, but the effects are expected to decrease in degree with depth. The overall effects would be consistent with the observations reported here.

Within the fracture carapace, a fracture could propagate by chemical weathering. Relatively fresh meteoric water would leach soluble cations, such as sodium and calcium, and anions, such as chlorides, from the marine rocks. These chemical dissolution processes acted locally to enhance primary porosity. The fracture apertures and solution cavities could propagate slowly over geologic time given a consistent supply of fresh water. The processes of chemical weathering and removal of salts in the fracture carapace is evident in the EM conductivity logs (Appendix C) described in Section 4 of this report. Because the fracture carapace is believed to be the mechanism for transmitting fresh water to depth, the fresh water alteration profile of the marine rocks reflects the geometry of the fracture carapace. The fact that the fresh water alteration does not extend to the full depth of the fracture carapace attests to the very poor permeability of the lower part of the fracture carapace.

Chemical precipitation of iron oxides could act to reduce the effective apertures, as well as decreasing the surface roughness of the fracture. The effects of dissolution would act to increase the hydraulic apertures, whereas the precipitation of secondary minerals acts to close the apertures (Barton and Hsieh 1989). The effects of these conditions on the efficiency of the channeling of water through the fracture cannot be evaluated.

3.8. DISCUSSION OF REGIONAL STRUCTURE OF THE CINCINNATI ARCH

The bedrock underlying the Mound Plant consists of several hundred ft of marine shales and limestones, Upper Ordovician in age. These rocks are well known world-wide because of their abundant fossil assemblages. The structure of the region is well known, but less understood and is relatively poorly studied. A broad structural arch, known as the Cincinnati Arch, of probable Late

Ordovician Age underlies the area. The Cincinnati Arch trends north-northeast from northern Kentucky into southwest Ohio (Figure 2.6). This arch has a poorly defined axis and is best observed by stratigraphic relief, rather than structural relief. Scotford (1964) reviewed the historical development of the understanding of the Cincinnati Arch and stated that:

"Recent work suggests that the traditional structural picture of the Cincinnati Arch as a reasonably well defined elongate but proportionately narrow fold with gently dipping yet discernible flanks may require modification. Green (1961) stated that the arch has no structural axis, but as shown by the regional structure...consists of a nearly level platform with westward dips not exceeding 1/3 degree and commonly less than this. In the 160 mile distance from Indianapolis to Columbus across the arch there are no dips as great as 1/4 degree.

"Information is still too limited to permit an accurate description of the Cincinnati Arch structure but what is emerging is the realization that the northern part of the arch which lies in Kentucky and Ohio is a broad, essentially flat, north south-trending zone situated between the subsided Appalachian basin on the east and the Illinois and Michigan basins on the west and northwest."

In the Site Description and Safety Assessment for the Mound Laboratory, Dames and Moore (1973) reiterated the observation that the arch may actually be a structural high situated between two basins.

Little research appears to have been conducted on the actual structure of the Cincinnati Arch. As discussed in subsection 3.4 above, Hofmann (1966) reviewed published studies that concluded that jointing was influenced by the regional arch structure. The recent study by Ritzi and Andolsek (1992) correlated the principal axis of groundwater transmissivity to the axis of the Cincinnati Arch that strikes approximately North 30 degrees East (see Figure 2.6).

Calculations performed as part of the hydrogeologic investigations support the observations of very low angle of bedding dip. Eleven calculations for strike and dip of beds encountered in the boreholes was performed using the standard three-point solution (Billings 1972). Even considering the precision of the ground surveys and vertical controls inherent in the geophysical surveys, the results are inconclusive and are not tabulated for this report. Results of the calculations, however, indicate bedding dips approximately 0.1 degree or about 0.22 percent, suggesting a regional dip of 11 ft per mile, about twice the reported value of 5 ft per mile (Hofmann 1966). Dip directions calculated, however, range from nearly due west to due east and all variations in between. No consistency can be determined within formations or even within beds. A general dip direction to the north may be inferred from this information, but this is vague.

These data suggest that relief on individual beds exceed the regional dip reported. Lithologic bedding is then assumed to be essentially flat lying, but possesses a slight rolling topography on the order of about one ft over the expanse of the Mound Plant. Slightly greater relief is observed on the top of the limestone and shale facies near the top of the Oregonia Formation (Plate 1). Relief on this unit is approximately 3 ft between boreholes. This suggests that the contact between the limestone and shale facies and the overlying shale and minor limestone facies is disconformable. This observation is consistent with the observations of others as a disconformity between the Oregonia and Waynesville Formations has been proposed by several workers (Tobin 1986; Hay 1981). Holland (1993) reports a major change in depositional sequence at the same contact.

3.9. CONCLUSIONS

The strong correlations between fracture frequency, water flow measurements, and the alteration characteristics of the bedrock indicate that the objectives of the OU 9 bedrock studies have largely been attained. Two outstanding issues appear to remain. First, there is little data to indicate that the fracture orientations of the SM/PP Hill are indeed the same as the Main Hill and fracture orientations may control groundwater flow directions in the bedrock. The only large outcrop in the area is the railroad cut to the west of the Mound Plant, but this cut is in the Main Hill structure. Region studies indicate that the north 20 degrees east orientation may correspond to the tensional stresses associated with the Cincinnati Arch, but since the arch is poorly defined, this is relatively speculative. It is suggested that additional limited investigations be conducted on smaller outcrops on the SM/PP Hill complex and perhaps the surrounding community to confirm that the orientation trends observed on the Main Hill are relevant for the SM/PP Hill.

Second, continuous bedrock cores are stored at Miami University, Oxford, Ohio. The identification of these cores was not made in time to include data in this report. It is believed that these cores may provide important data points for the fracture studies. It is recommended that the cores be examined for fracture characteristics. The cores were obtained by a water-wash rotary coring method, rather than the air rotary used by OU 9, and may possess a different population of induced fractures, but natural fractures will be evident.

4. BOREHOLE GEOPHYSICS

A detailed suite of borehole geophysical measurements were conducted as part of the OU 9 hydrogeological investigations to supplement lithologic descriptions and fracture analysis of the bedrock core collected from six boreholes. The borehole geophysics studies identify the 1) vertical variations in the properties of the bedrock to determine intervals that may transmit groundwater; and 2) zones of competent rock that may be aquitards. The bedrock flow system is considered to be a complex system dominated by fracture flow. Borehole geophysics provide measurements of the physical properties of rocks and the fluids within them. Geophysical logs consist of the measurement of a physical parameter that is plotted against depth. They have been shown to be effective in inferring the lithology, porosity, resistivity, and moisture contents of the rocks and fluids in the borehole. Limited borehole geophysical investigations were conducted on the Mound Plant bedrock during the Site Description and Safety Assessment (Dames and Moore (1973). These previous studies did not provide sufficient information to resolve specific questions concerning the characteristics of the bedrock flow system.

The bedrock at the Mound Plant consists of a thick sequence of interbedded marine shales and limestones. Most of the rocks encountered in the boreholes in this investigation retain higher salinities of water that was trapped during deposition. However, a mantle of fresh, meteoric water is apparent in the upper zones of all boreholes. This fresh water carapace is attributed to the leaching of the original salts from the rocks by meteoric water transmitted through fractures. The subsections that follow provide descriptions of the geophysical measurements performed on the rocks and their fluids, results, and discussions of the data. Discussions of the extent and geometry of the fresh water carapace on the Main and SM/PP Hills then follows.

4.1. METHODS

Locations of the six boreholes in which geophysical measurements were made are shown in Figure 1.3. Table IV.1 summarizes the geophysical logging suite performed. Downhole logging using radioactive source tools, specifically neutron and density logs, was not performed in 0335, located on City of Miamisburg property, because of concerns of losing the radioactive tools in the borehole. Borehole geophysical measurements were performed by Colog, Inc. of Golden, Colorado. With the exception of the borehole video and heat pulse flowmeter log, the geophysical logs furnish a continuous digital record that can be interpreted to provide physical properties of the rock matrix and the borehole fluids. The continuous logs were obtained by lowering the tool into the borehole to about 50 ft from the bottom, the lower 50 ft was logged as a quality check, and the borehole was logged completely from the bottom up to ensure constant speed and cable tension. Table IV.2 summarizes the applications

Table IV.1. Geophysical Logging Suite

Type of Geophysical Log	0335	0348	0349	0350	0352	0355
Borehole Video	X	X	X	X	X	X
Full Waveform Sonic	X	X	X	X	X	X
Three-Arm Caliper	X	X	X	X	X	X
Guard Resistivity	X	X	X	X	X	X
EM Conductivity	X	X	X	X	X	X
Neutron	NA ^a	X	X	X	X	X
Compensated Density	NA ^a	X	X	X	X	X
Natural Gamma	X	X	X	X	X	X
Temperature	X	X	X	X	X	X
Fluid Resistivity	X	X	X	X	X	X
Heat Pulse Flowmeter	X	X	X	X	X	X

^aLogging tool was not run at this City of Miamisburg location.

and borehole conditions for each log. Table IV.3 summarizes the depths at which each geophysical tool was run; and Table IV.4 summarizes the speed at which each geophysical tool was run. The borehole video required clear water conditions in the borehole to provide visibility so it was run first after the boreholes were allowed to stand for about a week so the sediments would settle.

The digitized logs were input into VIEWLOG™, a comprehensive computer program. This system operates on a personal computer and provides display control of well log data. Plotting and interpretation of borehole data on the computer screen can be performed. This system allows the user to modify log presentation for detailed and accurate interpretation and provides for cross-plotting and output to a printer. Logs from a single well or a number of wells can be correlated side-by-side using either depth or elevation as a means of control and correlation. The VIEWLOG™ presentation of the available geophysical records from each borehole is graphically presented on data sheets in Appendix C. These sheets show the unique responses of the geophysical logs in a side-by-side presentation for each borehole.

The borehole video is stored on standard VHS format tape. The heat pulse flowmeter (HPF) log was recorded manually and entered into a digital format for comparison plotting with other relevant logs. The variable density log (VDL), generated from the full waveform sonic log, was recorded digitally but the VIEWLOG™ software package used for interpretation and cross-plotting was unable to reproduce the VDL.

4.2. BOREHOLE VIDEO

The borehole video log is a videotape recording obtained with a thin downhole camera and lighting system. The system used is manufactured by Laval Underground Surveys. This is a complete stand-alone system utilizing an armored video coaxial cable, winch and control console. A high-resolution 1 5/8-inch black-and-white camera was placed in 3 7/8-inch diameter open boreholes. The video camera requires clear water to image the borehole walls. The borehole video was the first tool used in all the boreholes, as lowering the tools clouds the borehole water with sediment. The video tape images are used to assist in the determination of lithology, bedding thickness, fracture detection and orientation, fluid flow, and water levels.

Table IV.2. Criteria for Application and Selection of Borehole Logs

Type of log	Potential Applications	Required Hole Conditions
Borehole Video	Fracture location	Uncased borehole
Full Waveform Sonic	Porosity, lithology, and fracture location	Fluid-filled and uncased
Caliper	Lithology and fractures	Any conditions
Guard Resistivity	High resolution lithology	Uncased borehole filled with conductive fluid
EM Conductivity	Quality of borehole fluid and flow within borehole	Uncased, fluid-filled boreholes
Neutron	Saturated porosity, moisture content, and lithology	Optimum results in uncased boreholes
Compensated Density	Bulk density, porosity, moisture content, and lithology	Optimum results in uncased boreholes
Natural Gamma	Lithology	Any conditions
Fluid Resistivity	Quality of borehole fluid	Uncased, fluid-filled
Temperature	Flow within borehole	Uncased, fluid-filled
Heat Pulse Flowmeter	Flow determination at low flow	Uncased, fluid-filled

Table IV.3. Depths at Which the Individual Geophysical Tools Were Run

Type of Geophysical Log	0335	0348	0349	0350	0352	0355
Borehole Video	0-80	0-249	0-202	0-250	0-101	0-197
Full Waveform Sonic	15-77	19-246	51-198	22-251	6.5-97	2-193
Three-Arm Caliper	0-81	5-249	0-202	0-250.5	0-101	0.5-196.5
Guard Resistivity	28-80	63-248	51-197	30.5-246	22-96.5	28-192.5
EM Conductivity	30-78.5	15.5-246	41-198.5	22-249	23-98	30-165.5
Neutron	NA	1-248.5	5-201	5.5-250	5.5-100.5	5-195.5
Compensated Density	NA	8.5-248.5	1.5-201	1.5-250	2-100.5	1-195.5
Natural Gamma	0-75	0-240	0-192	0-241	0-92	0-187.5
Temperature	14.5-81.5	60.5-249.5	51-204	22-251	5-101.5	1-197
Fluid Resistivity	14.5-81.5	60.5-249.5	51-204	22-251	5-101.5	1-197
Heat Pulse Flowmeter	NA ^a	NA ^a	NA ^a	NA ^a	NA ^a	NA ^a

NOTE: All units in feet.

^aHeat pulse flowmeter measurements were conducted only at selected intervals.

Table IV.4. Logging Speed Data (ft/min)

Type of Geophysical Log	0335	0348	0349	0350	0352	0355
Borehole Video	Varied	Varied	Varied	Varied	Varied	Varied
Full Waveform Sonic	10	10	10	10	10	10
Three-arm Caliper	10	10	15	10	10	10
Guard Resistivity	10	15	15	15	15	15
EM Conductivity	10	15	15	15	15	15
Neutron	NA	15	15	15	15	15
Compensated Density	NA	15	15	15	15	15
Natural Gamma	10	10	15	15	15	15
Temperature	8	8	8	8	8	8
Fluid Resistivity	8	8	8	8	8	8
Heat Pulse Flowmeter	NA ^a	NA ^a	NA ^a	NA ^a	NA ^a	NA ^a

^aHeat pulse flowmeter was run at selected intervals.

6

Full length of borehole logged from bottom to top to ensure consistent speed.

Observations

Borehole 0335

Water level was at 16.5 ft; the bottom of the surface casing at 28.6 ft. A fracture is apparent at 38.1 ft and a fracture or lithology change is noted at 50.8 ft. A lithology change is noted at 41.8 ft.

Borehole 0348

Water level at 59.7 ft; a vertical fracture noted at 24.1 ft; highly fracture zone evident from 69 to 70 ft.

Borehole 0349

Angular breakout features noted at 65, 68.5, 70, 80.5, and 93.4 ft depths; numerous vertical fractures, ranging in length from 0.2 to 0.8 ft observed at depths of 71 to 83, 90.2, 101, 110, and 140.1 ft; possible horizontal fractures observed at 82.7, 91.1, 93.4, 117.6, 126, 141.7, 155.8, 166.4, 174.3, 177.3 and 178.9 ft depths.

Borehole 0350

Bottom of the protective casing at 12 ft and the water level at 29.1 ft; fractures observed at 14.1, 26.3, 152.5, 170.3, and 179.4 ft depths; vertical fractures noted at 51.6 and 64.5 ft; bubbles noted coming from a small fracture at 234.2 ft. The bottom of the borehole was observed at 247.9 ft.

Borehole 0352

Bottom of the protective casing at 22 ft and the water level at 5.2 ft; fractures observed at 23, 25.1, 27, 29.1, 30.3, 37.6, and 50.3 ft.

Borehole 0355

Cloudy water in borehole 0355 prevented the use of the borehole video at this location.

4.3. FULL WAVEFORM SONIC

The full waveform sonic (FWS) log is a measure of a formation capacity to transmit sound waves. The FWS log shows a formation's interval transit time, designated ΔT , the reciprocal of sonic velocity. Geologically, this capacity varies with lithology and with rock texture, notably porosity. Qualitatively, the FWS log was used to evaluate the lithology and permeability and to delineate geologic contacts and provide information on fracture analysis of the bedrock (Rider 1986).

The digital FWS acquisition software employed a small diameter sonic probe and advanced interactive FWS post processing to provide the ability to examine individual waveforms, interactively repick transit time, and calculate the amplitude of any portion of the waveform. Additionally, the technique of plotting vertically stacked waveforms as a VDL is utilized to enhance and contribute to the interpretation of the FWS logs. The equipment used consisted of a Mount Sopris dual receiver sonic probe, approximately 2.36-inch nominal outside diameter and 10 ft long, used to acquire digital sonic waveforms at a data density of one waveform every tenth of a foot while logging at approximately 10 ft/min. Calibration and repeatability of the tool is monitored by periodic logging of the U.S. Bureau of Measurements calibration test holes at the Denver Federal Center. Shop and field calibrations can also be performed using a section of free standing pipe of known velocity.

The FWS basically consists of the compression wave, shear wave, and tube wave. The tube wave is a low frequency, broad band event that travels along the borehole wall at a predictable velocity close to that of the speed of sound in water (approximately 5,000 ft/sec). Its amplitude, however, has been shown to vary inversely with permeability. Tube wave energy is attenuated by fluid interaction between the borehole and adjacent formation as the wave travels between the sonic transmitter and receivers. Because permeable fractures or porous media provide a path for this interaction, these conditions reduce the energy of the transmitted wave, resulting in lower tube wave amplitudes associated with more permeable rock.

The VDL is produced with multiple vertically stacked waveforms plotted in time, with alternating dark and light banding symbolizing the frequency and amplitude variation of the sonic waves. The term "variable density" refers to the use of a grey scale to represent amplitude content. Amplitude grey-scaling is an important part of VDL interpretation because this technique visually reveals the variation in amplitude, which is related to permeability and lithology. Parallel dark and light banding denotes homogeneous geology, whereas disturbed, non-parallel banding, or "chevron" banding, is characteristic of features such as contrasting lithology, bedding planes, and fractures. Two logs were actually obtained, one from a near-field receiver and one from a far-field receiver. The far-field receiver tends to penetrate deeper into the formation. These dual receivers are typically useful in situations where shallow borehole effects may mask formation conditions.

The VDL was not digitally recorded; an example log is depicted in Figure 4.1. The VDL logs from each borehole are included in Appendix C. For each borehole, digital plots of the transit time, acoustic velocity, and tube wave amplitude are presented in Figures 4.2, 4.3, and 4.4, respectively.

Interpretation

Of the FWS information generated, the tube wave amplitude record is the most indicative of the borehole hydrogeologic conditions. The tube wave amplitude provides a qualitative permeability profile (permeability increasing to the left). Tube wave energy is attenuated by fluid interaction between the borehole and the adjacent formation. Because open fractures or permeable porous media provide a path for this interaction, these conditions reduce the energy of the transmitted tube wave, resulting in lower wave amplitudes associated with more permeable rock (Crowder et al 1991). Additionally, limestone transmits higher frequency waves better than poorly consolidated shales; therefore, velocity values will be higher in limestones than in shales (USGS 1983). Sonic velocities are also high in steel casing as noted in boreholes 0335, 0352, and 0355. No differences are noted between the near-field and far-field receivers.

Figure 4.4 indicates that the tube wave amplitudes in all six boreholes are relatively low at shallow depths and increases sharply at depth. The low tube wave amplitudes are attributed to fractured rock in the shallow portions of the bedrock and the sharp increase is attributed to the lack of fractures.

4.4. CALIPER

The caliper tool measures borehole size and shape and the log represents the average borehole diameter determined by the extension of three spring-loaded arms. The arms are linked to the cursor of a variable resistance. The measurement of the borehole diameter is determined by the lateral movement of the arms that is translated into movements of the cursor along the resistance and, hence, variations in the electrical output. The caliper tool is calibrated in the shop and in the field before the tool is run into the borehole. Calibration standards consist of rings of known diameter that are placed over the arms and the tool response at these diameters is recorded (USGS 1988).

The caliper logs for all six boreholes are presented in Figure 4.5.

Interpretation

Open borehole diameters measured by the three-arm caliper ranged from 3.8 to 4.2 inches. The open portions of the boreholes were made by coring with a diamond-tipped bit that measured 3 7/8 inches in diameter. No unusual features were noted on the caliper logs for any of the six boreholes logged.

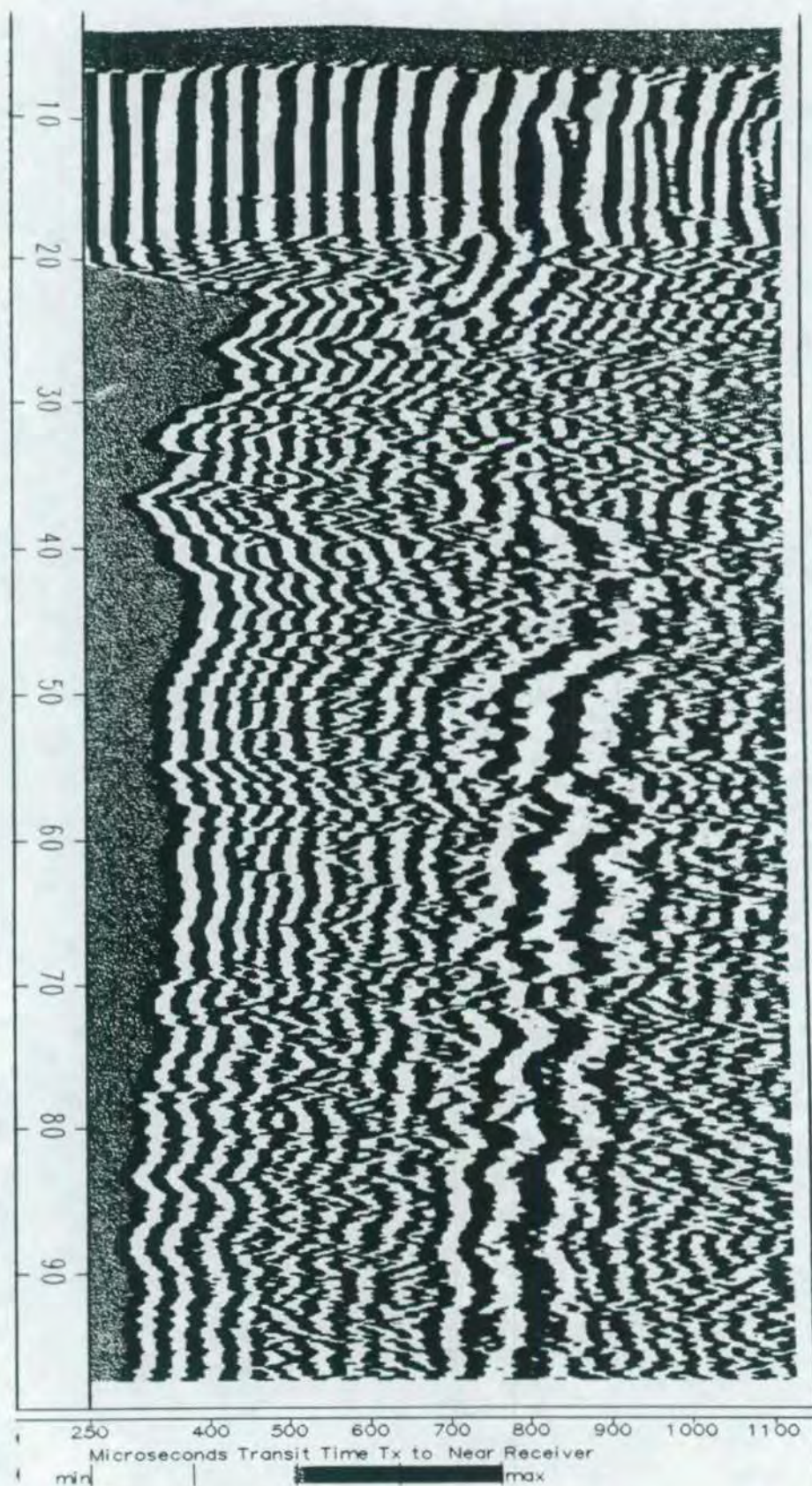


Figure 4.1. Example variable density log from borehole 0352.
Note tube wave propagation below 50-ft depth.

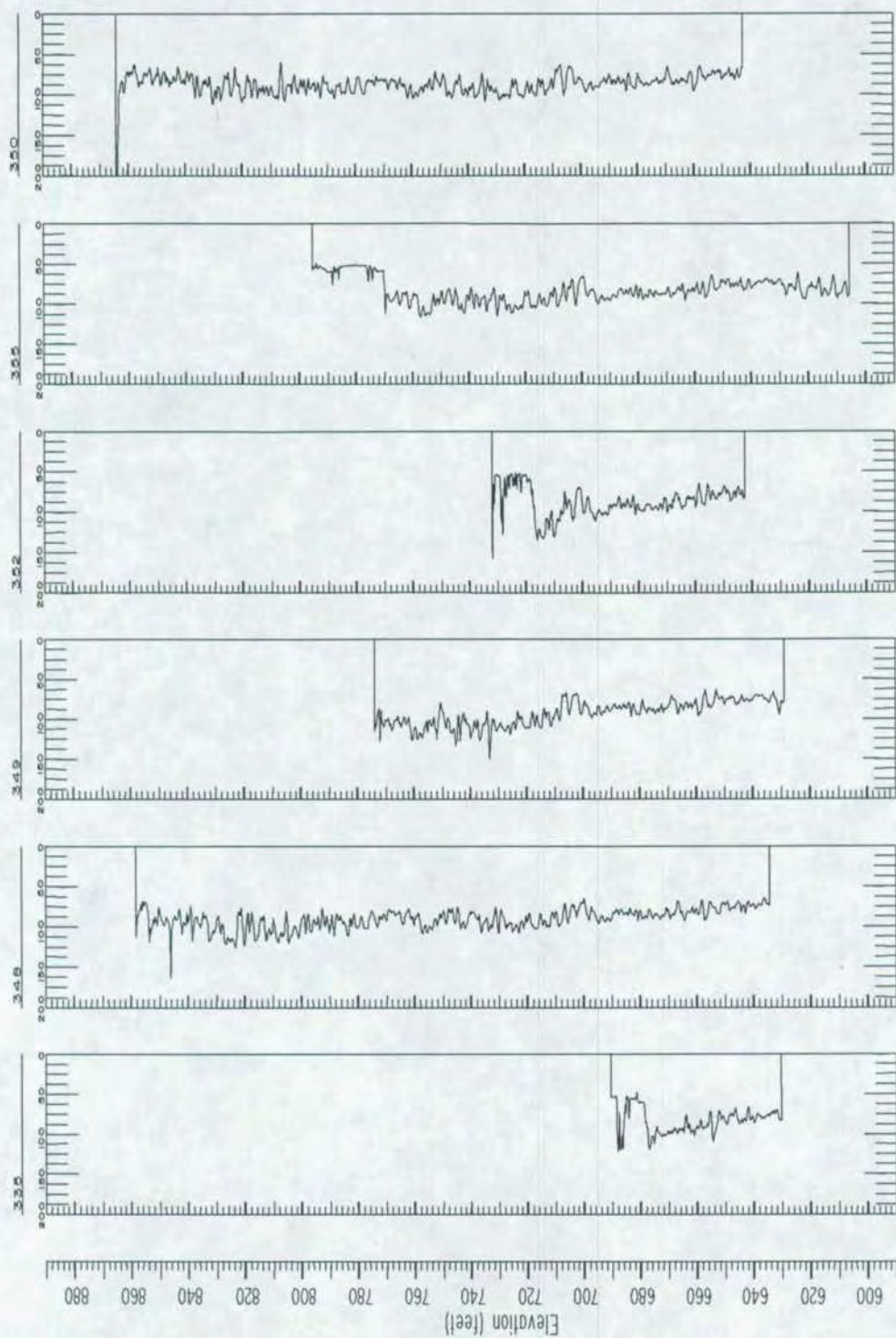


Figure 4.2. Correlation of acoustic wave transit times in boreholes (μsec/ft)

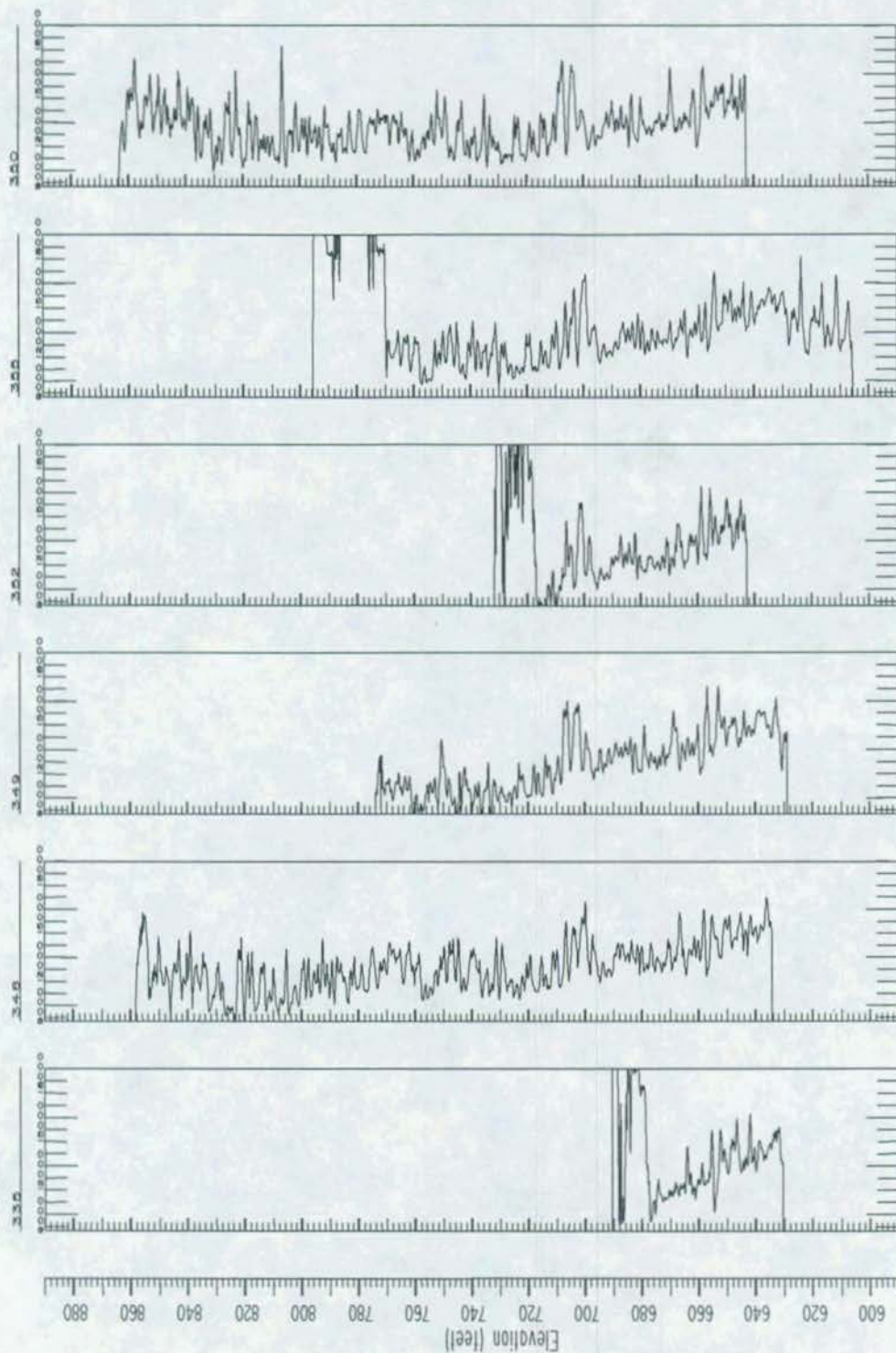


Figure 4.3. Correlation of acoustic wave velocity from boreholes (ft/sec).

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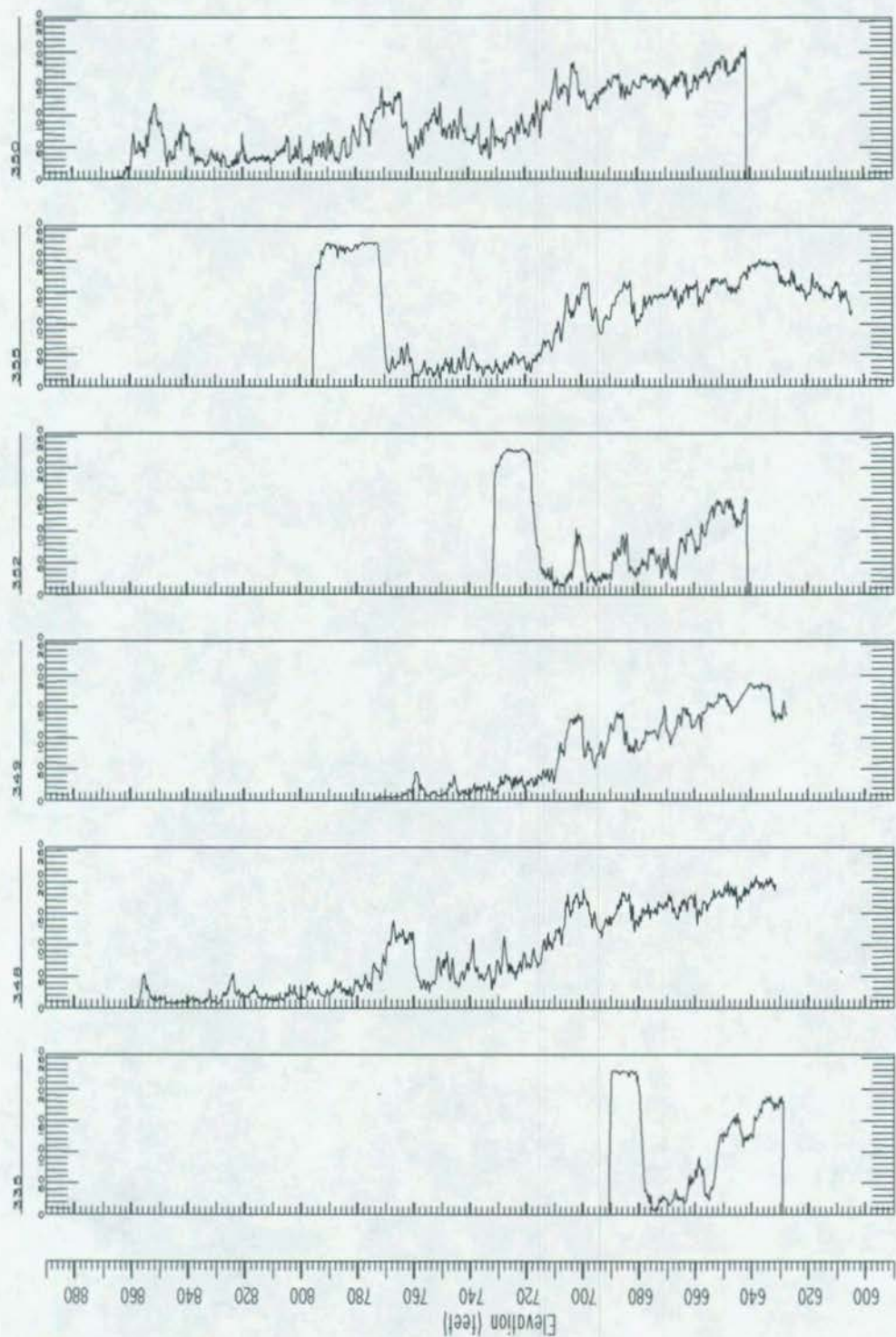


Figure 4.4. Correlation of tube wave amplitudes for boreholes (relative scale).

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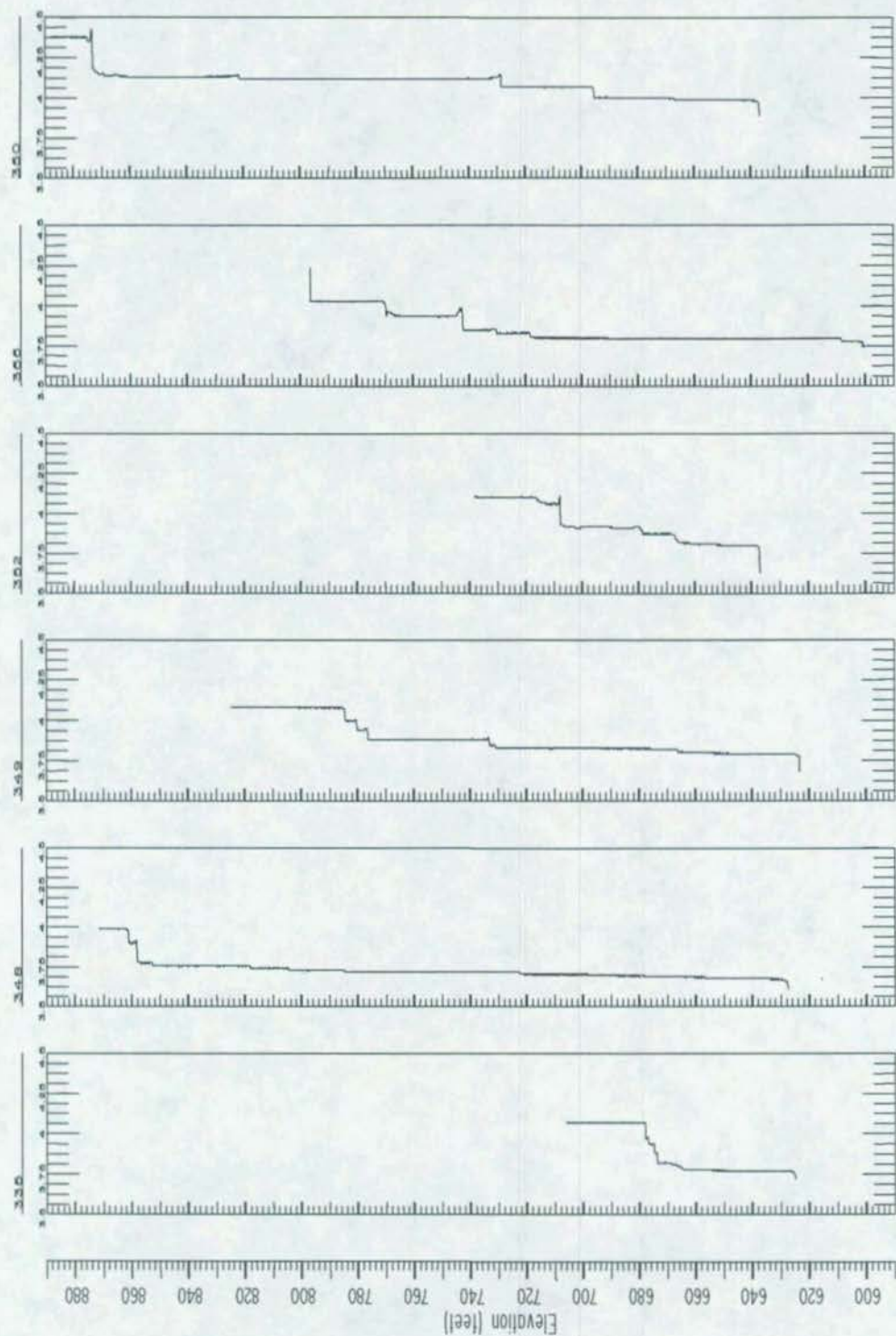


Figure 4.5. Correlation of caliper logs for boreholes (inches).

However, a trend was observed in all boreholes. Each borehole became narrower with depth because the rotating action of the drill steel is connected to the downhole core barrel. As the hole goes deeper and more drill steel is added, the length of drill steel whips about, slowly enlarging the borehole from top to bottom. Therefore, the boreholes become slightly tapered toward the bottom of the boring.

4.5. GUARD RESISTIVITY

The guard resistivity log is used as an indicator of lithology and is a focused-resistivity system designed to measure the resistivity of thin beds, providing high resolution and shallow formation penetration. The resolution is approximately 1 cm, so the instrument can detect beds of that order, but it only penetrates the formation about 1 cm. Focused-resistivity probes use guard electrodes above and below the current electrode to force the current to flow out into the rocks surrounding the well; hence, the name for this log is guard resistivity. Calibration and repeatability of the tool is monitored by periodic logging of the U.S. Bureau of Measurements calibration test holes at the Denver Federal Center. Shop and field calibrations can also be performed in a test well or pit where resistivity values are known (USGS 1988).

The guard resistivity logs for all six boreholes are presented in Figure 4.6.

Interpretation

The guard resistivity log is very useful for providing accurate resistivity values in thin and resistive rocks when conductivity of the borehole fluid is relatively high. The guard resistivity tool has the ability to resolve beds as thin as 1 to 2 inches thick, but the depth of investigation into the formation is as shallow (Rider 1986). Potable water was the only drilling fluid used (15.4 ohm/meters) and since it is not as conductive as bentonite-type drilling fluids, a large conductivity contrast was not expected to be observed in the boreholes.

The six guard logs indicate that high resistivity values are present in the upper 20 to 80 ft of the boreholes. In the upper portion of each borehole, the rock is very fractured and relatively fresh meteoric water is present within the fractures. The residence time of this water is typically short in duration and dissolution of minerals from the rock into the pore water has not occurred. Therefore, the pore water remains free of dissolved minerals and is relatively resistive.

Below the fractured portion of the bedrock, resistivity values are low and indicative of the connate water that resides in the pore space of low permeable shale rock. Resistivity values remain low until a change is observed in several of the boreholes between elevations 652 ft and 664 ft MSL. Between

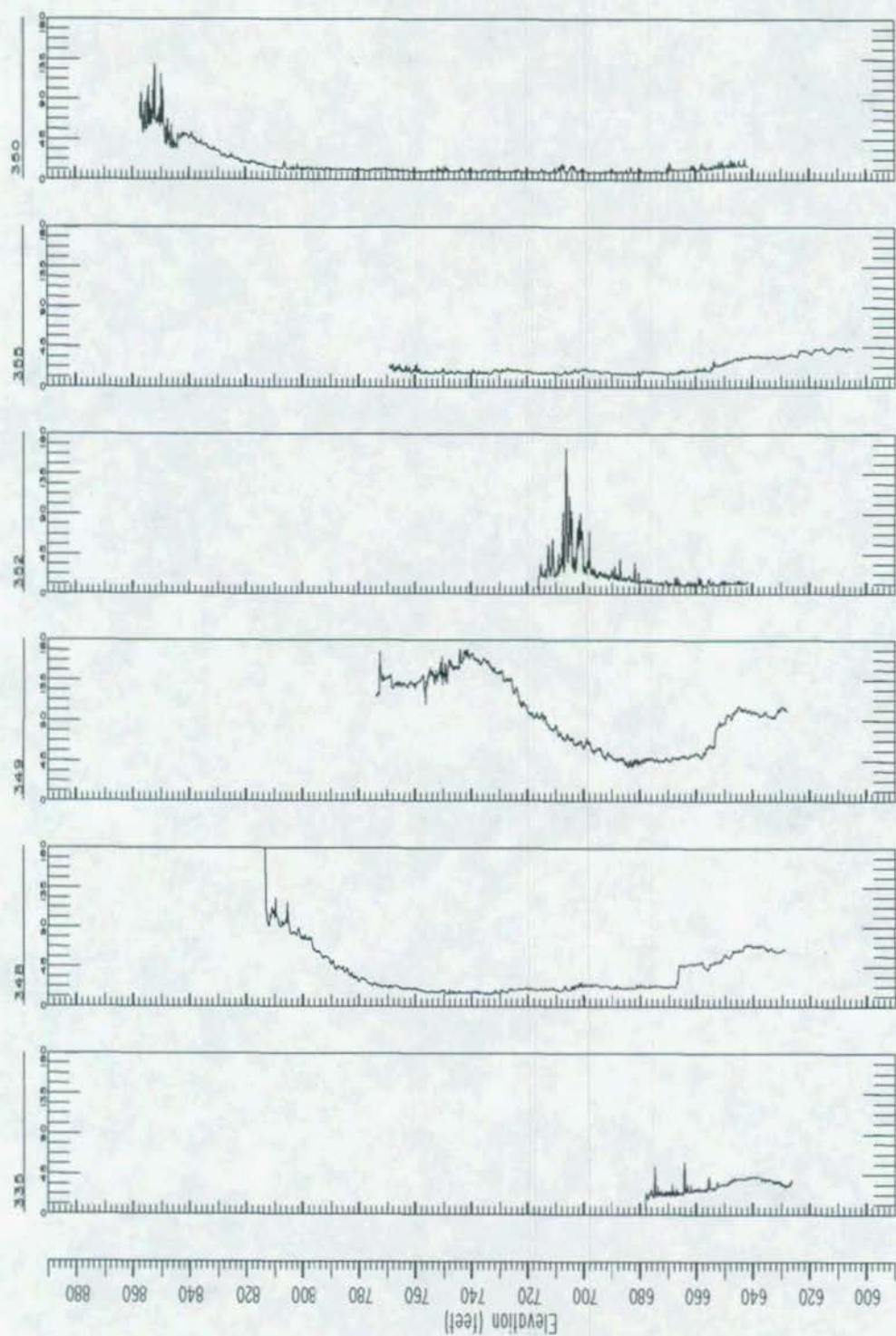


Figure 4.6. Correlation of guard resistivity logs in boreholes (ohm-meters).

these elevations, resistivities increase to the completion depths of the respective boreholes. This can be interpreted to indicate that formational water at depth is less conductive. Less conductive water would tend to indicate fresh water, thus suggesting that this zone of rocks may be more permeable and able to transmit more water than the overlying section of rock.

4.6. ELECTRO-MAGNETIC CONDUCTIVITY

The electro-magnetic (EM) conductivity logging device is an induction tool consisting of a transmitting coil oriented along the logging tool axis, and a receiving coil. This induction device records the conductivity (reciprocal of resistivity) of rocks by inducing a current to flow in the rocks. In general, the induction tool signals come from deeper in the formation than those of any other tool. The depth of penetration is approximately 10 to 15 ft. Induction logging provides measurements regardless of whether the well is filled with air or fresh water. The measurement of electrical conductivity usually is inverted to provide curves of both resistivity and electrical conductivity. Calibration is checked by suspending the probe in air, where the humidity is minimal, in order to obtain a zero electrical conductivity. A copper hoop is suspended around the probe while it is in the air to simulate known resistivity values (USGS 1988).

The EM conductivity logs for all six boreholes are presented in Figure 4.7.

Interpretation

Induction tool conductivity values come from deeper in the formation than with any other tool. This tends to smooth the conductivity values measured. The conductivity values measured in the six boreholes show that low conductive fluids are present in the upper reaches of the boreholes, in depths from 6 to 48 ft. Below these depths, the conductivity is relatively high and stable and appears related to a thick shale unit with thin discontinuous limestone layers throughout. The stable conductivity values are interpreted to indicate the conductive nature of the pore water contained within the shale unit. This pore water is interpreted to contain much of the original salts deposited with the marine sediments and is, therefore, more conductive. In the zones of low conductivity, the salts have largely been removed by the movement of meteoric water.

Two zones of low EM conductivity are apparent at depth in the boreholes. At approximate elevation 700 ft MSL, conductivity values sharply decrease over a short interval of about 10 ft in thickness and then increase again. This corresponds to a change in lithology from predominantly shale to a limestone with interbedded shale. Below this elevation, conductivities increase and decrease again sharply at approximately 650 ft MSL. The lower zone also corresponds to a change in lithology from dominantly

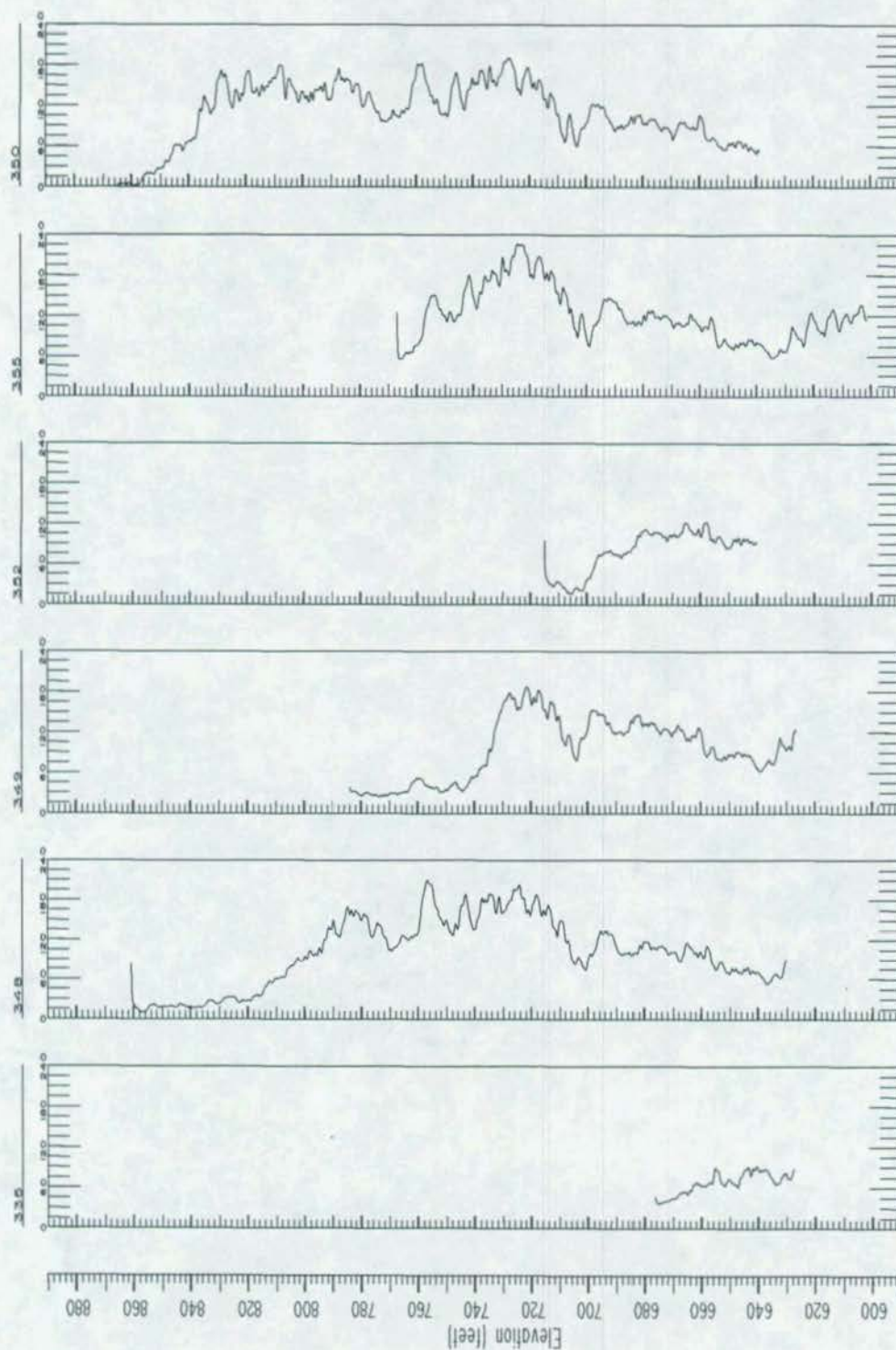


Figure 4.7. Correlation of EM conductivity logs in boreholes ($\mu\text{s}/\text{m}$)

shales to limestone and shales. Both of these low conductivity zones are interpreted to indicate the presence of relatively more permeable rocks that may conduct groundwater of relatively low conductivity.

4.7. NEUTRON

The neutron log provides a continuous record of a formation reaction to fast neutron bombardment. Rock formations absorb neutrons and attenuate fast neutrons rapidly when they contain abundant hydrogen nuclei, which in the geological context are supplied by water. The log is, therefore, principally a measure of a formation water content, be it bound water, water of crystallization, or free pore-water. Quantitatively, the neutron log is used to measure porosity. Qualitatively, it can be used to identify gross lithology and, when combined with the density log on compatible scales, is one of the best subsurface lithology indicators available.

High energy neutrons are generated by a 1 curie americium:beryllium radioactive source housed in the probe and interact with the media which surrounds the probe, including the borehole fluid and formation. The significant aspects of that interaction are the loss of energy due to collisions with hydrogen atoms and the subsequent capture of the neutrons by various nuclei (including hydrogen). The detector in the neutron tool is spaced 14 inches from the source and counts only the low energy (thermal) neutrons which have not been captured. Repeatability and stability of the neutron tool is routinely checked by measuring the neutron count rate in a barrel of water. No quantitative calibration is performed since the neutron log is a qualitative, relative measurement.

Within a certain (unspecified) range, the thermal neutron count rate is inversely proportional to the population of hydrogen atoms surrounding the tool. Therefore, for a constant borehole size, the neutron count rate can be related to total water content. The inverse counts versus water content relationship can be explained in terms of the degree of neutron capture that occurs. For example, lower water content captures fewer low energy neutrons and results in a higher neutron count rate at the detector. Total water content in a saturated formation is controlled by the clay content because clay minerals contain a significant volume of bound water. In view of the inverse relationship described above this means that lower neutron count rates are associated with higher clay content (Rider 1986).

The neutron logs for all six boreholes are presented in Figure 4.8. The neutron logging technique is effective in cased and uncased air- or fluid-filled boreholes. Therefore, the five boreholes that were logged using the neutron logging tool show results through the upper cased portions as well as the open hole. The neutron log was conducted twice in borehole 0348, once when the water table was at ambient conditions and once when the borehole was stemmed with water. No neutron log was run in borehole 0335 because of concerns of losing the tool in the offsite borehole.

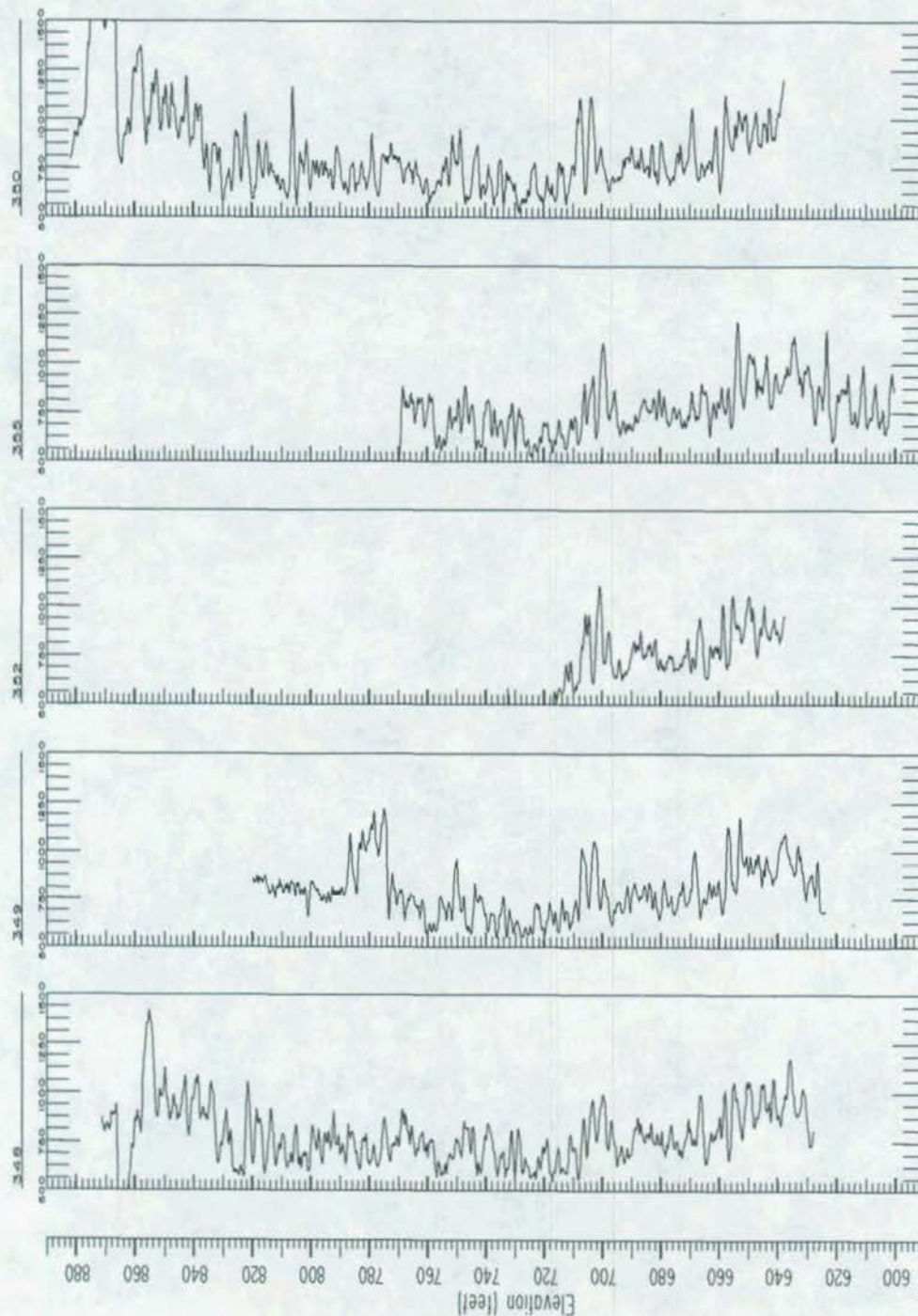


Figure 4.8. Correlation of neutron logs in boreholes (counts/sec).

Interpretation

Neutron logs indirectly measure the concentration of hydrogen ions in the vicinity of the borehole. It is interpreted that low neutron counts per second (CPS) indicates high neutron porosity and that the hydrogen ion concentration is high. Low neutron counts are interpreted to indicate higher clay (shale) content. Since the neutron log is sensitive to all hydrogen nuclei, it is sensitive to both free and bound water. The former is formation water, the latter occurs in clays either within the molecule or absorbed between clay mineral layers. The lower neutron count in the upper part of borehole 0348 when the borehole was full of water (neutron2 Figure 4.8) shows the attenuation effects of the stemming.

Neutron CPS were generally higher in the upper 10 to 50 ft of boreholes. This may be the effect of: 1) unsaturated conditions; 2) indicative of the upper fractured portion of the boreholes having lost pore water to the effects of weathering processes; and 3) an irregular borehole diameter as extraneous effects on the neutron logs may be caused by changes in hole diameter (Keys, et al. 1983). Below these depths, low neutron CPS are indicative of the shale that is present down to approximate elevation of 700 ft. Major deflections around the 700 ft elevation indicate the presence of limestone beds. Moderate neutron CPS between 655 and 690 are related to a shale unit with limestone interbeds.

4.8. COMPENSATED DENSITY

The density log is a continuous record of a formation bulk density and is the overall density of a rock including solid matrix and the fluid enclosed in the pores. Geologically, bulk density is a function of the density of the minerals forming a rock (i.e., matrix) and the volume of free fluids which it encloses (i.e., porosity). Quantitatively, the density log is used to calculate porosity and qualitatively, it is a useful lithology indicator (Rider 1986).

The principle behind density logging is the detection of Compton-scattered gamma rays that originate from a small radioactive source (100 millicurie of cesium-137) housed in the probe. The intensity of the radiation reflected back to the detectors is primarily a function of the bulk density of the media in which the gamma rays are introduced and scattered. Compensation is necessary to correct for the condition where the tool is not perfectly flush with the borehole wall (because the borehole is not perfectly smooth). When calibrated correctly, compensated measurements made with this tool can be accurate to within 1 percent of the true bulk density. The density compensation algorithm corrects the long-spaced detector measurement for near-borehole effects that are measured by the short-spaced detector. The density tool is calibrated by measuring the reflected gamma radiation from materials of

known densities. This is done routinely during shop calibrations using lucite and aluminum blocks and periodically checking those calibrations in the U.S. Bureau of Mines calibration test holes at the Denver Federal Center, Colorado.

The compensated density logs for all six boreholes are presented in Figure 4.9. No compensated density log was run in borehole 0335 because of concerns of losing a radioactive source tool down the borehole.

Interpretation

The density tool measures the average density of a relatively small volume of the borehole. It is, therefore, interpreted that, as presented on the density logs, bulk density increases to the right and that porosity increases to the left. Density measurements recorded from the five boreholes varied over a small range of values between 2.45 to 2.80 g/cc. Generally, density values increased with depth in each borehole. With a referenced value for the matrix density of limestone being 2.70 g/cc, the recorded density values suggest that bedrock becomes more lime-rich with depth.

4.9. NATURAL GAMMA

The gamma ray log is a record of natural radioactivity from a formation. The radioactivity emanates from naturally-occurring uranium, thorium and potassium. The geological significance of radioactivity lies in the distribution of these three elements. Most rocks are radioactive to some degree, igneous and metamorphic rocks more so than sediments. However, among the sediments, shales have by far the strongest radiation. The gamma ray log is principally used to quantitatively calculate shale volume. Qualitatively, it can be used to correlate, to suggest facies, and to identify lithology, principally the relative amounts of shale. Gamma ray logging provides measurements regardless of whether the borehole is open or cased or is filled with air or fresh water (Rider 1986).

The natural gamma log provides a CPS measurement that is proportional to the natural radioactivity of the formation. Actual counts depend upon the detector size and efficiency, but are often normalized in American Petroleum Institute (API) units. For the detector response of the gamma probe used, 1 CPS is approximately equal to 1 API unit. The depth of investigation for the gamma log is typically about 1 ft. The gamma logging tool measures gamma radiation with scintillation sodium-iodide detectors. The gamma-emitting radioisotopes that naturally occur in geologic materials are potassium-40 and nuclides in the uranium-238 and thorium-232 decay series. Potassium-40 occurs with all potassium minerals, including potassium feldspars. Uranium-238 is typically associated with dark shales and uranium mineralization. Thorium-232 is typically associated with biotite, sphene,

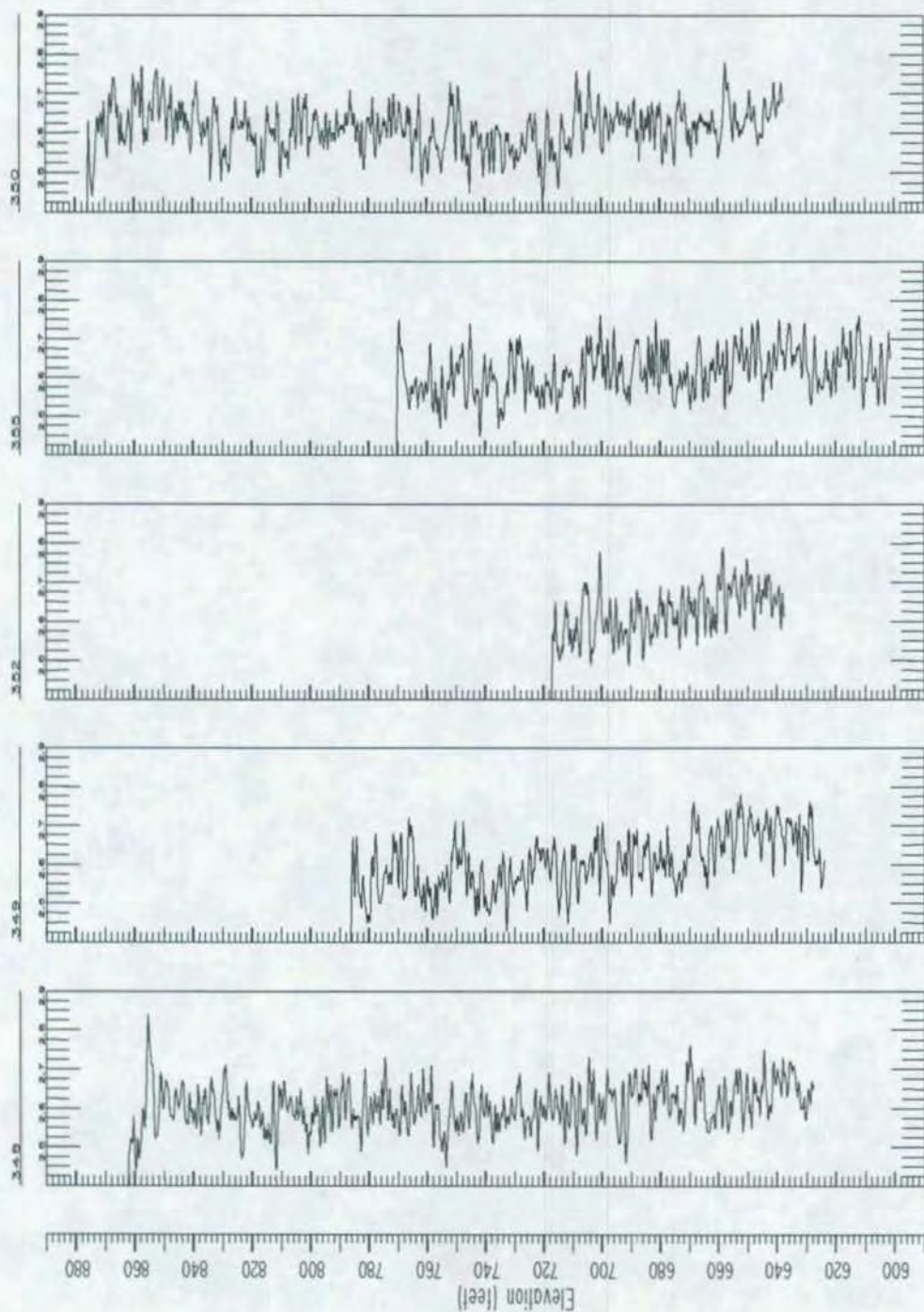


Figure 4.9. Correlation of compensated density logs in boreholes (g/cc).

zircon, and other heavy minerals. Calibration of the gamma logging tool is usually performed in cement blocks with known radioactivity. In hydrogeology, the gamma measurement is usually a relative log and quantitative calibrations are not routinely performed. However, the stability and repeatability of the natural gamma measurement are routinely checked with a sleeve of known radioactivity.

The natural gamma logs for all six boreholes are presented in Figure 4.10.

Interpretation

Like the neutron logging technique, the natural gamma log can also be employed in cased or uncased air- or fluid-filled boreholes. Therefore, the six boreholes that were logged with the natural gamma tool show a longer logging record compared to other logging tools since this method is effective in cased and uncased boreholes. The effects of logging through steel and PVC casing can be observed on the upper portions of the natural gamma ray logs. Logging through casing has a dampening effect on the recorded natural gamma ray values which is evident when the logging tool is removed from the casing and values are recorded.

The CPS are interpreted to indicate a higher clay (shale) content. The natural gamma logs run at Mound indicate a highly variable sequence of shales with thin beds of limestones. The logs show that, regardless of lithology, a high proportion of silt is present in all rocks. Grainstones exhibit the least amount of gamma radiation. Overall, Figure 4.10 depicts a broad increase of natural gamma radiation from the ground surfaces down to elevations about 700 ft MSL. This broad zone is correlative with the shale-rich Waynesville Formation (Plate 1). Below this elevation, the CPS is lower and more indicative of less clay-rich lithologies that are correlative with the Oregonia and Mount Auburn Formations (Plate 1).

4.10. FLUID RESISTIVITY AND TEMPERATURE

The thermal gradient and fluid resistivity profile of the borehole fluid is obtained with these measurements. A thermistor measures the fluid temperature in the borehole in degrees Celsius; fluid resistivity is measured with a closely-spaced Wenner electrical array. Both instruments are attached to the same probe. Shop calibration of these measurements is accomplished by immersing the probe in two water baths of known temperature and resistivity.

Plots of the fluid resistivity log and fluid temperature log are compared with one another for all six boreholes and are presented in Figures 4.11 and 4.12, respectively.

J:\dgn\moundb\m997.dgn 121393

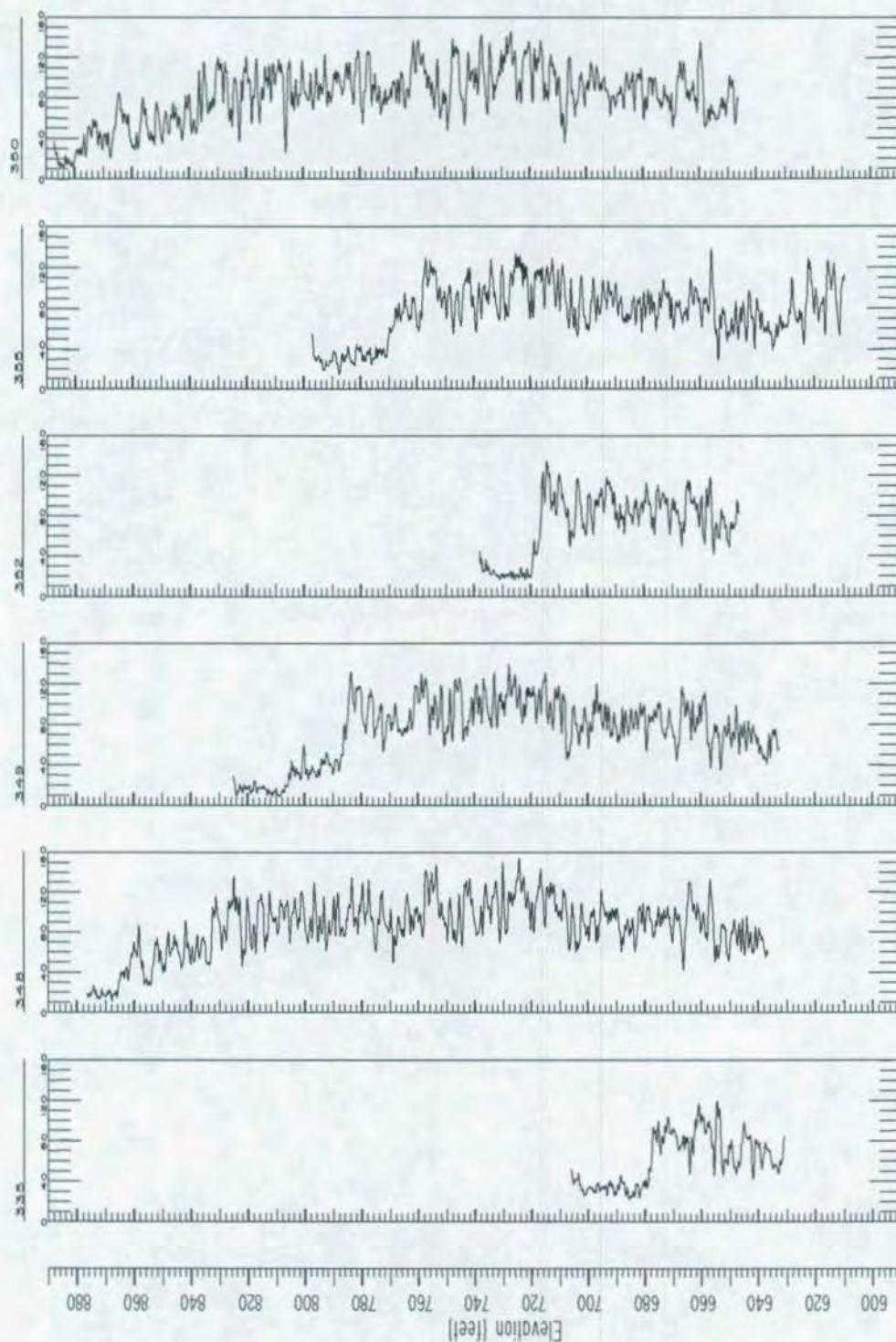


Figure 4.10. Correlation of natural gamma logs in boreholes (counts/sec).

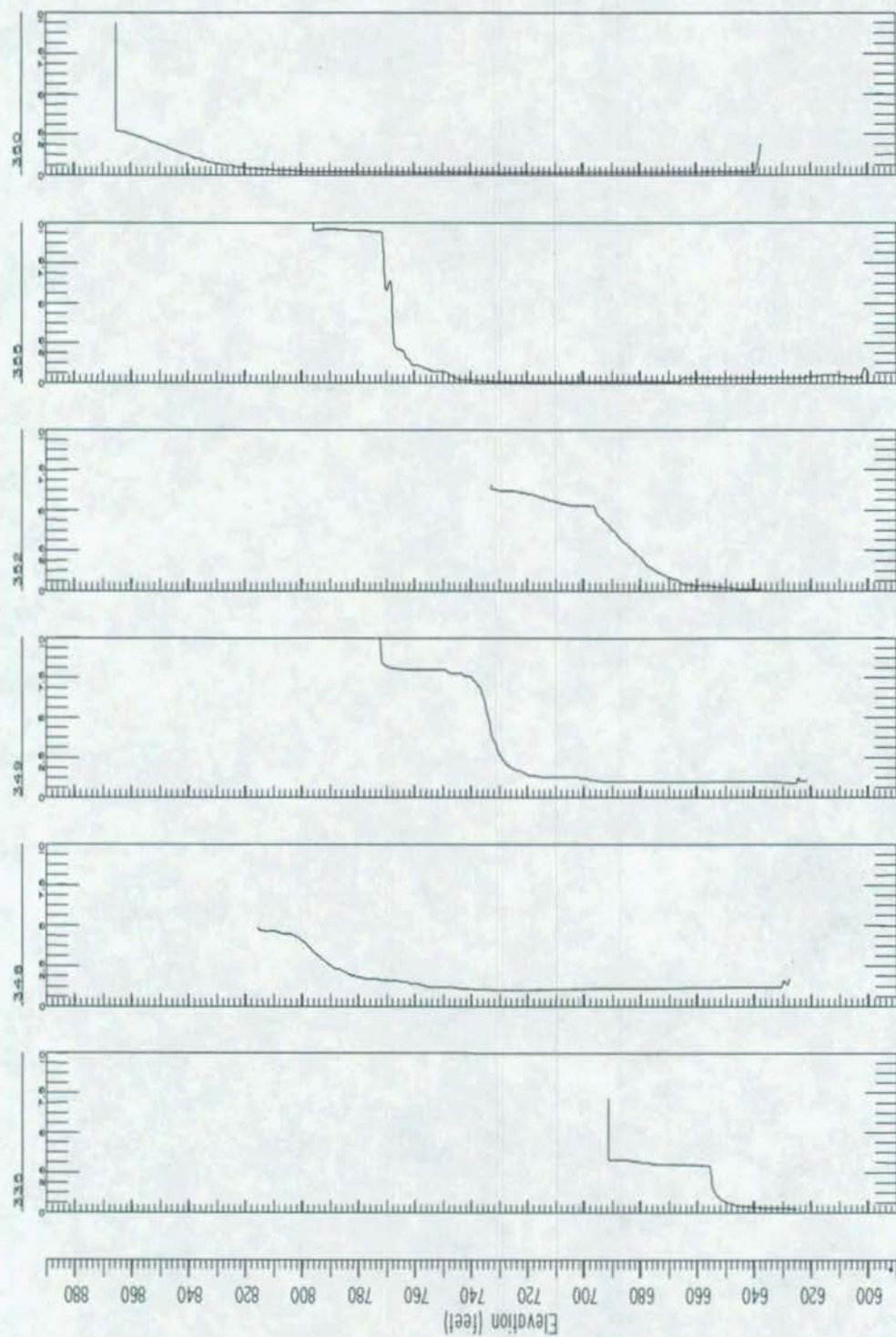


Figure 4.11. Correlation of fluid resistivity logs in boreholes (ohm-meters).

J:\dgn\moundb\m8989.dgn 12/1993

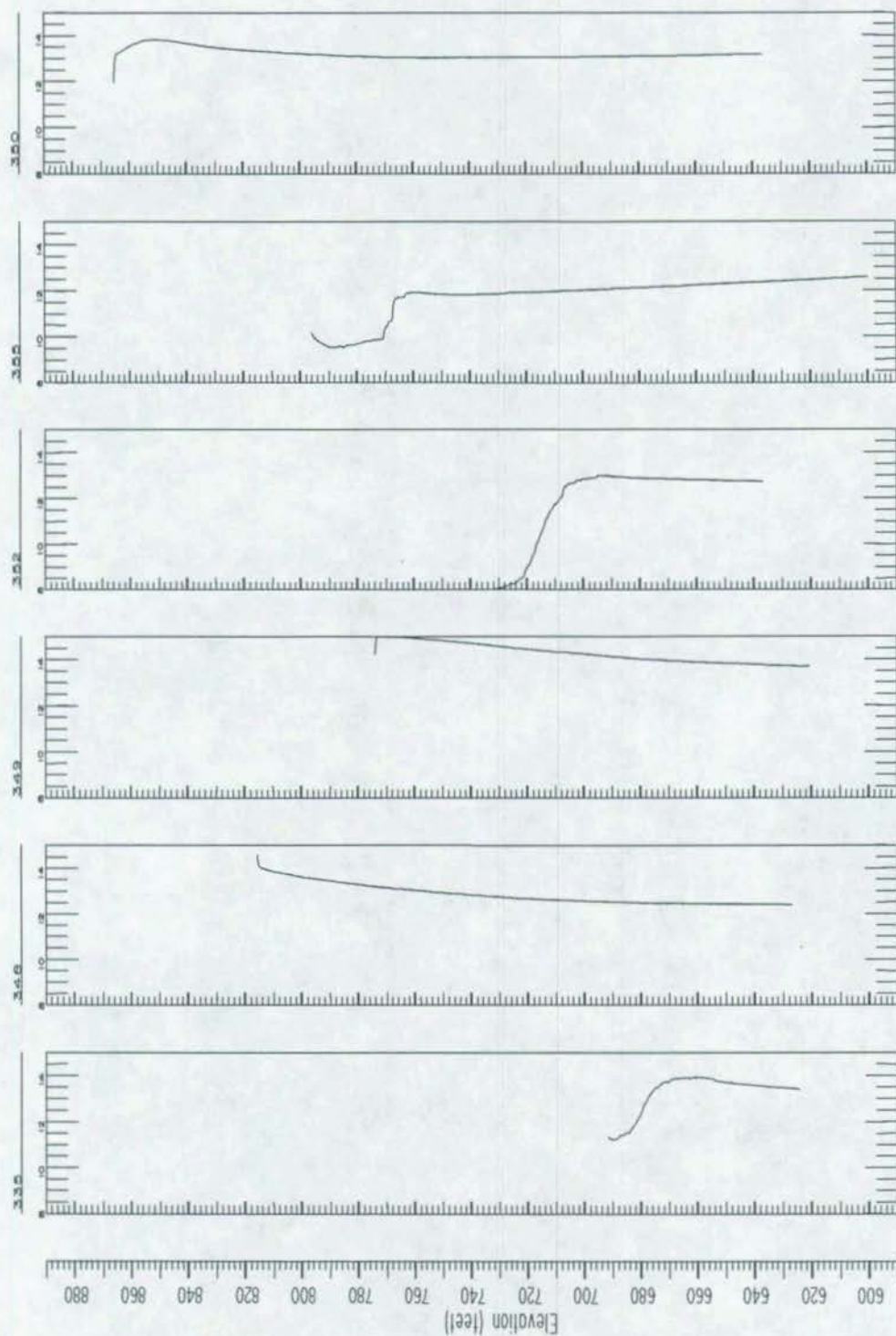


Figure 4.12. Correlation of fluid temperature logs in boreholes (degrees Celsius).

Interpretation

The fluid resistivity in the borehole is controlled primarily by its salinity. Therefore, salinity stratification or the introduction of a fluid of different water quality into the borehole can be observed by changes in the fluid resistivity log. The exchange of fluid between the formation and the borehole often influences both the temperature and the fluid resistivity such that the response is evident in both logs.

Geothermal gradients in the near surface earth are usually dominated by conduction and are generally linear due to the relative constancy of the thermal conductivity of earth materials. Therefore, deviations from the linear thermal gradient can be attributed to convective heat flow. More commonly, convective heat flow is within the borehole fluid and is caused by formation fluid entering or leaving the borehole at some permeable interval. Abrupt changes in the temperature log are strong evidence of fluid flow between the formation and the borehole; subtle changes in the gradient can also be attributed to fluid flow. Figure 4.11 shows that fluid temperatures within the boreholes are relatively stable below a shallow depth in which mild variations occur. Temperature logs run in the upper portions of the six boreholes ranged from 8 to 15 degrees Centigrade, while those at depth were a near constant 13 degrees.

The fluid resistivity is the record of the capacity of the borehole fluid to conduct electrical current. Fluid resistivity curves for the six boreholes show a similar trend. Fluid resistivities are relatively low through much of the length of the boreholes and increases in the upper 46 to 76 ft of the boreholes. This is interpreted to be due to the mixing of shallow meteoric water entering the boreholes through fractures and mixing with water standing in the borehole. The water standing in the borehole is interpreted to have lower resistivities as it has come to equilibrium with formational pore waters with relatively high salt contents. Below the mixing zones, the resistivity of the borehole fluids is relatively constant.

4.11. HEAT PULSE FLOWMETER

The most direct method for determining permeability profiles in open boreholes is to employ the use of flowmeter methods. Flowmeters are downhole instruments that measure the vertical velocity profile of fluid flow in a borehole, either under natural conditions or during withdrawal or injection. Hess (1986) described HPF that can resolve fluid velocities as low as 0.03 m/min (0.1 ft/min) and can, therefore, be applied to the measurement of natural flow or very low induced flow in a borehole.

The heat pulse flowmeter used in this study is based on an USGS design that Mount Sorpis incorporated into the HFP-4293. This design incorporates the use of a diverter, providing accurate

flow velocity and direction information. Detection limits range from 1200 mL/minute at the ceiling down to 7 mL/min. This extreme sensitivity in the low flow range is not possible with conventional spinner or impeller tools. The ultra low flow measurement capability makes the HFP ideal for evaluating extremely small flows within fractured rock systems and for evaluating small inflows or crossflows to verify zone isolation.

Data recorded by the HFP in the six bedrock boreholes are summarized in Tables 4.5 through 4.10. Flow rates were measured in the boreholes at selected intervals. The intervals were selected on the basis of the fluid resistivity and borehole video information. Three measurements were taken at each interval. In boreholes 0348 and 0349, flow rates were measured under ambient and stressed conditions. In both boreholes, the water levels under ambient conditions were deep enough (about 50 ft) that stemming the borehole with water provided a significantly increased hydraulic head. For the latter, a tank of potable water was adjusted to maintain a constant head. In this report, this condition is referred to as stressed conditions. No actual meter was used to measure the supply of water to the borehole. The shallow water levels in the other boreholes precluded measurements under stressed conditions.

Interpretation

The flow direction downward is reported from all measurements taken by the HPF meter in the six boreholes. Flow rates ranged from 0 to greater than 1,200 ml/min (0.3 gal/min). Measured flows decreased with depth in all six boreholes. The depths in each borehole where no flow measurements were encountered under both ambient, non-stress conditions and stressed conditions, is summarized in Table IV.11. Under stressed conditions, increased flow rates over ambient conditions are evident. Both the absolute rates and the depths at which flow is observed to occur increase under stress conditions (Tables IV.6 and IV.7).

4.12. DISCUSSION OF PHYSICAL CHARACTERISTICS OF THE MAIN HILL (BOREHOLES 0348 AND 0349)

The physical characteristics of the Main Hill are exhibited in boreholes 0348 and 0349. Borehole 0348 is on the top of the Main Hill and was started in the Liberty Formation at an elevation of 876 ft MSL. Borehole 0349 is on the south flank of the Main Hill in the Waynesville Formation; the Liberty Formation has eroded away. The cores from these locations indicate that fracturing is relatively frequent at the surface and decreases in frequency and degree with depth. The Waynesville Formation in borehole 0349 appears almost as intensely fractured as the Liberty Formation in borehole 0348. The borehole lithologies correlate well between the core descriptions and neutron and natural gamma

Table IV.5. Flowmeter Data for Well 0335

Test #	Depth (Ft)	Flow Rate (ml/min)	Flow Direction	Comments
1	34	60	down	
2	34	63	down	
3	34	63	down	avg 62 down
4	38	63	down	
5	38	61	down	
6	38	59	down	avg 61 down
7	49	52	down	not used
8	49	50	down	not used
9	49	94	down	
10	49	88	down	
11	49	88	down	
12	49	82	down	avg 88 down
13	53	0	--	no test (5min)
14	53	0	--	no test (5min)
15	53	0	--	no test (5min) avg 0 flow
16	31	85	down	
17	31	81	down	
18	31	72	down	avg 79 down
19	25	0	--	no test (5min)
20	25	12	down	
21	25	0	--	no test (5min) avg 0 flow
22	34	77 earlier tests	down	confirmed

Table IV.6. Flowmeter Data for Well 0348

Test #	Depth (ft)	Flow Rate (ml/min)	Flow Direction (ml/min)	Comments
1	69	0	--	no test (5min)
2	69	0	--	no test (5min) avg 0 flow
3	76	0	--	no test (5min)
4	76	0	--	no test (5min) avg 0 flow
5	90	0	--	no test (5min)
6	90	0	--	no test (5min) avg 0 flow
7	62	22	down	
8	62	22	down	
9	62	23	down	avg 22.3 down
10	53	22	down	
11	53	23	down	
12	53	22	down	avg 22.3 down
13	46	23	down	
14	46	22	down	
15	46	21	down	avg 22 down
STRESSED FLOWMETER TESTS (BOREHOLE FILLED WITH WATER)				
16	46	73	down	not used
17	46	197	down	
18	46	156	down	
19	46	210	down	
20	46	238	down	avg 200 down
21	69	20	down	
22	69	20	down	
23	69	19	down	avg 19.7 down
24	90	11	down	not used
25	90	0	--	no test (5min)
26	90	0	--	no test (5min) avg 0 flow
27	76	15	down	
28	76	14	down	
29	76	11	down	avg 13 down

Table IV.6. (page 2 of 2)

Test #	Depth (ft)	Flow Rate (ml/min)	Flow Direction (ml/min)	Comments
30	62	80	down	
31	62	77	down	
32	62	70	down	avg 75.7 down
33	54	74	down	
34	50	77	down	
35	46	173	down	confirmed flow
36	35	164	down	not used
37	35	218	down	
38	35	206	down	
39	35	219	down	avg 214 down
40	28	> 1200	down	
41	28	> 1200	down	avg > 1200 down
42	28	0	--	packer deflated
43	10	> 1200	down	
44	10	> 1200	down	avg > 1200

Table IV.7. Flowmeter Data for Well 0349

Test #	Depth (ft)	Flow Rate (ml/min)	Flow Direction	Comments
1	100	0	--	no test (10min)
2	100	0	--	no test (5min) avg 0 flow
3	133	0	--	no test (9min)
4	133	0	--	no test (5min) avg 0 flow
5	122	0	--	no test (5min)
6	122	0	--	no test (5min) avg 0 flow
7	82	0	--	no test (10min)
8	82	0	--	no test (6min) avg 0 flow
9	88	0	--	no test (5min) avg 0 flow
10	55	14	down	
11	55	15	down	
12	55	14	down	avg 14.3 down
13	68	12	down	
14	68	13	down	
15	68	13	down	avg 12.7 down
16	77	8	down	
17	77	8	down	avg 8 down
STRESSED FLOWMETER TESTS (BOREHOLE FILLED WITH WATER)				
18	77	10	down	not used
19	77	20	down	
20	77	20	down	
21	77	19	down	avg 19.7 down
22	55	38	down	
23	55	39	down	
24	55	37	down	avg 38 down
25	82	16	down	
26	82	15	down	avg 15.5 down
27	100	0	--	no test (10min)
28	36	171	down	
29	36	182	down	

Table IV.7. (page 2 of 2)

Test #	Depth (ft)	Flow Rate (ml/min)	Flow Direction	Comments
30	36	186	down	avg 179.7 down
31	45	109	down	
32	45	112	down	
33	45	113	down	avg 111.3 down

Table IV.8. Flowmeter Data for Well 0350

Test #	Depth (ft)	Flow Rate (ml/min)	Flow Direction	Comments
March 31 1993				
1	26	0	--	
2	26	0	--	avg 0 flow
3	38	0	--	
4	38	0	--	no test (10min) avg 0 flow
5	56	0	--	no test (10min)
6	56	0	--	no test (5min) avg 0 flow
7	80	0	--	
8	80	38	down	not used
9	80	0	--	no test (5min) avg 0 flow
10	92	0	--	
11	92	0	--	no test (5min) avg 0 flow
12	16	0	--	not used
13	16	20	down	
14	16	12	down	
15	16	10	down	avg 14 down

Table IV.9. Flowmeter Data for Well 0352

Test #	Depth (ft)	Flow Rate (ml/min)	Flow Direction	Comments
1	28	20	down	
2	28	18	down	
3	28	17	down	avg 18 down
4	34	0	--	no test (5min)
5	34	0	--	
6	34	0	--	avg 0 flow
7	40	0	--	no test (5min)
8	40	0	--	no test (5min) avg 0 flow
9	45	0	--	no test (10min)
10	45	0	--	no test (5min) avg 0 flow
11	62	0	--	no test (10min)
12	62	0	--	no test (5min) avg 0 flow
13	74	0	--	no test (5min)
14	74	0	--	no test (6min) avg 0 flow
15	28	20	down	confirmed earlier tests

Table IV.10. Flowmeter Data for Well 0355

Test #	Depth (ft)	Flow Rate (ml/min)	Flow Direction	Comments
1	31	0	--	no test (10min)
2	31	0	--	no test (5min) avg 0 flow
3	37	0	--	no test (10min)
4	37	0	--	no test (5min) avg 0 flow
5	44	0	--	no test (10min)
6	44	0	--	no test (5min) avg 0 flow
7	54	0	--	no test (10min)
8	54	0	--	no test (5min) avg 0 flow
9	126	0	--	
10	126	0	--	avg 0 flow
11	134	0	--	no test (10min)
12	134	0	--	no test (5min) avg 0 flow

Table IV.11. Depth at Which No Groundwater Flow Was Measured in Open Boreholes Across the Mound Plant

Borehole	Depth (ft. bls)	Range of Flow Rates (ml/min)
0335	53	0-94
0348	90 69	0->1200 ^a 0-23 ^b
0349	100 82	0-186 ^a 0-15 ^b
0350	26	0-38
0352	34	0-20
0355	31	0

^aHigh flow rates where achieved under stressed conditions of having water introduced into the hole prior to taking HPF meter readings.

^bMeasured under ambient borehole conditions.

logs. Lithologic bedding is horizontal and undeformed except for fractures. The caliper logs indicate the boreholes are straight and not affected by breakouts or local irregularities that would indicate instability of the rocks. The various geophysical measurements indicate a consistent pattern of shallow fracture, alteration, and weathering of the bedrock.

Physical fracturing of the rocks in the shallow portions of the boreholes is indicated not only by direct visual observation of fractures, but also by indirect geophysical means. The pattern of the full waveform sonic logs indicate that tube waves have low amplitudes in the upper 100 ft of both boreholes. Tube wave energy is attenuated by fluid interaction between the borehole and adjacent formation as the wave travels between transmitter and receivers. Because permeable fractures or porous media provide a path for this interaction, these conditions reduce the energy of the transmitted wave, resulting in lower tube wave amplitude with more permeable rock. Figure 4.13 displays the relationship between tube wave amplitude and fracture frequency in borehole 0348. These data indicate that the upper zones of very weakly fractured rocks strongly correlate with the zones of attenuated tube wave propagation. Plate 3 depicts the geometry of the fracture carapace on the Main Hill based on these data.

The flowmeter measurements, fluid resistivity, and fluid temperature in both boreholes indicate that groundwater flow is restricted to the upper 100 ft below ground surface. Flow measurements of groundwater in borehole 0348 indicate that at very shallow depths (less than 40 ft) flows are greater than the instrument can measure (greater than 1200 mL/min), decrease to 200 mL/min at depths of 40 to 60 ft, then decrease to zero by 90 ft depth (Figure 4.14). A sharp decrease in the fluid resistivity measurements occur at depths of 70 to 100 ft correlates with the deepest extent of water flow. Similar relationships are observed in borehole 0349 (Figure 4.15). These data are interpreted to indicate inflow of groundwater to the borehole and mixing with water standing in the borehole. Fluid resistivity is stable below those depths, indicating that pore water in the formation is relatively rich in salts that yield lower resistivities, indicative of formation waters. These data indicate that flow rates decrease with depth and drop to zero near the base of the fracture carapace (Plate 3). The lower part of the fracture is interpreted to be the zone where frequency of fractures and interconnection of fractures is reduced to the point to the point of no-flow.

The guard resistivity and EM conductivity logs in boreholes 0348 and 0349 (Appendix C) also indicate the upper 60 to 80 ft of rock contains relatively fresh, meteoric water that is less conductive and more resistive than the water contained in the rocks below these depths (Plate 4). The differences cannot be attributed solely to lithology since the less conductive zone occurs in the shale with minor limestone facies in the upper part of the Waynesville Formation in borehole 0349, whereas the Waynesville Formation is unaffected in borehole 0348. The less conductive and more resistive nature of the rocks

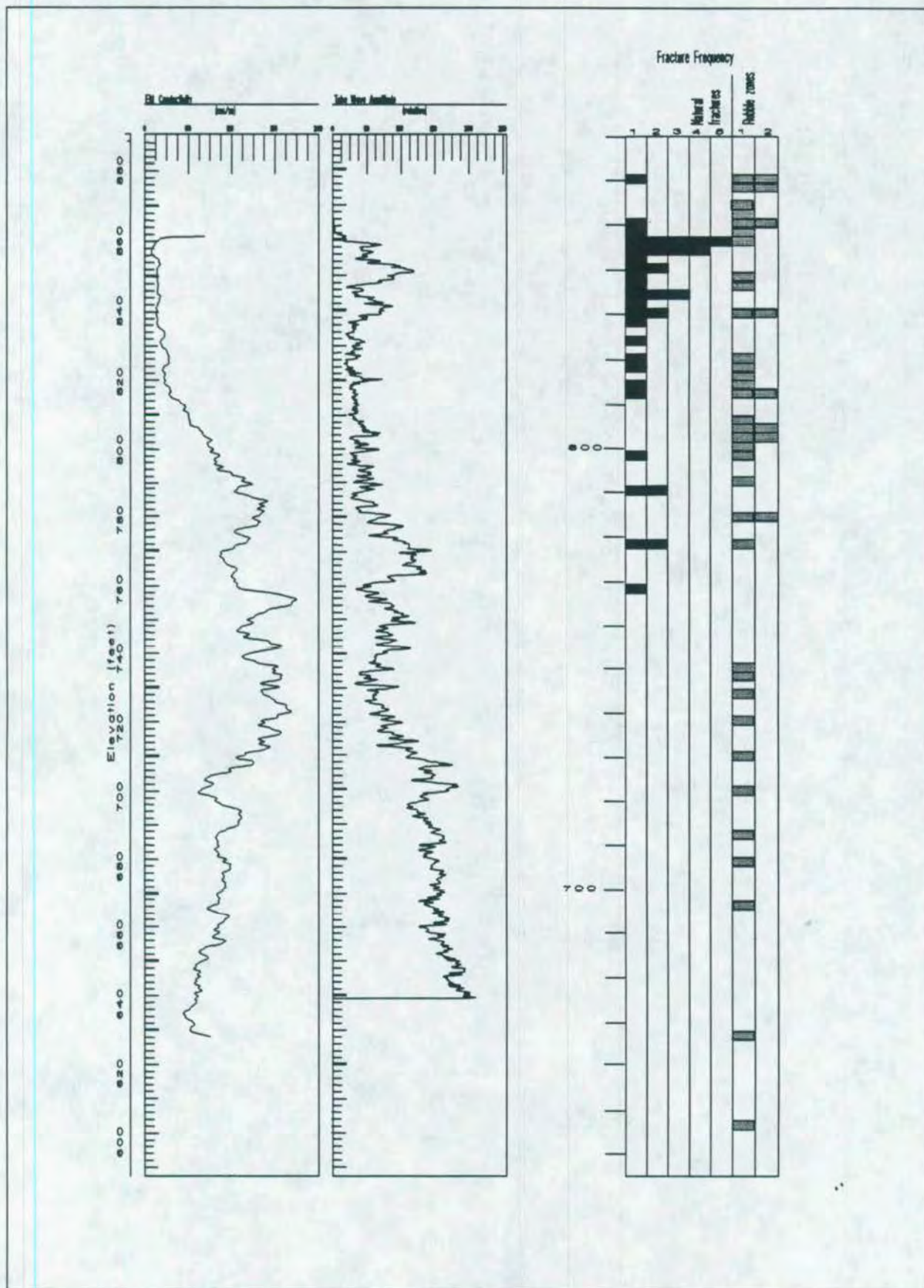


Figure 4.13. Correlation of tube wave amplitude, EM conductivity and fracture frequency in borehole 0348.

Well Name: 348
STRESSED CONDITIONS

KEY:

 Water Level: 44'
 Inner Casing: 15.5'
 Observed Log Anomalies
 Measurement Point with Packer Interval
 Flow Amount Indicated

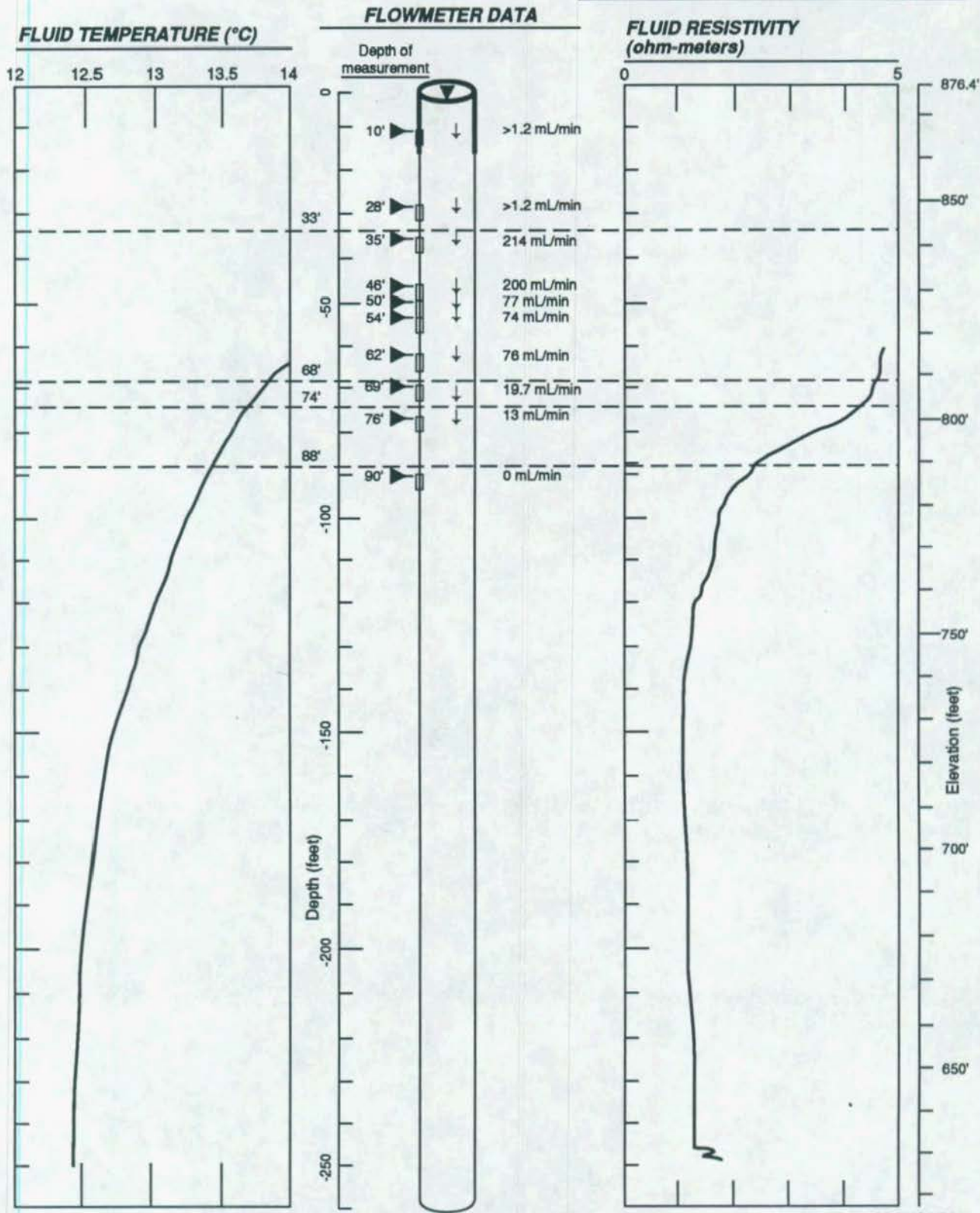


Figure 4.14. Correlation of flowmeter, fluid resistivity, and fluid temperature measurements in borehole 0348

KEY:

-  Water Level: 0'
-  Inner Casing: 40'
-  Observed Log Anomalies
-  Measurement Point with Packer Interval
Flow Amount Indicated

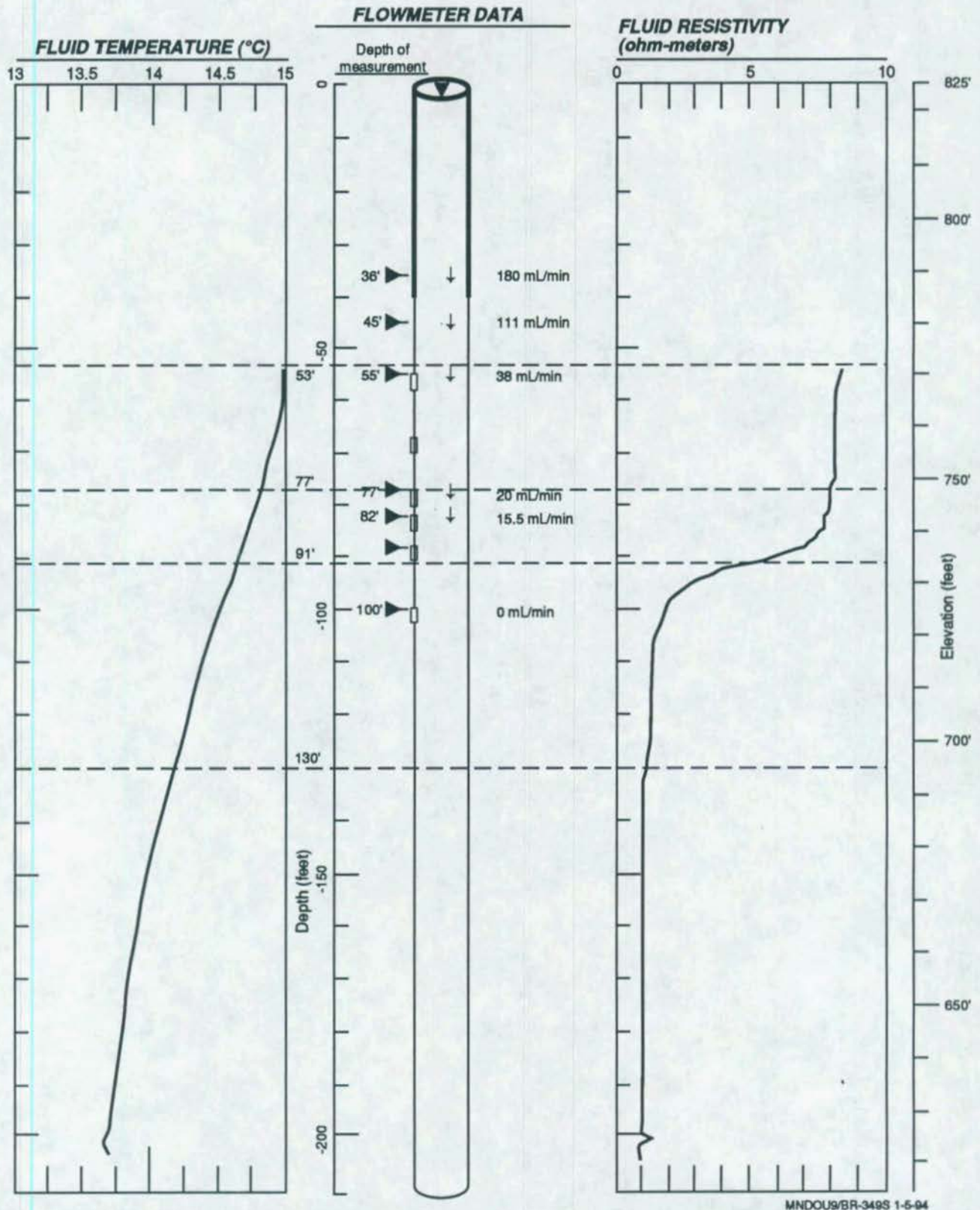


Figure 4.15. Correlation of flowmeter, fluid resistivity, and fluid temperature measurements in borehole 0349.

in the shallow parts of boreholes 0348 and 0349 is attributed to the leaching of salts from the rocks by meteoric groundwater. In this report, the shallow zone of fresh water is referred to as the fresh water carapace. Plate 4 indicates that the fresh water carapace is entirely contained within the fracture carapace, but does not extend to the base of the fracture carapace.

The correlation of observed fracture frequency and tube wave amplitude with flowmeter measurements, fluid resistivity, and fluid temperature indicates that fractures control groundwater flow in the upper few tens of feet in the two boreholes on the Main Hill. The separate geophysical responses recorded from each borehole are related to depth, and that the two boreholes are located at elevations 60 ft apart, indicate that the fracture carapace mimics surface topography on the Main Hill. Part of the fracture carapace may have been removed by glaciation on the western margin of the Main Hill (Plate 3). The fact that the fresh water carapace does not extend to the base of the fracture carapace is attributed to the decreasing groundwater flow rates with depth. Water in fractures near the base of the fracture carapace does not move very efficiently and the very slow movements have allowed little removal of the salts from the rocks (Plate 4).

Relative EM conductivity lows are observed in boreholes 0348 and 0349 at depth: one at approximately 700 ft MSL elevation and another below 660 ft MSL elevation. The localized conductivity lows in each borehole suggest a zone, from 10 to 20 ft thick, that is more permeable than the enclosing beds. These zones correlate with limestone-dominated facies composed of packstones and few shales (Plate 1). A broader zone of low EM conductivity, apparent below 660 ft elevation MSL is correlative with the nodular limestones and shales of the Oregonia and Mound Auburn Formations. The low EM conductivity values are interpreted to indicate the presence of groundwater having relative short residence time and containing less salts.

4.13. DISCUSSION OF PHYSICAL CHARACTERISTICS OF THE SM/PP HILL (BOREHOLES 0350 AND 0355)

Boreholes 0350 and 0355 exhibit similar physical characteristics with those boreholes on the Main Hill, but the data indicate that the fracture and fresh water carapaces on the SM/PP Hill are less deeply developed than the Main Hill. Borehole 0350 is on the top of the SM/PP Hill in the Whitewater Formation at an elevation of 887 MSL. Borehole 0355 is on the northwest flank of the SM/PP Hill in the Waynesville Formation; the Whitewater and Liberty Formations have been eroded away at this location.

The cores from these two locations indicate that fracturing is limited to very shallow depths and decreases rapidly in frequency and degree with depth. The Waynesville Formation in borehole 0355

appears almost as intensely fractured as the Whitewater Formation in borehole 0350. The borehole lithologies are well correlated between the two in their core descriptions, and the neutron and natural gamma logs from each borehole. Lithologic bedding is horizontal and undeformed except for fractures. The caliper logs indicate the boreholes are straight and not affected by breakouts or local irregularities that would indicate instability of the rocks. The geophysical measurements on the boreholes and the borehole fluids form a consistent pattern of very shallow fracture, alteration, and weathering.

Physical fracturing of the rocks in the shallow portions of the boreholes is indicated not only by direct visual observation of fractures, but also by indirect geophysical means. The pattern of the full waveform sonic logs indicate that tube waves have low amplitudes and, thus, permeable fractures in the upper 90 ft of both borehole 0350 and 0355. Figure 4.16 displays the relationship between tube wave amplitude and fracture frequency in borehole 0350. Tube waves are observed in the upper 50 ft, but have low amplitudes through a zone from 50 to 70 ft deep. Tube waves are well developed below a depth of 90 ft. These data indicate that the deeper zones of very weakly fractured rocks strongly correlate with the zones of tube wave propagation and correlate with low permeable rock. The low amplitude the tube waves from depths of 50 to 70 ft correlate with fractures observed in core 0350, the lower part of the Liberty Formation. Plate 3 depicts the geometry of the fracture carapace on the SM/PP Hill based on these data.

The flowmeter measurements, fluid resistivity, and fluid temperature in boreholes 0350 and 0355 all indicate that groundwater flow is restricted to the upper 20 ft below ground surface (Figure 4.17). Groundwater flow was measured with the heat pulse flowmeter only in the upper 20 ft below ground surface in boreholes 0350 and 0352 on the SM/PP Hill. The maximum flow measured was 14 mL/min at a depth of 16 ft in borehole 0350. The fluid resistivity and temperature logs indicate that groundwater flow is restricted to the upper 20 ft below ground surface. No flow was measured in borehole 0355 (Figure 4.18). Fluid resistivity is relatively stable through the entire length of the boreholes indicating that water in the borehole is relatively stagnant. These data are interpreted to indicate that inflow of groundwater to the borehole and mixing with water standing in the borehole is very weakly developed on the SM/PP Hill. Fluid resistivity is stable below those depths, indicating that pore water in the formation is relatively rich in salts that yield lower resistivities, indicative of formation waters. These data indicate that flow rates decrease with depth and drop to zero near the base of the fracture carapace (Plate 3).

The guard and EM resistivity logs in both boreholes additionally indicate that the upper few feet of rock are less conductive and more resistive than the rocks at depth (Plate 4). The magnitude of the changes indicate that the fresh water carapace is not as well developed on the SM/PP Hill as it is on the Main Hill. As with the boreholes on the Main Hill, the differences cannot be attributed to lithology,

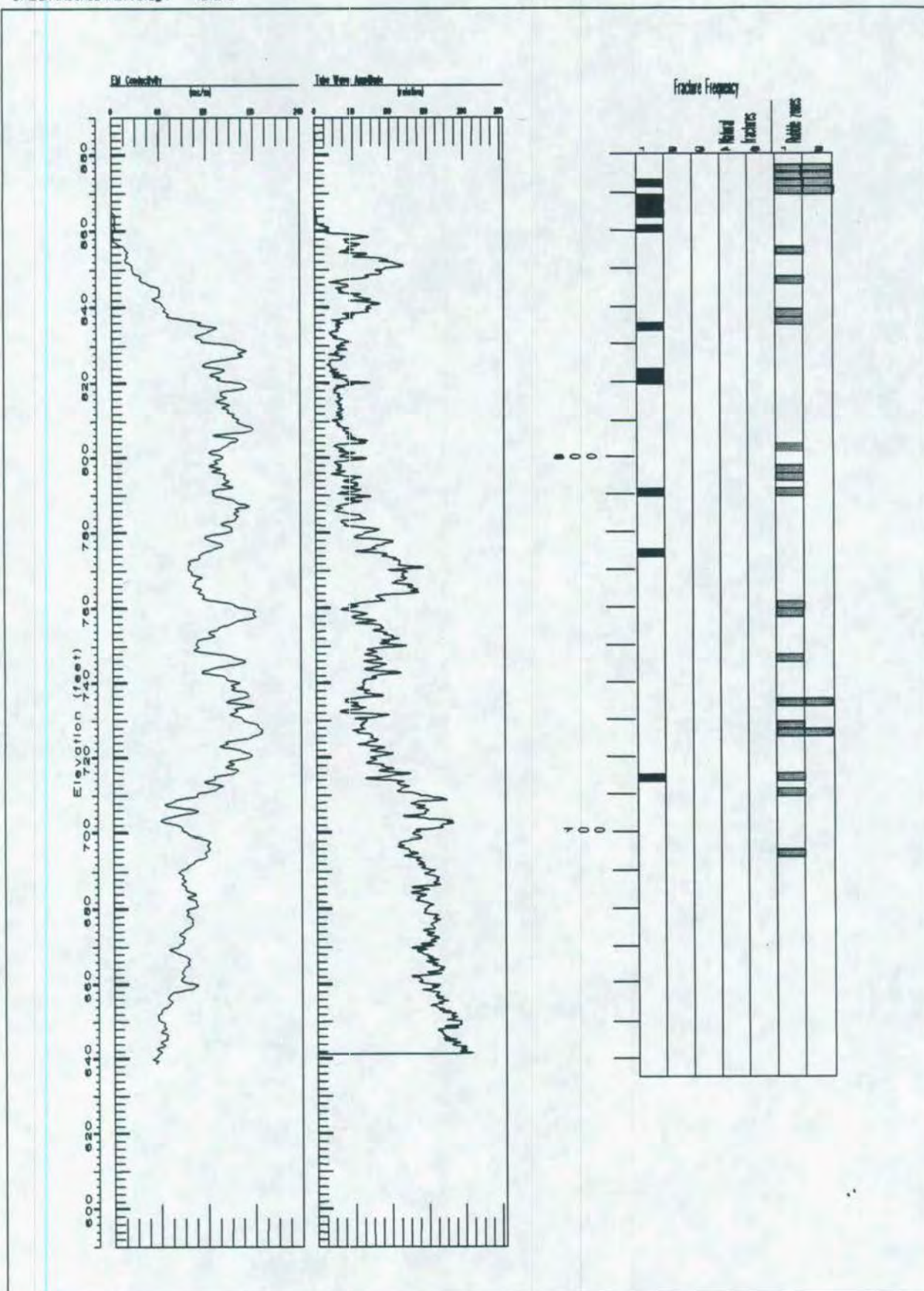
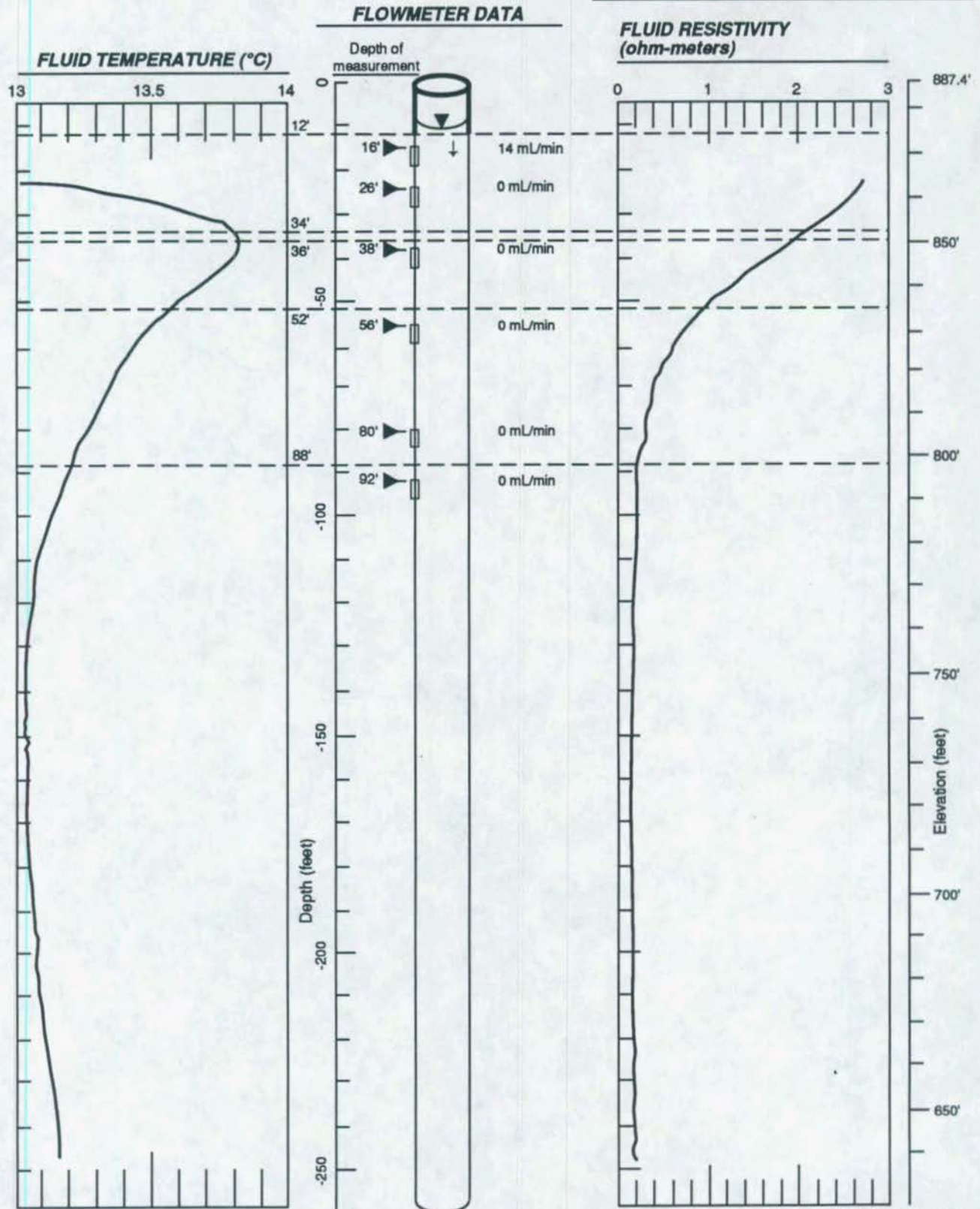
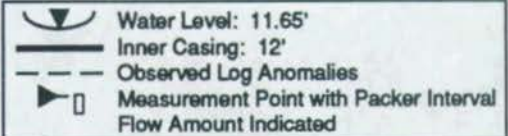


Figure 4.16. Correlation of tube wave amplitude, EM conductivity, and fracture frequency in borehole 0350.

Well Name: 350

KEY:



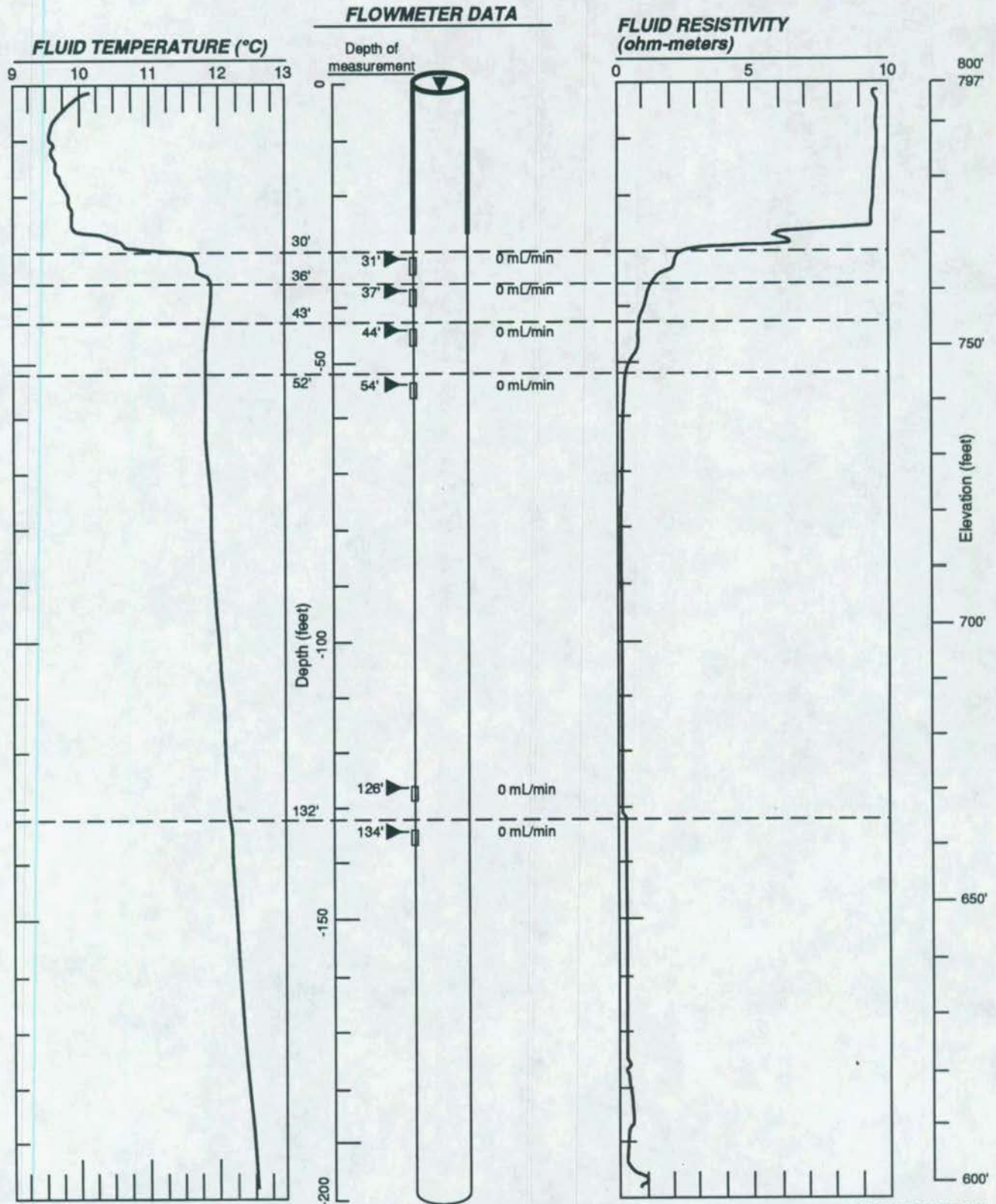
MND09/BR-350 1-5-94

Figure 4.17. Correlation of flowmeter, fluid resistivity, and fluid temperature measurements in borehole 0350.

Well Name: 355

KEY:

-  Water Level: 0.4'
-  Inner Casing: 27'
-  Observed Log Anomalies
-  Measurement Point with Packer Interval
Flow Amount Indicated



MND OU9/BR-355 1-5-94

Figure 4.18. Correlation of flowmeter, fluid resistivity, and fluid temperature measurements in borehole 0355.

since the less conductive zone occurs in the middle part of the Waynesville Formation in borehole 0355, whereas the middle part of the Waynesville Formation is unaffected in borehole 0350. The less conductive and more resistive nature of the rocks in the shallow parts of boreholes 0350 and 0355 is attributed to the leaching of salts by groundwater. The depth of the fresh water carapace is much shallower on the SM/PP Hill than it is on the Main Hill. The lower part of the Liberty Formation is unaffected in borehole 0350 and in borehole 0355, the Waynesville Formation is effected only to shallow depths (Plate 4). As with the Main Hill, Plate 4 indicates that the fresh water carapace is entirely contained within the fracture carapace, but does not extend to the base of the fracture carapace.

The correlation of observed fracture frequency and tube wave amplitude with flowmeter measurements, fluid resistivity, and fluid temperature indicates that fractures control groundwater flow in the upper few tens of feet in the two boreholes on the SM/PP Hill. The fact that the geophysical responses are related to depth and that the two boreholes are located at elevations 80 ft apart indicates that the fracture system mimics surface topography of the SM/PP Hill. As with the Main Hill, the fact that the fresh water carapace does not extend to the base of the fracture carapace is attributed to the decreasing groundwater flow rates with depth. The fact that the fresh water carapace (Plate 4) extends to depths of approximately 50 ft suggest that flowmeter tests under stressed conditions would indicate only slightly deeper flows than those observed.

As with boreholes 0348 and 0349, a relative EM conductivity low is observed at approximately 700 ft MSL elevation in boreholes 0350 and 0355. This relative low suggests that a zone of approximately 10 to 20 ft thick may be more permeable than the enclosing beds. This zone correlates with a limestone dominate facies composed of packstones and few shales (Plate 4). The EM conductivity low is interpreted to indicate that some fresh groundwater may be present in this zone and that connate electrolytes may have been leached from the rocks. This zone is, however, isolated from groundwater in the shallow bedrock by the thick Waynesville Formation composed of largely impermeable shales.

4.14. DISCUSSION OF PHYSICAL CHARACTERISTICS OF BOREHOLES 0335 AND 0352

Boreholes 0335 and 0352 exhibit many similar physical characteristics between each other and the boreholes of their respective hill slopes. Both boreholes are located on the western flanks of hills along the eastern margin of the glacial valley that contains the Buried Valley aquifer (DOE 1992a). Borehole 0335 is located on the western flank of the Main Hill in the base of the Waynesville Formation at an elevation of 705 ft MSL. Borehole 0352 is located on the western flank of the SM/PP Hill in the Waynesville Formation; the Whitewater and Liberty Formations have been eroded away at both locations. The cores from these two locations indicate that fracturing is limited to very shallow depths and decreases rapidly in frequency and degree with depth.

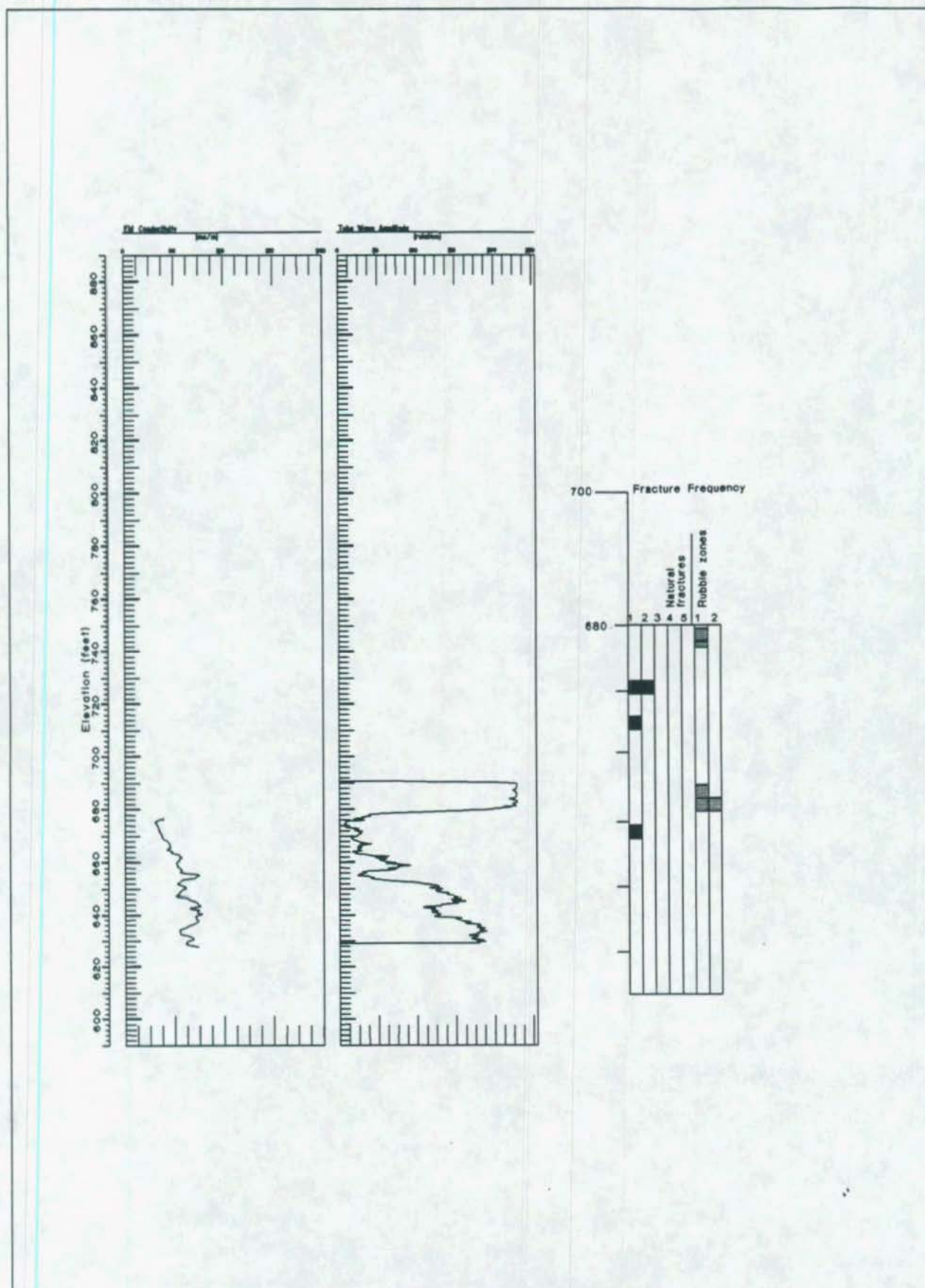


Figure 4.19. Correlation of tube wave amplitude, EM conductivity, and fracture frequency in borehole 0335.

Well Name: 335

KEY:

-  Water Level: 14.5'
-  Inner Casing: 28.5'
-  Observed Log Anomalies
-  Measurement Point with Packer Interval
Flow Amount Indicated

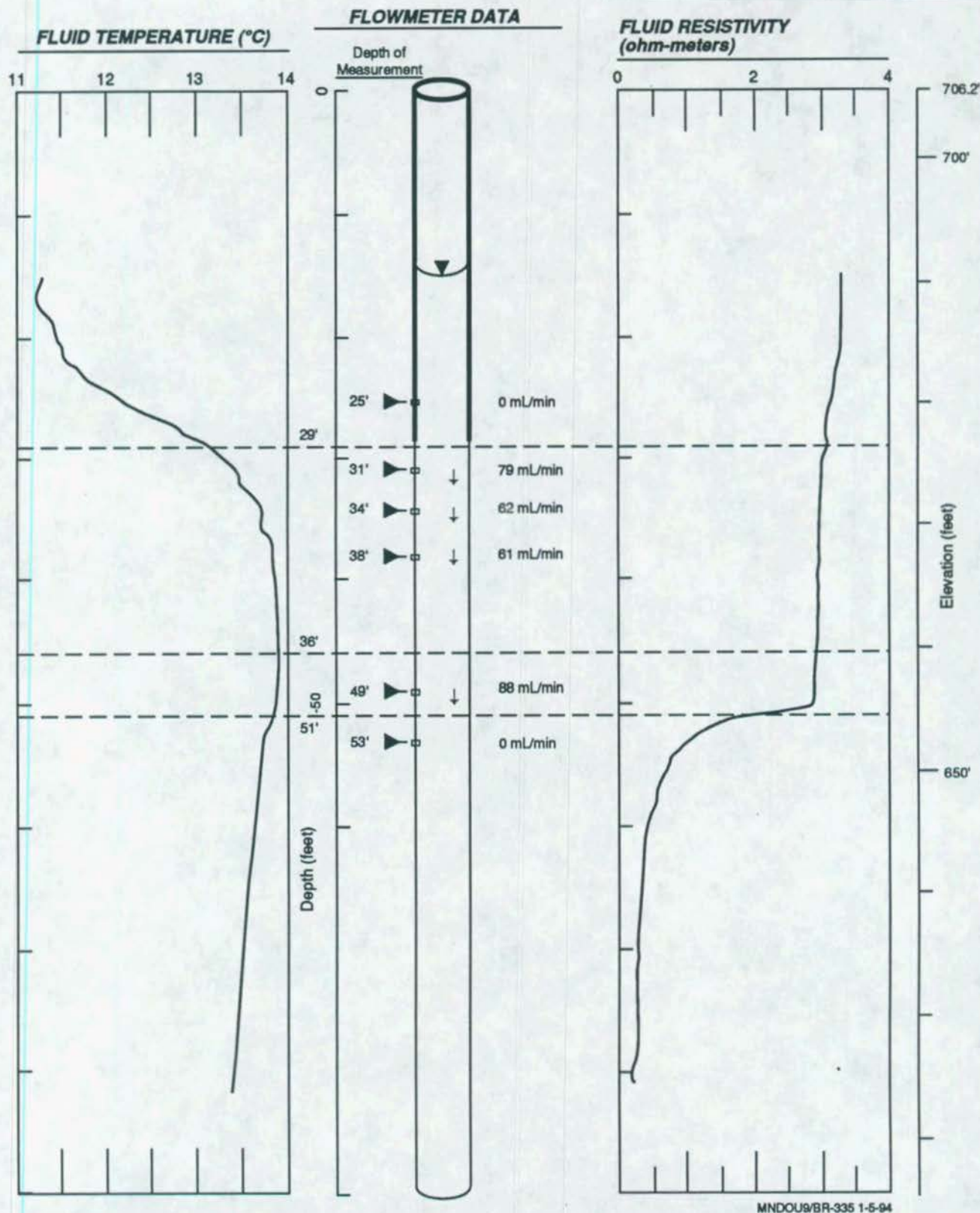


Figure 4.20. Correlation of flowmeter, fluid resistivity, and fluid temperature measurements in borehole 0335.

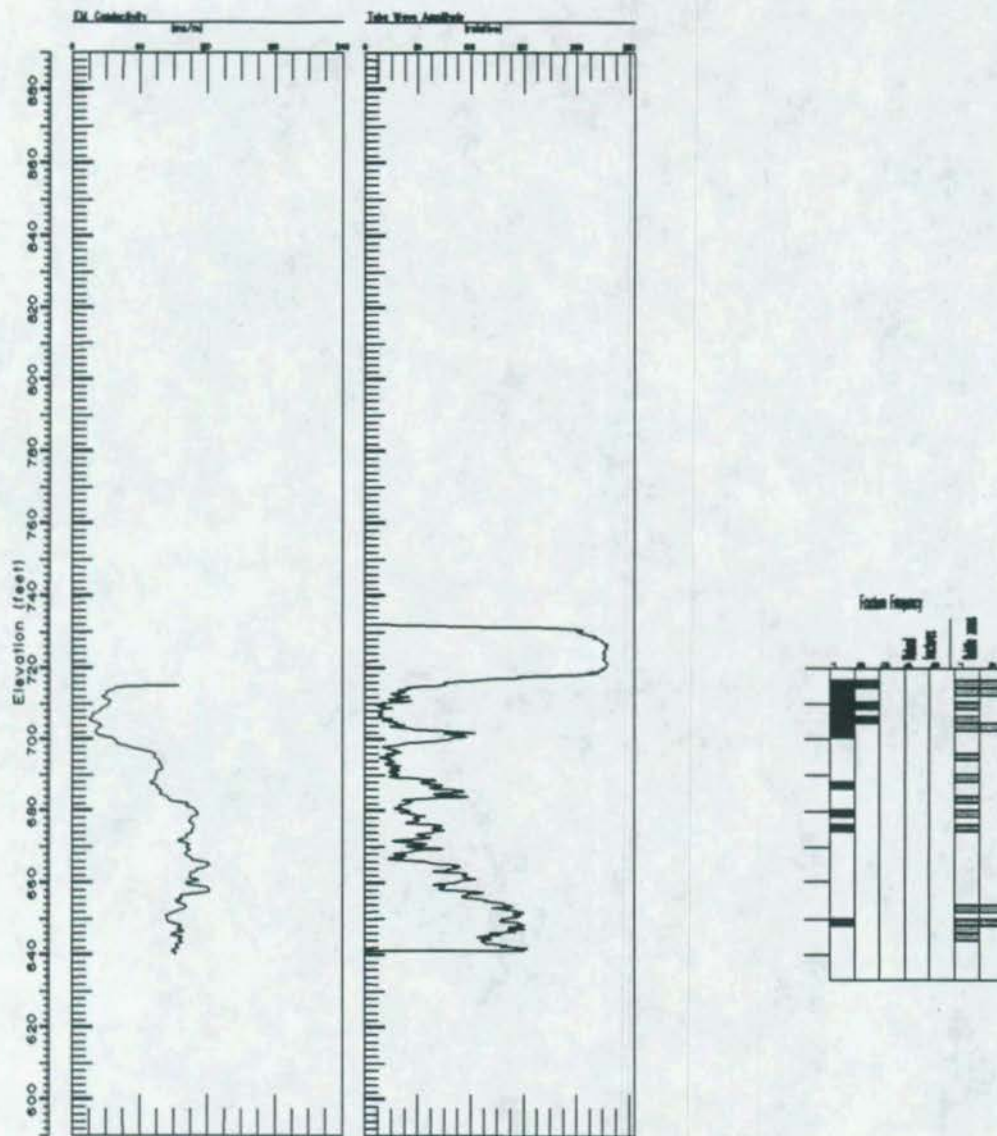


Figure 4.21. Correlation of tube wave amplitude, EM conductivity, and fracture frequency in borehole 0352.

In borehole 0335, the physical conditions observed are similar to other boreholes on the Main Hill (0348 and 0349 described above). However, the sonic logs, flowmeter measurements, fluid resistivity, and fluid temperatures indicate that weak groundwater movement is limited to the upper 30 to 50 ft of rock (Figure 4.19). The sonic log indicates that good tube wave propagation is achieved below 33 ft depth with a disturbance at approximately 50 ft. This correlates well with the flowmeter log that indicates that maximum flow occurs at 49 ft and decreases to zero at 53 ft. The maximum inflection of fluid resistivity also occurs at approximately 50 ft (Figure 4.20). These data suggest physical conditions at borehole 0335 are similar to other parts of the Main Hill, that is, shallow bedrock exhibits fractures that control groundwater flow.

In borehole 0352, the physical conditions observed are similar to other boreholes on the SM/PP Hill (0350 and 0355 described above). As with the other data on the SM/PP Hill, the sonic logs, flowmeter measurements, fluid resistivity, and fluid temperatures indicate that weak groundwater movement is limited to the upper 20 to 30 ft of rock. The sonic log indicates that high tube wave propagation is achieved below 35 ft depth (Figure 4.21) suggesting low permeable rock. The flowmeter log indicates that maximum flow of 18 mL/min occurs at 28 ft depth (Figure 4.22). This depth corresponds to an elevation of 706 ft MSL at which a more permeable zone of limestones is apparent in other logs (Plate 4). At the location of borehole 0352, the permeability of this zone may be enhanced by weathering and fracturing superimposed on the natural lithology. No flow was measured, however, below a depth of 34 ft. These data suggest that physical conditions at borehole 0352 are similar to parts of the SM/PP Hill.

4.15. DISCUSSION OF THE POSSIBLE PRESENCE OF A REGIONAL WATER PRESSURE SURFACE

One of the objectives of the OU 9 hydrogeologic investigations of the Mound Plant bedrock is to identify the presence of a regional groundwater surface. If this surface is present a determination of possible communication between bedrock and the Buried Valley aquifers would be required. The OU 9 Site-Wide Work Plan recognized the unknown aspects of the fracture system and was designed to collect information concerning the possible presence of a deep, through-penetrating fracture system. If present, the postulated through-penetrating fracture system may have allowed vertical movements of groundwater from the shallow, contaminated zones on the Main Hill into the Buried Valley aquifer. This report presents extensive physical evidence that such a system does not exist at the Mound Plant. On the contrary, the bedrock flow that underlies the Mound Plant is contained within a fracture carapace that mantles topography. There is evidence in the data, however, to support the presence of a deeper, isolated bedrock aquifer that is unconnected to the fracture carapace.

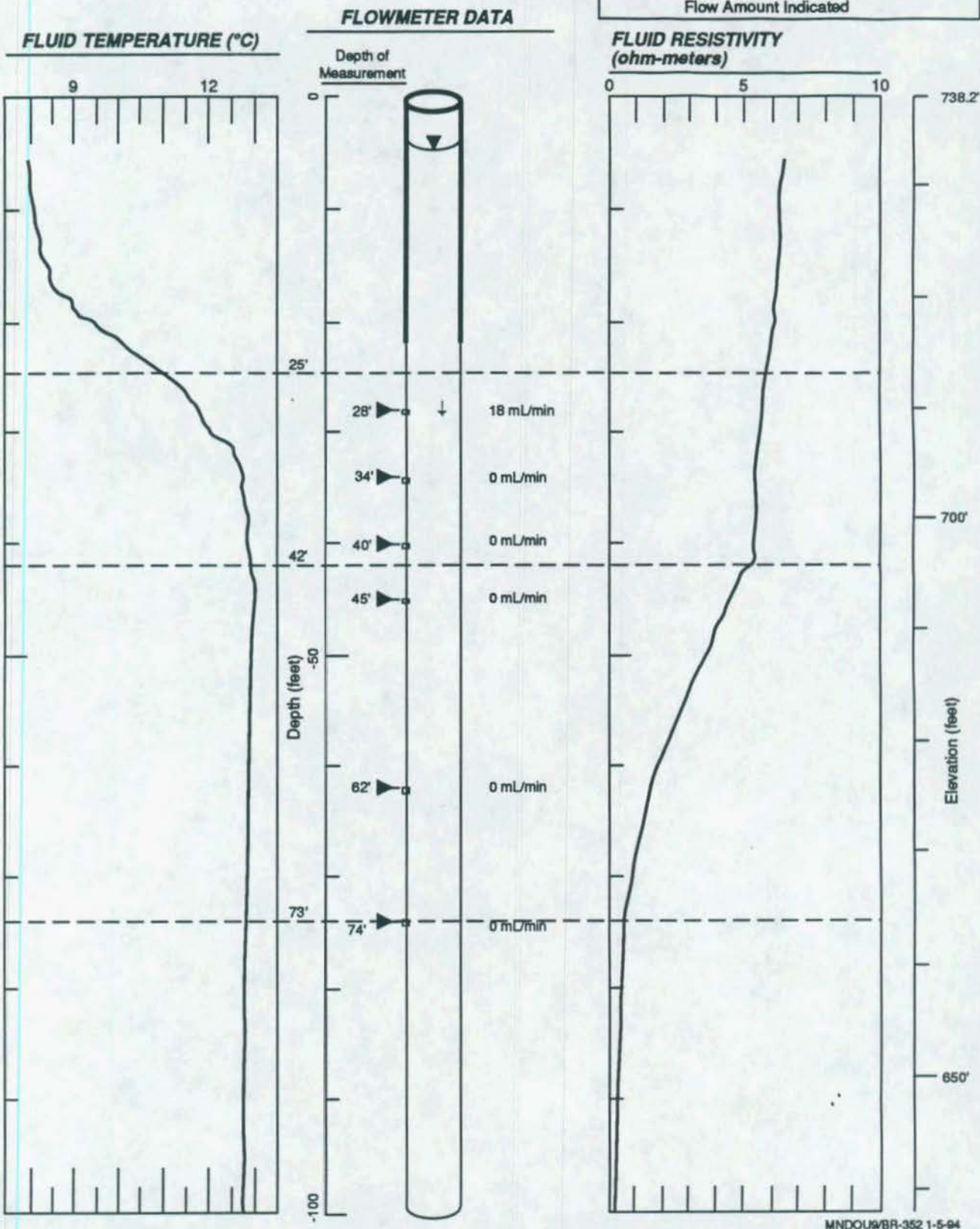
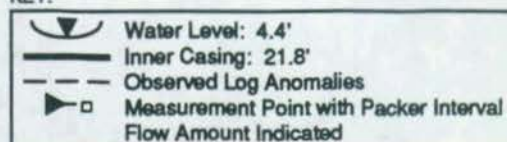


Figure 4.22. Correlation of flowmeter, fluid resistivity, and fluid temperature measurements in borehole 0352.

The data from the EM conductivity logs indicates a broad zone of relatively low electrical conductivity below elevations of approximately 660 ft MSL. These lows are interpreted to represent the presence of relatively fresh water that possesses less marine salts than the enclosing rocks. The leaching of the salts from the marine rocks is interpreted to result from the lateral movement of groundwater through relatively permeable beds over periods of geologic time. The movement of groundwater through shales is inhibited by low permeable rock. Indeed, the relatively high electrical conductivity of the shale-rich rocks demonstrates that little fresh water has moved through them. Since the zone of rock below the 660-ft elevation appears to be more permeable than the enclosing rocks and is below the 680-ft MSL elevation of the average stage of the Great Miami River, a potential regional bedrock groundwater surface is recognized.

This regional groundwater surface may be present beneath the Mound Plant within the rocks of the Mount Auburn Formation and the lowermost Oregonia Formation. Whether this zone may be in hydraulic communication with the Buried Valley aquifer has yet to be determined. A detailed hydrologic study involving the continuous monitoring of groundwater levels in selected Buried Valley aquifer and bedrock wells is ongoing. Data collection will not be completed until December 1993 and the results of this hydrologic study will be presented in the forthcoming OU 9 Glacial Hydrogeology Report in early 1994. This current study indicates that these rocks are overlain by shale-rich rocks of inherently low permeability, groundwater may be present under confined conditions. It is probable that the zone (660-ft MSL) is not hydraulically connected to the groundwater in the fracture carapace of the upper bedrock. If this zone of groundwater is present, it is not of primary or even secondary concern to groundwater pathway description.

4.16. CONCLUSIONS

The results of the extensive suite of borehole geophysics performed indicate that sufficient information exists on the characteristics of the bedrock flow system beneath Mound Plant to satisfy the objectives of OU 9. These results identify the geometry of the fracture carapace and the associated alteration of the marine rocks. The strong correlation among the fracture distribution, borehole flowmeter measurements, and low conductivity rocks indicate that the fracture carapace has served as the mechanism to supply meteoric water within the bedrock hills that has leached marine salts from the rocks. The apparent attenuation of salt removal below the fracture carapace tests to the very low primary permeability of the bedrock. No additional investigations are warranted under OU 9. However, site specific investigations concerning hydraulic characteristics of the fracture carapace may be warranted by other OUs as source term investigations proceed.

5. HYDRAULIC CHARACTERISTICS OF THE BEDROCK

An analysis of the hydrologic properties of the bedrock that underlies Mound Plant has been conducted as part of the Operable Unit 9 hydrogeologic investigations. The objectives of these studies are to 1) ascertain the degree of interconnection between the fracture carapace and the underlying bedrock; and 2) calculate hydraulic characteristics of the fracture carapace and the underlying bedrock. Techniques used to characterize the bedrock hydraulics included falling head tests, long-term water level monitoring of the fracture and non-fractured zones, and calculation of permeability from previous investigations.

The bedrock at the Mound Plant consists of a thick sequence of interbedded marine shales and limestones that have been chemically altered by processes of groundwater flow. The bedrock flow system underlying Mound Plant is considered to be confined to a fractured carapace that mimics surface topography. The fracture carapace is believed to be more deeply developed on the Main Hill than the SM/PP Hill (Plate 3). The base of the fracture carapace is defined as a no-flow zone with a position estimated from fracture studies and borehole geophysical measurements.

As part of the Site Description and Safety Assessment, Dames and Moore (1973) conducted water pressure tests on selected boreholes. An inflatable double packer was used to isolate ten-ft thick sections of bedrock through the length of the 200-ft deep boreholes. The results were reported on the boring logs. These data are considered sufficient to provide data on the primary permeability of the bedrock at Mound Plant. The measurements by Dames and Moore did not, however, provide sufficient data on the enhanced permeability of the fracture carapace. Additional calculations of the enhanced permeability of the fracture carapace are determined in this report and are comparable to the Dames and Moore shallow measurements.

The following subsections describe the methods and results of estimates of the permeability and hydraulic conductivity of the fracture carapace and underlying rocks. Techniques used to characterize the bedrock hydraulics included falling head test, long-term water level monitoring of the fractured and non-fractured zones, and determination of permeabilities from the previous investigation. Falling head tests are used to estimate a permeability value for the fracture carapace.

5.1. FALLING HEAD TESTS

Water levels in the fracture-dominated bedrock flow system are expected to vary according to local fracture distribution, but water levels in the fracture carapace indicate systematic patterns. During the borehole geophysical tests in borehole 0348 (Section 4) initial water level was measured at 59.7 ft.

After stemming the borehole twice with water to conduct the other tests, the water level stabilized at 44 ft. On the SM/PP Hill, initial water level was measured in borehole 0350 at 29 ft. After stemming the borehole with water to conduct the other tests, the water level stabilized at 12 ft. This data suggests that water levels in the fracture carapace vary rapidly enough that short-term monitoring could provide permeability information. After the geophysical downhole logging was completed, a falling head test was conducted at each borehole.

The falling head tests were conducted to qualitatively and quantitatively determine the secondary permeability created by fractures intersected in each bedrock borehole. The open borehole was instrumented with a pressure transducer and datalogger and subsequently filled with water to ground surface. The drop in water level was monitored for approximately 24 hours with the pressure transducer and datalogger. Manual water level measurements were made at the test beginning and end to verify several datalogger readings. This test procedure was conducted at boreholes 0335, 0348, 0349, 0350, 0352, 0355.

5.1.1. Results of Falling Head Tests

Decline in the water level is related to head of initial water column, porosity and permeability of the unit. Representative linear graphs of the decline in water level for boreholes 0348 and 0350 are presented in Figure 5.1. Appendix D contains the graphs for boreholes 0335, 0349, 0352, 0355. These results indicate that in several boreholes, the decline in water occurs at two different rates as shown by the change in slope of the water level drop. The most pronounced example is from borehole 0348 where the water slug declined 31 ft within an hour (Figure 5.1). This is equivalent to the fracture flow of 0.34 gallons per minute (gpm). After the initial decline of 31 ft, the rate of decline is reduced to 8.75×10^{-3} gpm. Water level declines were significantly slower in all other boreholes tested. In borehole 0350 the water level dropped to a depth of 10 ft below ground surface with no significant change in the rate of 5.53×10^{-3} gpm. Borehole 0335 water level dropped 13 ft in the first 220 minutes or 3.85×10^{-2} gpm. Borehole 0349 declined 49.2 ft in 1350 minutes or 2.40×10^{-2} gpm. Qualitatively, these tests indicate that at least the upper part of the fracture carapace on the Main Hill can sustain a water inflow rate of less than a gallon a minute. On the SM/PP Hill the water inflow rate is two orders of magnitude less.

The falling head tests were also used to estimate the permeability of the fracture carapace. The falling head test was considered to be similar to a slug test where the borehole is subjected to an

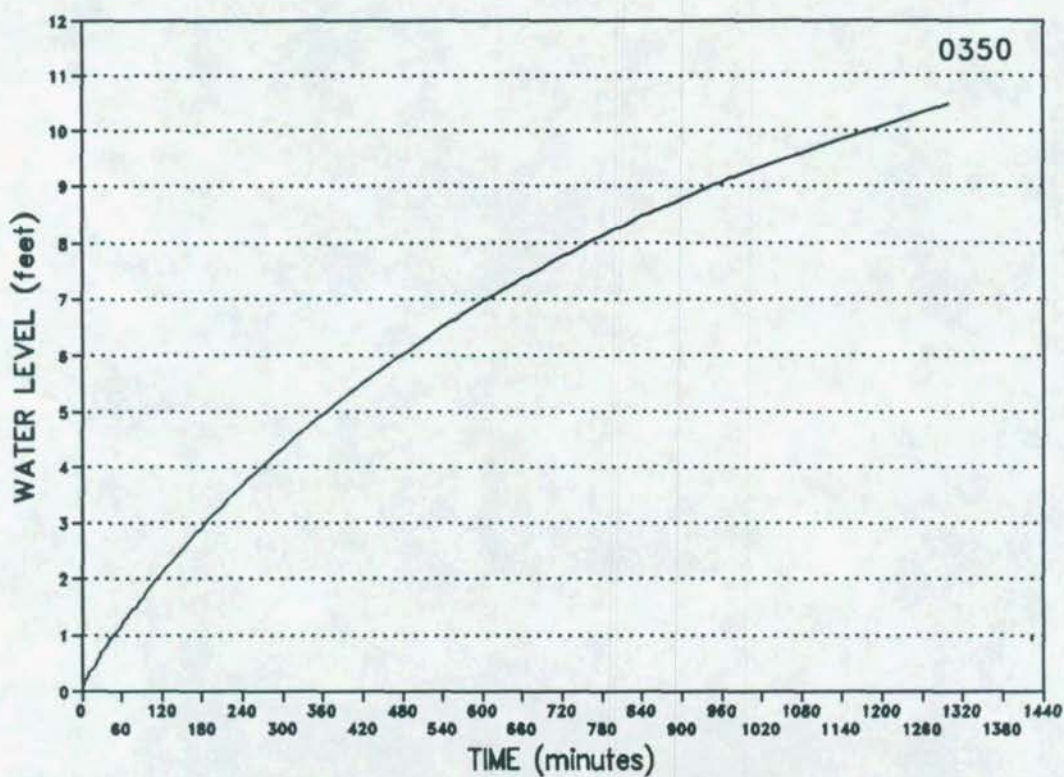
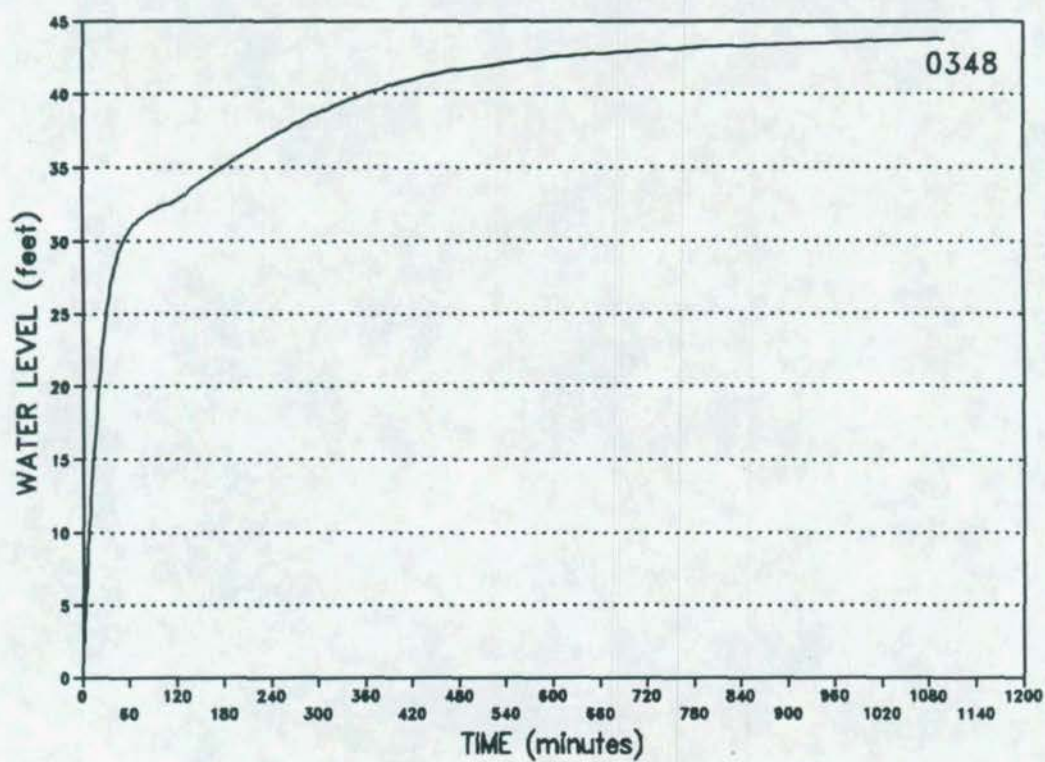


Figure 5.1. Water level changes in boreholes 0348 and 0350 during falling head test, March and April 1993.

instantaneous injection of water. The data were analyzed using unconfined slug test analysis methods to determine the permeability of the fracture zone. Assumptions made for this analysis are that:

- the saturated zone is the entire depth between water level stabilization depth and ground surface, and
- the fracture zone is acting as a porous medium.

The Bouwer and Rice (1976) slug test method for unconfined aquifers as presented in the computer program AQTESOLV by Geraghty & Miller was used for this analysis. Graphs of the straight line fit for each of the boreholes is presented in Appendix D.2. The results of these analyses are presented in Table V.1. Boreholes 0348, 0349, and 0350 all have two distinct slopes that could be matched. Results for these boreholes have a range of hydraulic conductivity of 0.09 to 0.93 ft/day with the exception of borehole 0352. No unique interpretation could be made for borehole 0352 as the early-time data is poor quality.

5.1.2. Interpretation

The changes in water levels during the borehole geophysics studies are interpreted to indicate that the small amount of water introduced to the boreholes simply saturated the fractures in the shallow part of the fracture carapace. In the upper part, water was able to drain through the interconnected fracture network. In the lower part of the fracture carapace, the lack of interconnected fractures reduces permeability.

The falling head tests provided additional insight into the flow rate and permeability of the fracture carapace. During the falling head tests, the water levels stabilized at a level below ground surface that is interpreted to represent the approximate water table within the fractures. On the Main Hill, both 0348 and 0349 water levels stabilized at 44 and 50 ft below ground surface, respectively. The water level in 0350 stabilized at only 10 ft below ground surface. The heat pulse flow and fluid resistivity logs also indicated the decline of flow at these levels. Water level decline measured in the bedrock boreholes is related to the size and interconnectedness of the fractures. But without knowledge of fracture characteristics, an assumption of an equivalent porous medium is necessary. Using this assumption, permeability values are determined from the falling head test using an unconfined slug test method. Due to the stabilization level, these tests evaluate the entire fracture carapace. Results of the falling head test indicate that the carapace has a permeability of 0.09 to 0.93 ft/day. These values are representative of hydraulic conductivity values listed in the literature for limestones. The permeability values determined from the falling head test indicate that there is no difference between

**Table V.1. Summary of Hydraulic Conductivity for
Boreholes 0335, 0348, 0349, 0350, 0352, 0355**

Bedrock Borehole Number	Depth of Water Level Stabilization (Ft BGS)	Top of Packer (ft BGS)	Falling Head Hydraulic Conductivity (ft/day)
0335	14.9	NA	0.93
0348	43.6	110	0.23-1.42
0349	49.2	125	0.09-0.12
0350	10.0	100	0.24-0.32
0352	4.6	60	9.62
0355	NA	100	NA

BGS - below ground surface

NA - Not applicable as no measurements were possible

the Main Hill and SM/PP Hill. However, the thickness of the carapace on SM/PP Hill is half the size of the Main Hill (Plate 3). If hydraulic conductivities are equal, there would be twice as much flow on the Main Hill versus SM/PP Hill. The quality of the early-time data for borehole 0352 is poor and no unique interpretation is possible using the Bouwer and Rice (1976) technique. Therefore, the relatively high permeability value for borehole 0352 may be considered anomalous.

Water levels in the new boreholes and adjacent wells indicate a regular pattern consistent with older data. Boring No. 2 drilled by Dames and Moore (1973) approximately 500 ft east of borehole 0348 on the Main Hill had water level 45 ft below ground surface (BGS) on February 8, 1973. Well 0113, approximately 75 ft east of borehole 0348, has recorded water levels of 54 to 55 ft BGS. Well 0114, approximately 400 ft southwest of borehole 0348, has recorded water levels of 50 to 54 ft BGS (DOE 1992a). Water levels in borehole 0350 and adjacent wells indicate a pattern of very shallow, regular groundwater on the SM/PP Hill. Boring No. 1 drilled by Dames and Moore (1973) approximately 500 ft north of borehole 0350 had water level at 10 ft BGS on March 2, 1973. These are essentially the same depth to water recorded through 1993.

These data suggest that the bedrock flow system can be subdivided into three zones: the upper, shallow part of the fracture carapace; the lower, deeper part of the fracture carapace; and the bedrock beneath the fracture carapace. The upper part of the fracture carapace is interpreted to extend from the surface to a depth of about 50 ft on the Main Hill and a depth of about 25 ft on the SM/PP Hill. This upper zone exhibits evidence of frequent, interconnected fractures that are partially saturated with groundwater. The lower part of the fracture carapace is interpreted to extend from a depth of approximately 50 to a maximum depth of approximately 100 ft on the Main Hill and a depth of approximately 60 ft on the SM/PP Hill. This lower zone exhibits evidence of less frequent, poorly interconnected fractures that are probably water saturated. The degree of interconnection is interpreted to decrease with depth through the lower zone until the magnitude of groundwater flow is unable to be measured by modern standard instrumentation. Beneath the fracture carapace is probably a zone of no flow in which isolated fractures are not interconnected. Very weak groundwater flow may occur below the depth indicated, but it is below the detection limit of the borehole flowmeter instrument (7 mL/min).

5.2. WATER LEVEL MONITORING

All data acquired and reviewed for this report indicate that the fracture carapace is much more permeable than the underlying bedrock. The objective of the water level monitoring was to individually assess the water level changes in the fracture carapace and the relatively impermeable underlying

bedrock. A secondary objective was to observe the response of the bedrock water to outside hydrogeologic influences such as regional water level decline or barometric pressure changes.

An investigation was conducted that instrumented these borings with inflatable packers, pressure transducers above and below the packers, and data loggers which recorded water level changes over a three-month period. The period of record for this investigation was from April 30, 1993 to July 31, 1993. Five of the bedrock boreholes were fitted with inflatable packers for separating portions of the borehole. Tiggra-Terra packers were installed in boreholes 0348, 0349, 0350, 0352, 0355. The packers were installed below the fracture carapace as determined at the time from the tube wave amplitude logs. The depths below ground surface that each packer was installed are listed in Table V.1. When positioned at the selected depths, each packer was inflated and maintained at 100 psi.

Independent water level measurements were made possible by instrumenting each borehole with two pressure transducers and a datalogger for continual water level monitoring. Instrumentation included two Druck Model 640 pressure transducers and an In-Situ Model 1000c datalogger. A pressure transducer was placed above the packer and one below the packer. The pressure transducers are capable of measuring water level changes within ± 0.01 ft.

At the beginning of the three-month monitoring, an attempt was made to better assess the interaction between the fracture carapace and the underlying bedrock by increasing the water level difference between the packed-off zones. A 1/2-inch stainless steel bailer was lowered through the packer support pipe to bail down the water level in the lower zone several ft below each packer.

5.2.1. Results

The recovery of the lower bedrock drawdown can be seen at the beginning of the three-month linear water level graphs, Figures 5.2 and 5.3, for boreholes 0348 and 0349, respectively. Graphs for 0350, 0352, and 0355 are included in Appendix D.3. Despite continued attempts at bailing down borehole 0349, water level of the lower zone remained nearly identical to the water level above the packer. There were no recognizable effects in the fracture carapace as a result of the lowered water level in the bedrock below the carapace. As shown on graphs for boreholes 0348, 0352, and 0355 recovery did occur in the bedrock. The source of recharge for this recovery is unknown at this time.

Between April 30 and July 31, 1993, water levels for many of the site wells were measured for the OU 1 investigation aquifer test (DOE 1993c). During these water level measurement runs, the bedrock wells water levels were measured and packer pressure checked. A manual reading and pressure

transducer reading were made simultaneously. Because the manual water level indicator could not go below the packer due to the small internal support pipe diameter, QA/QC readings for water levels in the lower zone are inaccurate. Most hand measurements and pressure transducer measurements correlate well, however, for the zone above the packers.

Change in water level above and below the packers in boreholes 0348 and 0349 from April 30 to July 31, 1993, are shown in Figure 5.2; results from other boreholes are included in Appendix D. Water level fluctuations in borehole 0348 seem to follow a dissipated barometric effect but the change in water level is too great to be caused solely by barometric pressure (Figure 5.2). It may be a reflection of recharge due to precipitation events associated with low barometric pressures. Below the packer, the initial recovery from the bail down is evident and the water level declines until it is below the pressure transducer. The pressure transducer was lowered and reset and the same general slope of decline continued. A similar water level response was found at borehole 0350. The water level below the packer declined continuously from the start. Borehole 0350 water level above the packer fluctuated similar to 0348 but with an amplitude 5 times less. Water levels above and below the packer in borehole 0349 fluctuated identically with a displacement between them of 0.1 ft. The only water level change recorded in 0349 was determined to be due to barometric pressure (Figure 5.3). A barometric efficiency of 52 percent is indicated using the method of Clark (1967). Water levels in borehole 0352, after recovering from bail down, stabilized with two anomalous fluctuations. Borehole 0355 declined only slightly throughout the three-month period with no difference in water level between the two zones.

Overall, water levels changed little in the fracture carapace above the packers. In some boreholes, water levels reflected barometric pressure and possibly recharge from precipitation. Water level in the bedrock changed very little.

5.2.2. Interpretation

Water level monitoring was conducted individually in the fractures carapace and the underlying bedrock. These two zones were separated by installation of inflatable packers in five boreholes (0348, 0349, 0350, 0352, 0355). Four of the five boreholes had similar water level trends in the two zones. In these four boreholes (0348, 0350, 0352, 0349), the fracture carapace responded to changes in barometric pressure, possible recharge due to precipitation, and showed a minimal general decline. The magnitude of water level response to changes of barometric pressure, although discernible, varied at each borehole. The zone below the packer showed either a steady decline or stabilization in water level for the time period monitored.

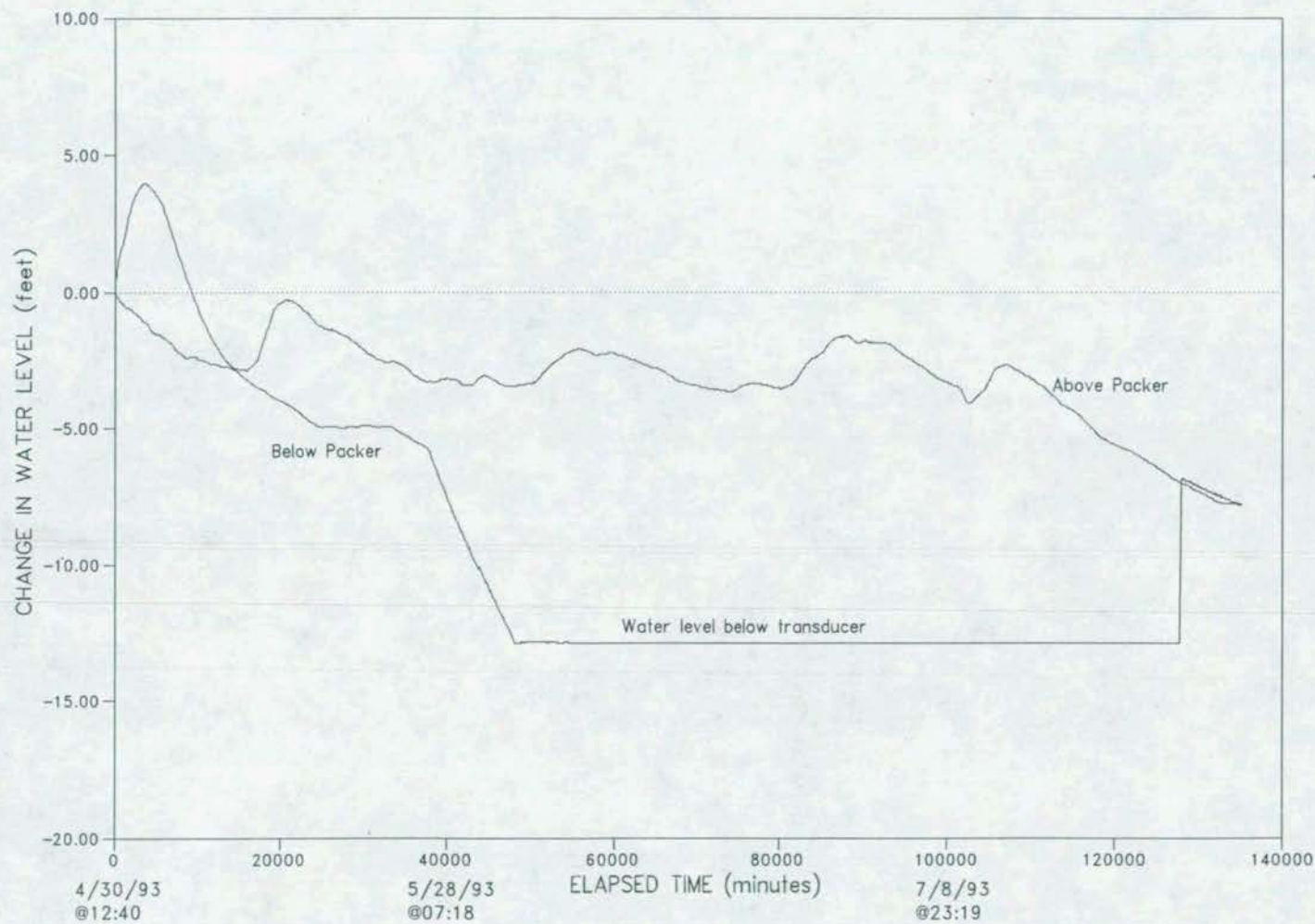


Figure 5.2. Water levels above and below packer in borehole 0348, April 30 to July 31, 1993.

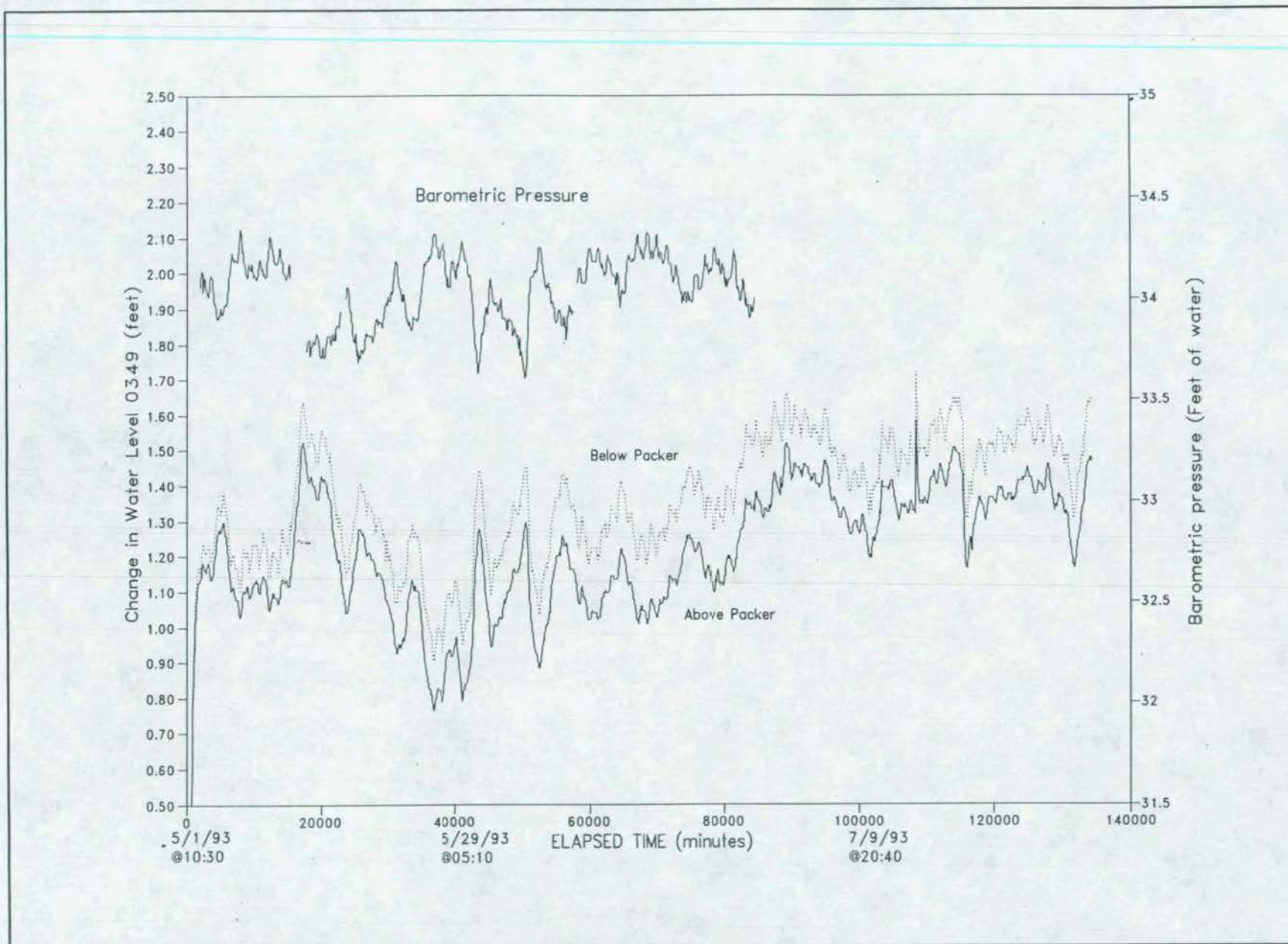


Figure 5.3. Correlation between water levels and barometric pressure in borehole 0349.
Water levels shown above and below packer, April 30 to July 31, 1993.

The water levels in borehole 0349 above and below the packer reacted simultaneously with barometric pressure changes (Figure 5.2). This is thought to be the result of either an insufficient packer against the borehole or that the packer was set too high in the borehole and fractures extend below the level of the packer. The high barometric efficiency of borehole 0349 (52 percent) attributed as much as 0.6 ft change in water level (Figure 5.3) superimposed upon a generally decreasing water level trend. The water level monitoring and falling head tests information correlate well with geophysical and lithology differences between the Main Hill and SM/PP Hill.

5.3. ANALYSIS OF PUMPING DATA FROM THE NORTH TRENCH

As part of the efforts to estimate or calculate permeabilities of the fracture carapace, existing data concerning measured groundwater flow on the Main Hill was examined. One set of data is that concerning the volume of water extracted from a trench on the north part of the Main Hill. The objective of reviewing the pumpage data from the north trench sump was to calculate a coefficient of permeability for the near-surface bedrock fracture zone on the Main Hill.

As part of an initial investigation to study the bedrock characteristics in the vicinity of identified seeps, a trench was excavated into the bedrock on the north side of the Main Hill, just east of the steep north slope. The north trench begins near the hilltop security fence gate and extends southwest approximately 650 ft (see Figure 4.1 in the Site Scoping Report: Volume 2 - Geologic Log and Well Information Report [DOE 1992c]). The excavation was 4 ft wide and 23 ft deep. It was constructed with a slight slope toward a manhole-covered vertical concrete pipe equipped with a submersible pump and flowmeter. The well is known as well 0712 (DOE 1992c). The trench was backfilled to within 3 ft of the surface with pea size gravel prior to placing 2-to-3 ft of clay and asphalt for surface sealing.

Periodically, as part of the environmental monitoring program for site operations, water samples are collected from the north trench. During the sample collection activities, the flowmeter is read and a total volume of water pumped since the last meter reading is calculated. These water volume data (Table V.2) were used to calculate the fracture bedrock permeability.

Table V.2 Measured Discharges in the North Trench, August 1993

Date of Reading	Gallons
8/05/93	455
8/12/93	370
8/19/93	420
8/31/93	340
Total for Month	1,585

5.3.1. Results

The north trench possesses a known surface area that contributes groundwater to the collection sump. An estimate of permeability is calculated using Darcy's Law. Simply stated:

$$Q = KiA$$

where:

Q = rate of flow (L³/t)

K = permeability (L/t)

i = hydraulic gradient (non-dimensional)

A = area normal to the direction of flow (L²)

Because of the north trench location so near the steep slope of the bedrock on the Main Hill and the apparent north-northwest flow of the groundwater in the bedrock, only the south, east, and west walls of the trench are considered in the calculation of area. The area (A) was determined to be 15,134 square ft.

The hydraulic gradient (i) in the vicinity of the north trench was determined from water level measurements made in September 1993 in bedrock wells 0113 and 0114. These wells were selected since they were completed in the near surface bedrock, were located near the north side of the Main Hill, and were sufficiently separated (575 ft) to allow the calculation of a low hydraulic gradient. Using this information, the value for i was calculated to be 0.00078 in the northeast direction.

It was assumed the total flow measured from the north trench flowmeter occurred more or less continually during the month of August 1993. This assumption was made since rainfall was minimal during this period. A flow rate (Q) was determined to be 7.09 cubic ft/day.

Substituting the calculated values into Darcy's equation, a permeability of 0.60 ft/day was determined from the August 1993 north trench discharge data.

5.3.2. Interpretation

Analysis of the flow rate into the north trench was used to provide additional information on the permeability of the fracture carapace on the Main Hill. A permeability was determined at the trench face using Darcy's Law. The saturated portion of the bedrock is assumed to be a porous medium. A

bedrock groundwater gradient was calculated to be 0.00078 ft/ft which is equivalent to 4 ft per mile. This is in general accordance with regional structural information discussed in subsection 3.7. The permeability determined using Darcy's law is 0.6 ft/day, within the same range determined from the falling head tests described above.

These data are also consistent with the packer tests previously conducted. As part of the Site Description and Safety Assessment (Dames & Moore 1973) field permeability tests were performed at 10-ft intervals through the entire 200-ft length of the boreholes on both the Main and SM/PP Hills. Results from the shallowest measurements are considered indicative of conditions in the fracture carapace. The tests indicated that the bedrock within the fracture carapace had permeabilities that ranged from 2.05 to 7.65 gals/day/ft² (0.27 to 1.02 ft/day), certainly within the range calculated for this report.

5.4. DISCUSSION OF ESTIMATES OF HYDRAULIC CHARACTERISTICS OF THE FRACTURE CARAPACE AND BEDROCK

Based on the available data, the fracture carapace and underlying bedrock have different hydraulic characteristics. The fracture carapace is described in other sections of this report as extending to about 100 ft below land surface on the Main Hill and about half that on the SM/PP Hill. The fracture carapace is generally described as a zone of fractured rock that possesses secondary permeability due to fracture flow. It is subdivided into an upper part of interconnected fractures that appear to be unsaturated and a lower part of poorly interconnected fractures that appear to be saturated with groundwater. The bedrock underlying the fracture carapace has primary permeability which is low in relation to the fracture carapace. Water levels in the fracture carapace may fluctuate in response to recharge from precipitation and there is some magnitude of fluctuation caused by the change in barometric pressure.

The techniques used to assess the hydraulic characteristics of the bedrock did not differentiate between the upper and lower parts of the fracture carapace. Falling head tests results show that the fracture carapace has permeabilities from 0.09 to 0.9 ft/day. Analysis of the north trench provided a permeability estimate of 0.60 ft/day. These data are consistent with previous packer test results that indicated that the fracture carapace had permeability of 0.27 to 1.02 ft/day (Dames and Moore 1973).

Flow rates determined from the heat pulse flow method and the falling head method both measured the maximum flow at borehole 0348. Boreholes 0350 and 0355 had 10 times less flow than 0348 and 0349. The greater presence of flow in the bedrock carapace of the Main Hill correlates well with the location and existence of seeps found on the site. Seep 601 located on the southwest corner of

the Main Hill was measured in 1987 and 1988 to have a flow of approximately 1 gallon per minute (DOE 1992a). The maximum flow rate from the falling head test was 0.34 gpm at 0348. These values are within an order of magnitude and are a good representation of the bedrock carapace flow. Few seeps are known to exist on the SM/PP Hill and no discharge rates have been measured.

Results of the borehole flowmeter tests and fracture studies indicate that permeability decreases with depth within the fracture carapace. The results of the falling head tests and north trench analysis suggest relative maximum permeabilities of the upper part of the fracture carapace. In the revised conceptual model of the bedrock flow system, permeability of the fracture carapace is believed to decrease to bedrock values through the lower part of the carapace. The lower boundary of the fracture carapace depicted in Plate 3 is interpreted to indicate a no-flow boundary, below which permeability is restricted to primary values of the bedrock.

The general water level decline in the bedrock boreholes and lack of water level fluctuation indicates that very little flow occurs in the bedrock below the fracture carapace. As part of Site Description and Safety Assessment, Dames and Moore (1973) conducted laboratory permeator tests and field permeability tests. The laboratory permeameter results from samples from three boreholes indicated values of vertical permeabilities of less than 10^{-8} gallons per day per square ft (2×10^{-9} ft/day) and that greater than 500 psi was necessary to start the flow of water through the rock (Dames and Moore 1973). The field permeability tests were performed at 10-ft intervals through the entire 200-ft length of the boreholes on both the Main and SM/PP Hills. The tests indicated that the bedrock below the fracture carapace had permeabilities less than 0.01 to 0.22 gals/day/ft² (1.3×10^{-3} to 2.9×10^{-2} ft/day). Borehole 1 on the SM/PP Hill had an average permeability of 0.08 gals/day/ft² (1.1×10^{-2} ft/day) and borehole 2 on the Main Hill had an average permeability of 0.07 gals/day/ft² (9.4×10^{-3}). Although these data vary over an order of magnitude, they are 2 to 3 orders of magnitude lower than the values calculated for the fracture carapace. The highest values at depth within the bedrock (0.22 and 0.17 in boreholes 1 and 2 on the SM/PP and Main Hills, respectively) occurred at approximately 150 ft. This depth approximates the zone of low EM conductivity (subsections 4.12 and 4.13) at about 700 ft elevation MSL. This zone consists of interbedded limestone and shale and is apparently more permeable than the surrounding shale beds.

The permeability of the fracture carapace and bedrock that underlie the Mound Plant is at least three orders of magnitude less than the Buried Valley aquifer. The fracture carapace has permeabilities values from 0.09 to 0.9 ft/day and the underlying bedrock has permeabilities that range from 1.3×10^{-3} to 2.9×10^{-2} ft/day. In sharp contrast, The Buried Valley aquifer has an average permeability of 500 to 1500 ft/day as calculated from the 1993 OU 1 aquifer test (DOE, 1993c).

6. REVISED CONCEPTUAL MODEL OF THE BEDROCK FLOW SYSTEM

The rocks of the Cincinnati Series form the bedrock in the area of Mound Plant. These rocks are composed of relatively undeformed shales and interbedded limestones that possess little primary permeability. It has long been recognized that water is stored and transmitted principally in the shallow portions through fractures and weathered bedding planes. Sedam and Stein (1970) reported that no fresh water aquifers exist below the upper parts of the Cincinnati Series. Salinity was noted to increase rapidly with depth because of low permeabilities that inhibit fresh water replacement of connate brines. In the vicinity of Mound Plant, the approximate elevation of the base of potable water was 800 ft MSL (Sedam and Stein 1970). As part the Site Description and Safety Assessment, Dames and Moore (1973) conducted field permeability tests. These tests indicated that groundwater flow was limited to the upper 30 to 35 ft of weathered bedrock (elevations of approximately 830 to 850 ft MSL at Mound Plant).

A conceptual model of the bedrock flow system, based on observations in a series of shallow excavations, was presented by Terran (1987) and repeated in the OU 9 Site-Wide Work Plan (DOE 1992a). This model was one in which shallow groundwater on the hill tops percolated through the weathered bedrock, along fractures and bedding planes until it hit one of three thick shale layers where it was diverted laterally. This diversion gave rise to groundwater seep along the hillsides. Relatively thick shales were identified at approximately 860-, 820- and 780-ft elevations MSL by Terran (1987). The 820-ft elevation is one typically associated with the largest hillside seeps, number 0601 (DOE 1992a). This paper presents a large body of physical data that serves to refine the conceptual model of bedrock flow. The revision does not significantly change the model, but provides additional focused information. However, no single, thick shale beds are now believed to be responsible for inhibiting vertical migration of groundwater.

The initial conditions of the conceptual model indicate that the bedrock at the Mound Plant consists of a thick sequence of interbedded shales and limestones that are relatively undeformed. The lithology possesses little primary permeability, but has enhanced permeability due to bedding plane fractures and through-penetrating vertical fractures that decrease in frequency and interconnection with depth from the surface. In this report, the fracture network is called the fracture carapace. The upper part of the fracture carapace is interpreted to extend from the surface to a depth of about 50 ft on the Main Hill and a depth of about 25 ft on the SM/PP Hill. This upper zone exhibits evidence of frequent, interconnected fractures that are partially saturated with groundwater; it has a calculated permeability of about 1 ft/day. The lower part of the fracture carapace is interpreted to extend from a depth of approximately 50 ft to a maximum depth of approximately 100 ft on the Main Hill and a depth of approximately 60 ft on the SM/PP Hill. This lower zone exhibits evidence of less frequent, poorly

interconnected fractures that are probably water saturated. The degree of interconnection is interpreted to decrease with depth through the lower zone until the magnitude of permeability approaches the primary value of the rocks, approximately 0.01 ft/day. The base of the fracture carapace is interpreted to be a no-flow boundary. Below this boundary, groundwater flow is almost completely precluded by the exceedingly low primary permeability.

In the revised model (Plate 5), infiltration of surface water migrates vertically until it reaches the water table. Bedding plane fractures may intersect flow to divert groundwater horizontally, but the dominant migration is believed to be downward to the water table. Within the saturated fractures, the decreasing interconnection acts to reduce vertical permeability and groundwater flow is then diverted laterally through the shallower, more hydraulically conductive portions of the rock until it emerges as a hillside seep. Horizontal flow is controlled largely by open vertical fractures and bedding plane fractures that create an interconnected network. In the lower part of the fractured carapace, fractures are assumed to be present but are not interconnected, so that permeability is reduced and capillary forces are probably dominant. Groundwater seeps may be present at any elevation in which saturated fractures occur, but flow at lower elevations is likely to be so low as to be imperceptible. Since the water table, i.e., the elevation at which fractures are saturated may change with time, individual seeps may change flow rates. The near vertical outcrop at the railroad cut may seep water over the entire exposure (Plate 5). Where the water table intersects fill or glacial deposits, groundwater may flow along the interface contact as the glacial tills may be less permeable than the fracture carapace.

Horizontal flow may be anisotropic. The major fracture orientations north 20 degrees east and north 60 degrees west are probably the dominant flow directions. Bedding plane fractures and minor fractures oriented north 40 degrees west may influence flow within the fracture carapace. The detailed character of horizontal flow components cannot be determined with the existing data and are best resolved by Operable Unit specific investigations.

At least within the fracture carapace, individual shale beds do not appear to impede the vertical flow of groundwater. The fracture carapace affects rocks of both limestone and shale affinities. On the south flank of the Main Hill, rocks of the Waynesville Formation (70 percent shale) are as intensely fractured as the rocks of the overlying Liberty Formation (50 percent shale) on the topographically higher central part of the hill. Similar relationships are apparent on the SM/PP Hill.

The geometry of the fracture carapace strongly correlates with the geometry of the fresh water carapace indicating that the fractures are the principal control of shallow groundwater flow. Rocks in the upper part of the fracture carapace have been altered by processes of groundwater flow. A mantle of fresh, meteoric water is apparent in the upper zones of all boreholes. Rocks encountered

in the deeper portions of the boreholes retain much of the signature of the marine salts that were trapped during deposition; they have relatively high electrical conductivities. This fresh water carapace is attributed to the leaching of the original salts from the rocks by meteoric water transmitted through fractures. The fact that rocks below the fracture carapace retain much of the high conductivities associated with marine rocks attests to the low primary permeability of the shales present.

In the revised model, the Main Hill is interpreted as a different hydrogeologic environment than the SM/PP Hill. The Main Hill is viewed as much more intensely fractured than the SM/PP Hill, the fracture carapace extends to greater depths and measured absolute groundwater flow rates within the fracture carapace are greater. Likewise, the fresh water carapace is observed to extend to greater depths, approximately 100 ft, on the Main Hill and about twice that on the SM/PP Hill.

7. SUMMARY OF RECOMMENDATIONS

7.1. LITHOLOGY

Lithologic and stratigraphic studies indicate that sufficient information exists concerning the bedrock beneath the Mound Plant. No additional lithologic investigations for the OU 9 hydrogeologic studies are warranted.

7.2. FRACTURE STUDIES

The strong correlations between fracture frequency, water flow measurements, and the alteration characteristics of the marine bedrock indicate that the objectives of the OU 9 bedrock studies have largely been obtained. Two outstanding issues appear to remain.

First, there is little data to indicate that the fracture orientations of the SM/PP Hill are indeed the same as the Main Hill. It is suggested that additional limited investigations be conducted on smaller outcrops on the SM/PP Hill complex and perhaps the surrounding community to ascertain the dominant orientations of fractures.

Second, continuous bedrock cores are stored at Miami University, Oxford, Ohio. The identification of these cores was not made in time to include data in this report. It is recommended that the logs be examined for fracture characteristics. These cores may provide an important auxiliary data for the fracture studies.

7.3. BOREHOLE GEOPHYSICS

The results of the extensive suite of borehole geophysics performed indicate that sufficient information exists on the characteristics of the bedrock flow system beneath Mound Plant to satisfy the objectives of OU 9. No additional investigations are recommended under OU 9. However, site specific investigations concerning hydraulic characteristics of the fracture carapace may be warranted by other OUs as source term investigations proceed.

7.4. ESTIMATES OF HYDROLOGIC CHARACTERISTICS

The results of the limited hydrologic testing conducted during this and previous investigation indicate that the objectives of the OU 9 bedrock studies have largely been obtained. However, one of the

principal objectives of OU 9 is to identify the presence of a regional water pressure surface that may be in hydraulic communication with the Buried Valley aquifer. A possible confined regional water pressure surface may be present at an elevation of approximately 650 ft MSL, in the upper part of the Mount Auburn and Oregonia Formations. It is recommended that water from the lower portion of the boreholes be removed to the extent possible and allowed to recharge under natural conditions and instrumentation installed to continuously monitor the recharge. This will supply data for calculation of hydraulic conductivity.

The final disposition of the boreholes requires considerable thought. The amount and detail of lithologic, hydraulic, and geophysical data for these bedrock locations are unsurpassed anywhere else on the Mound site. It is recommended that the closure plan for these boreholes evaluate options which allow the installation of specialized instrumentation for obtaining additional hydrogeologic data in lieu of simply sealing with grout.

Consideration will be given to additional hydraulic testing in the five remaining open bedrock boreholes at the Mound Facility; both active and passive testing techniques will be contemplated. An example of active testing techniques will include straddle packer tests in selected zones to better determine permeability. Another active test to consider will be a single-well tracer test to determine the effective porosity of the bedrock unit.

Passive monitoring is suggested to observe recharge rates and possible piezometric surfaces below the fracture carapace. Once the lower portion of the borehole has been isolated and evacuated of standing water, long-term water level recovery will be documented. This data will be analyzed in concert with other meteorological information to quantify groundwater movement.

Passive monitoring of groundwater temperature at many discrete intervals in the bedrock boreholes is suggested for at least one dry and wet season. Monitoring of this type is an inexpensive method that will provide temperature profiles for each discrete point. This monitoring will provide qualitative information concerning recharge to the bedrock system over a period of time.

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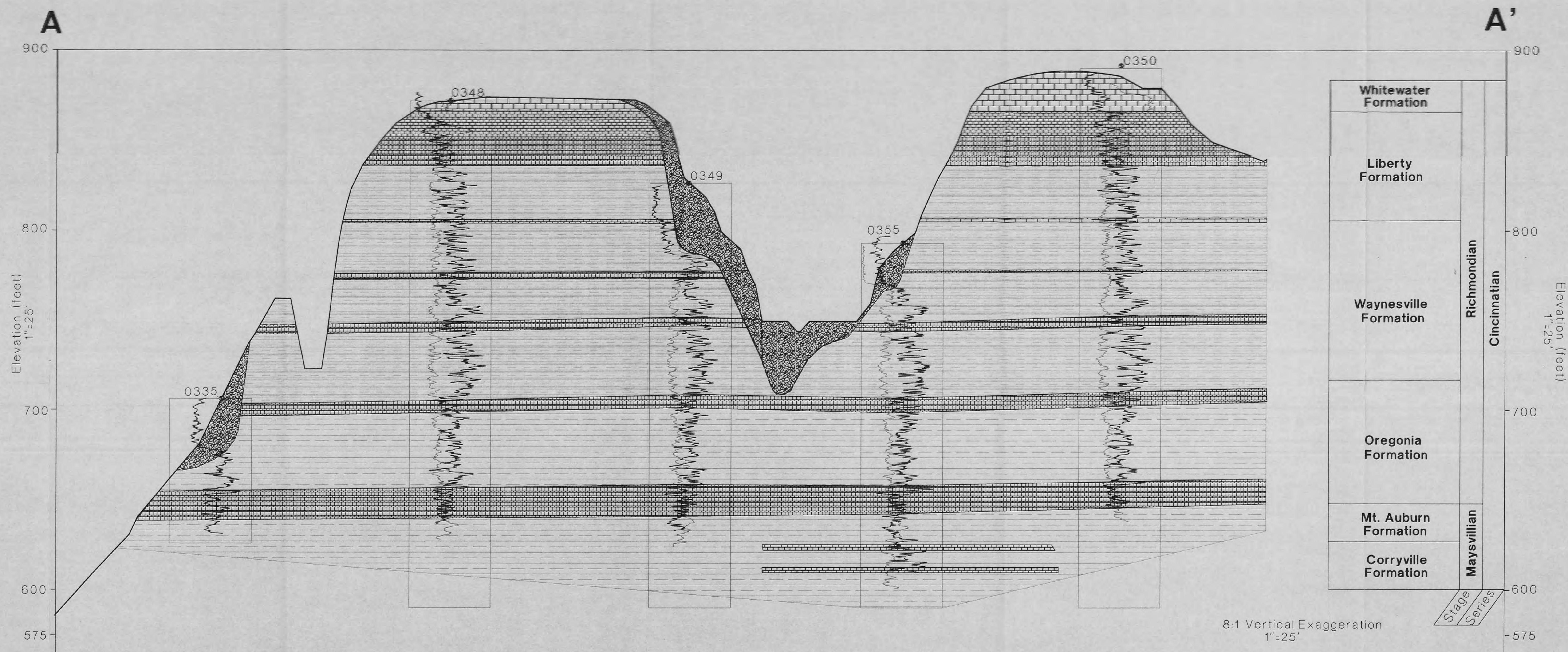
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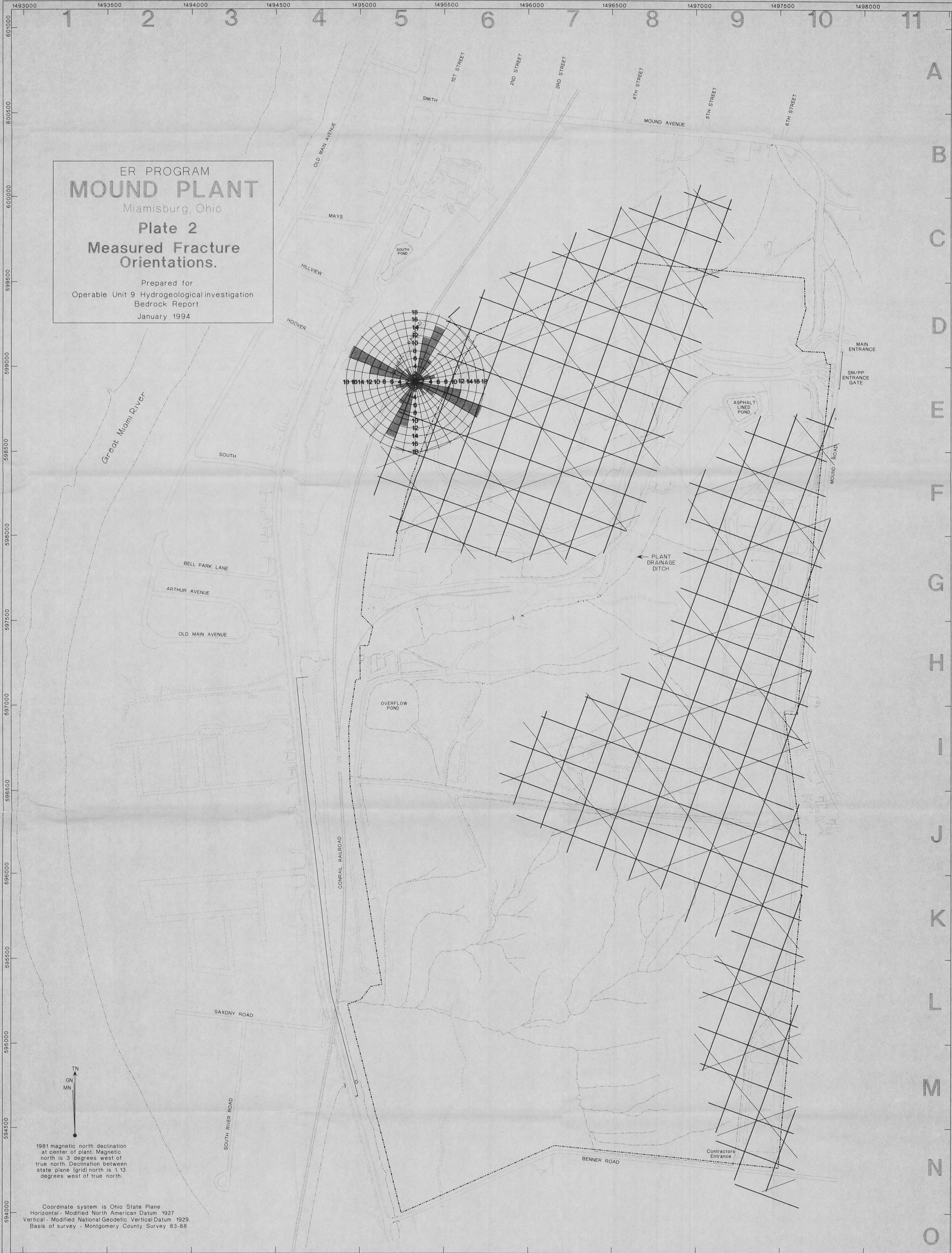
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ER PROGRAM
MOUND PLANT
 Miamisburg, Ohio
Plate 1
Lithologic cross section
of Mound Plant Bedrock
 Prepared for
 Operable Unit 9 Bedrock Report
 January 1994

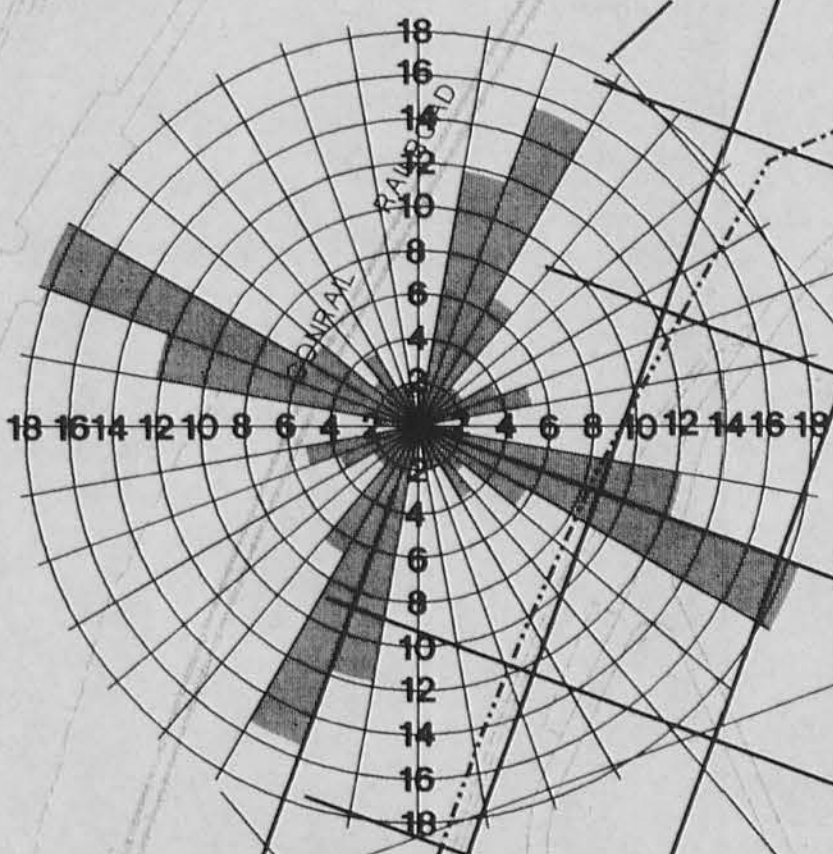
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 Horizontal Scale in Feet

1981 magnetic north declination
 at center of plant. Magnetic
 north is 3 degrees west of
 true north. Declination between
 state plane (grid) north is 1.13
 degrees west of true north.





ER PROGRAM
MOUND PLANT
Miamisburg, Ohio
Plate 2
Measured Fracture Orientations.
Prepared for
Operable Unit 9 Hydrogeological investigation
Bedrock Report
January 1994



1981 magnetic north declination
at center of plant. Magnetic
north is 3 degrees west of
true north. Declination between
state plane (grid) north is 4.13
degrees west of true north.

Coordinate system is Ohio State Plane
Horizontal - Modified North American Datum 1927
Vertical - Modified National Geodetic Vertical Datum 1929
Basis of survey - Montgomery County Survey 83-88

Legend

53

- Structures
- Paved roadway
- Unpaved roadway
- Railroad
- Water course
- Fence
- Retaining wall
- Mound Plant boundary
- Contour line



Major Fracture set

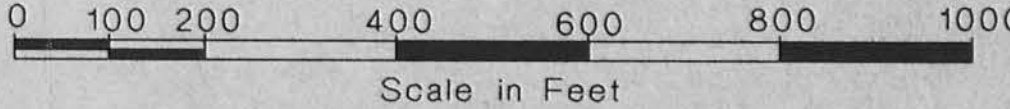


Minor Fracture set

Notes

- The electronic base map data file was obtained by WESTON from Woolpert Consultants, Inc., Dayton, Ohio. The data were photogrammetrically compiled from aerial photography dated 12/08/85.
- WESTON converted MOUND plant coordinates to Ohio State Plane Coordinates using an algorithm provided by Oak Ridge National Laboratory, Grand Junction Project Office.
- Area west of Dayton-Cincinnati Pike was digitized from a hand drafted map, dated 3/12/86 from Monsanto Research Corp.
- Fracture orientations projected across site from measurements taken at railroad cut outcrop (shown as rose diagram)
- Extend of fractures depicts approximate base of fracture carapace: 750 feet MSL on Main Hill; and 820 feet MSL on SM/PP Hill.

Contour interval 10 ft.



ER PROGRAM MOUND PLANT

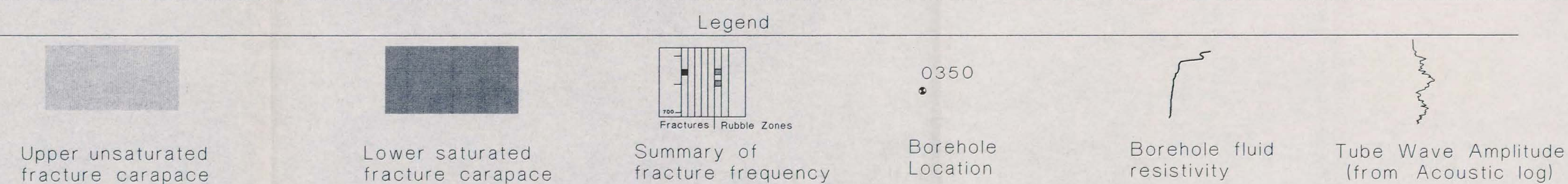
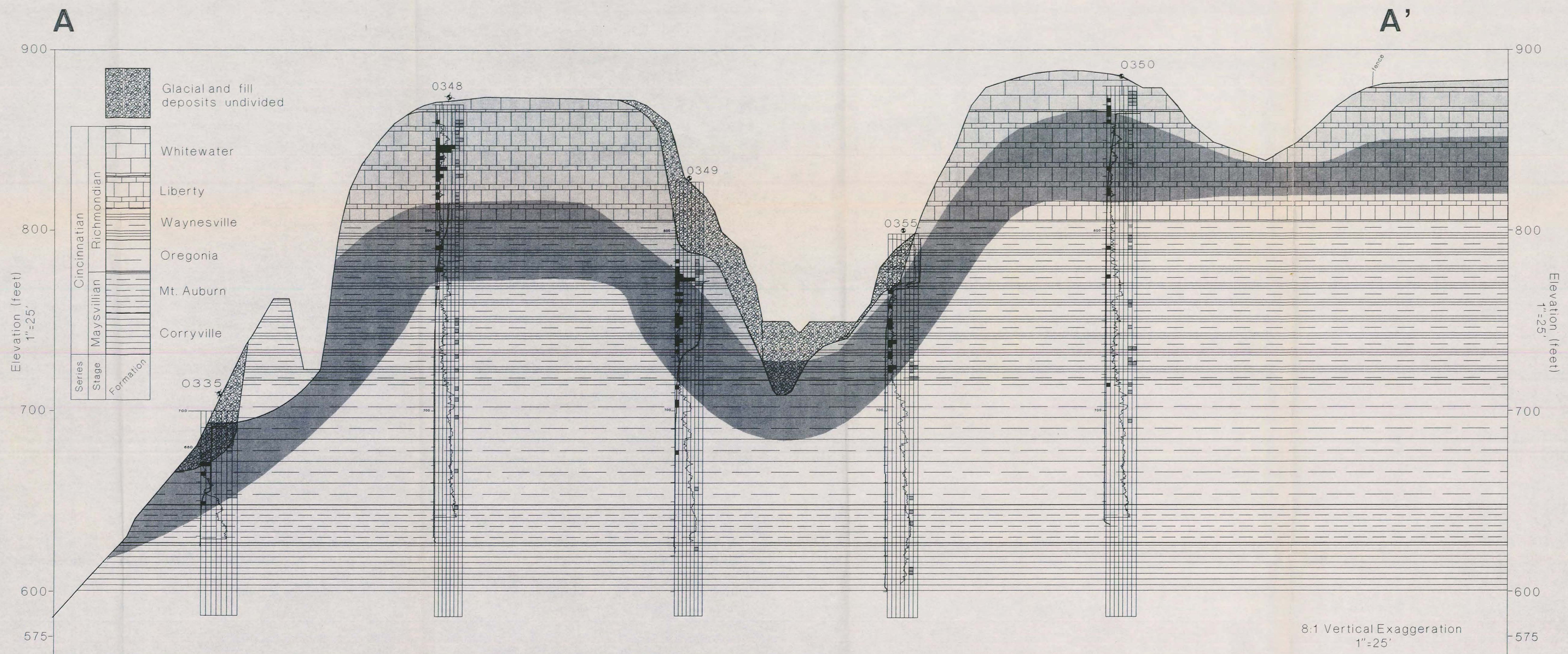
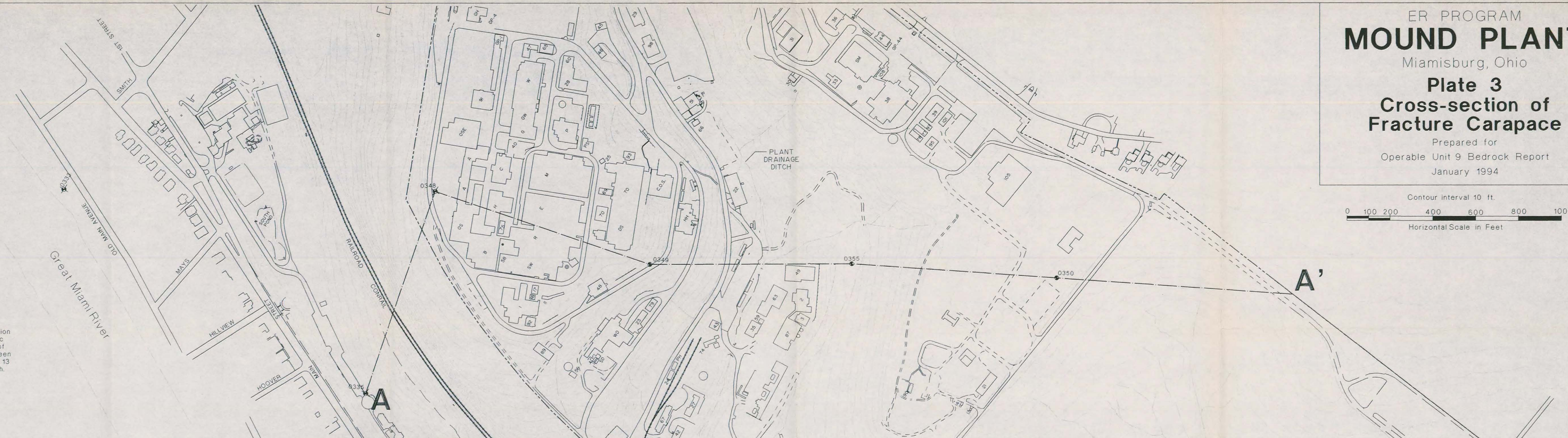
Miamisburg, Ohio

Plate 3 Cross-section of Fracture Carapace

Prepared for
Operable Unit 9 Bedrock Report
January 1994

Contour interval 10 ft.
0 100 200 400 600 800 1000
Horizontal Scale in Feet

1981 magnetic north declination
at center of plant. Magnetic
north is 3 degrees west of
true north. Declination between
state plane (grid) north is 1.13
degrees west of true north.

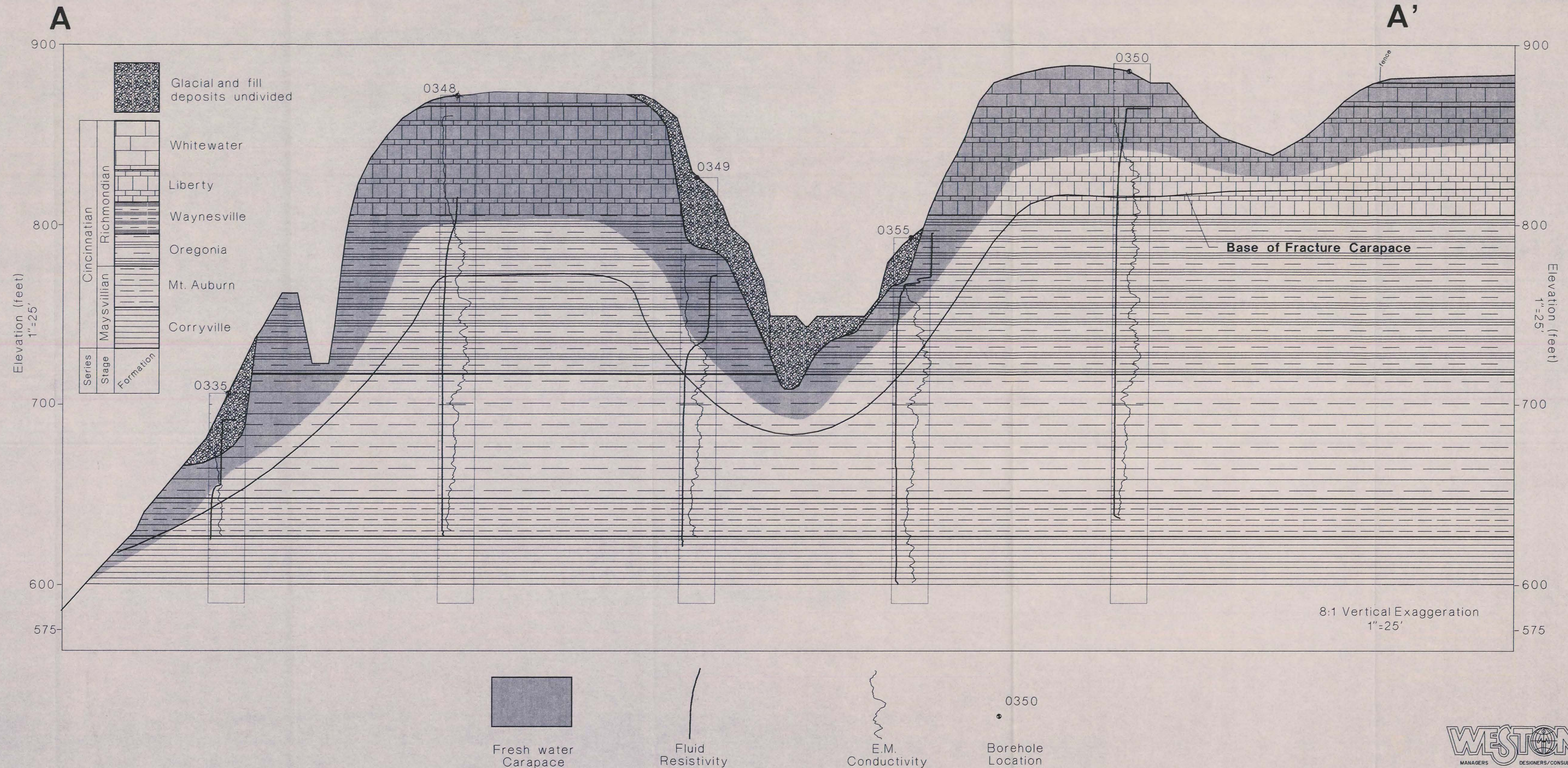


ER PROGRAM
MOUND PLANT
 Miamisburg, Ohio
Plate 4
Cross section of
weathering profile
(Fresh water Carapace)

Prepared for
 Operable Unit 9 Bedrock Report
 January 1994

Contour interval 10 ft.
 0 100 200 400 600 800 1000
 Horizontal Scale in Feet

1981 magnetic north declination
 at center of plant. Magnetic
 north is 3 degrees west of
 true north. Declination between
 state plane (grid) north is 1.13
 degrees west of true north.



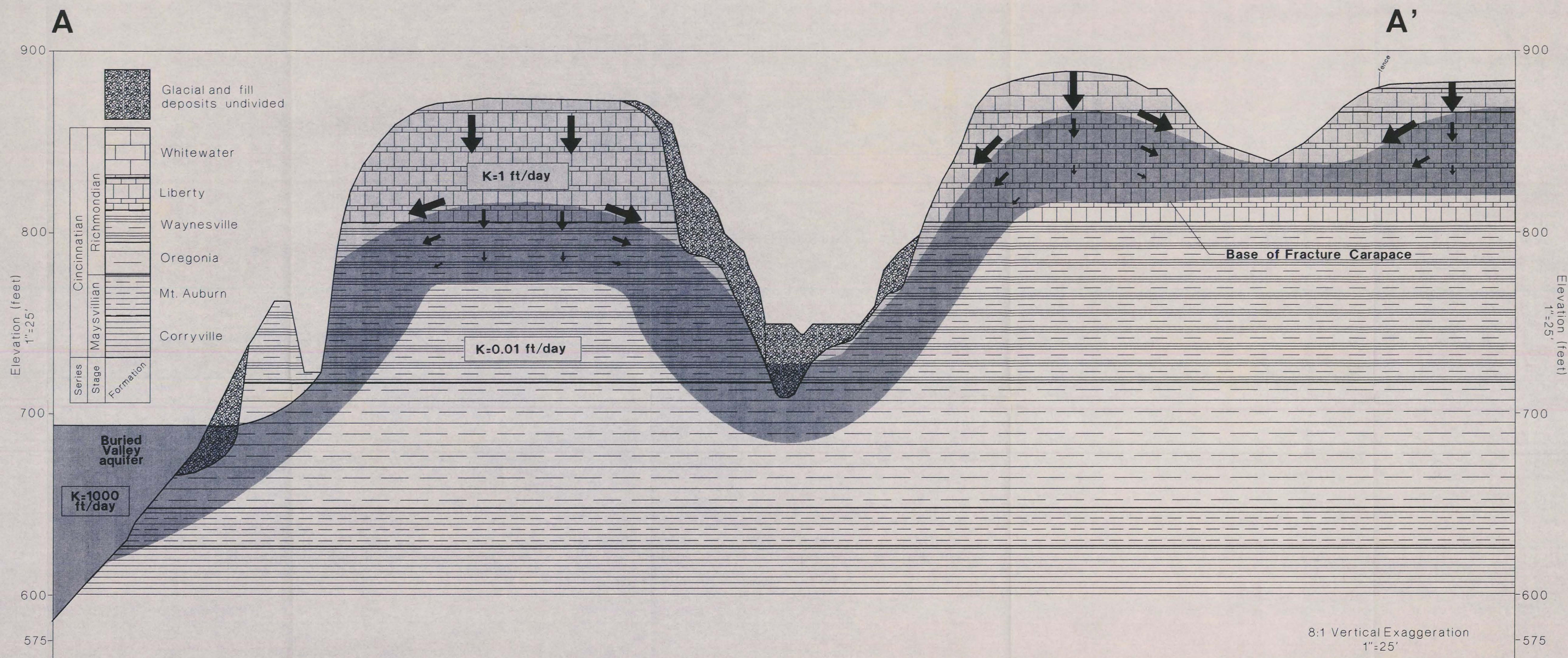
ER PROGRAM
MOUND PLANT
 Miamisburg, Ohio
Plate 5
**Conceptual model of
 bedrock flow system**

Prepared for
 Operable Unit 9 Bedrock Report
 January 1994

Contour interval 10 ft.

0 100 200 400 600 800 1000
 Horizontal Scale in Feet

1981 magnetic north declination
 at center of plant. Magnetic
 north is 3 degrees west of
 true north. Declination between
 state plane (grid) north is 1.13
 degrees west of true north.



8:1 Vertical Exaggeration
 1"=25'

Legend

Upper unsaturated
 fracture carapace

Lower saturated
 fracture carapace

Groundwater flow direction.
 Size of arrow indicates relative
 magnitude of permeability.

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