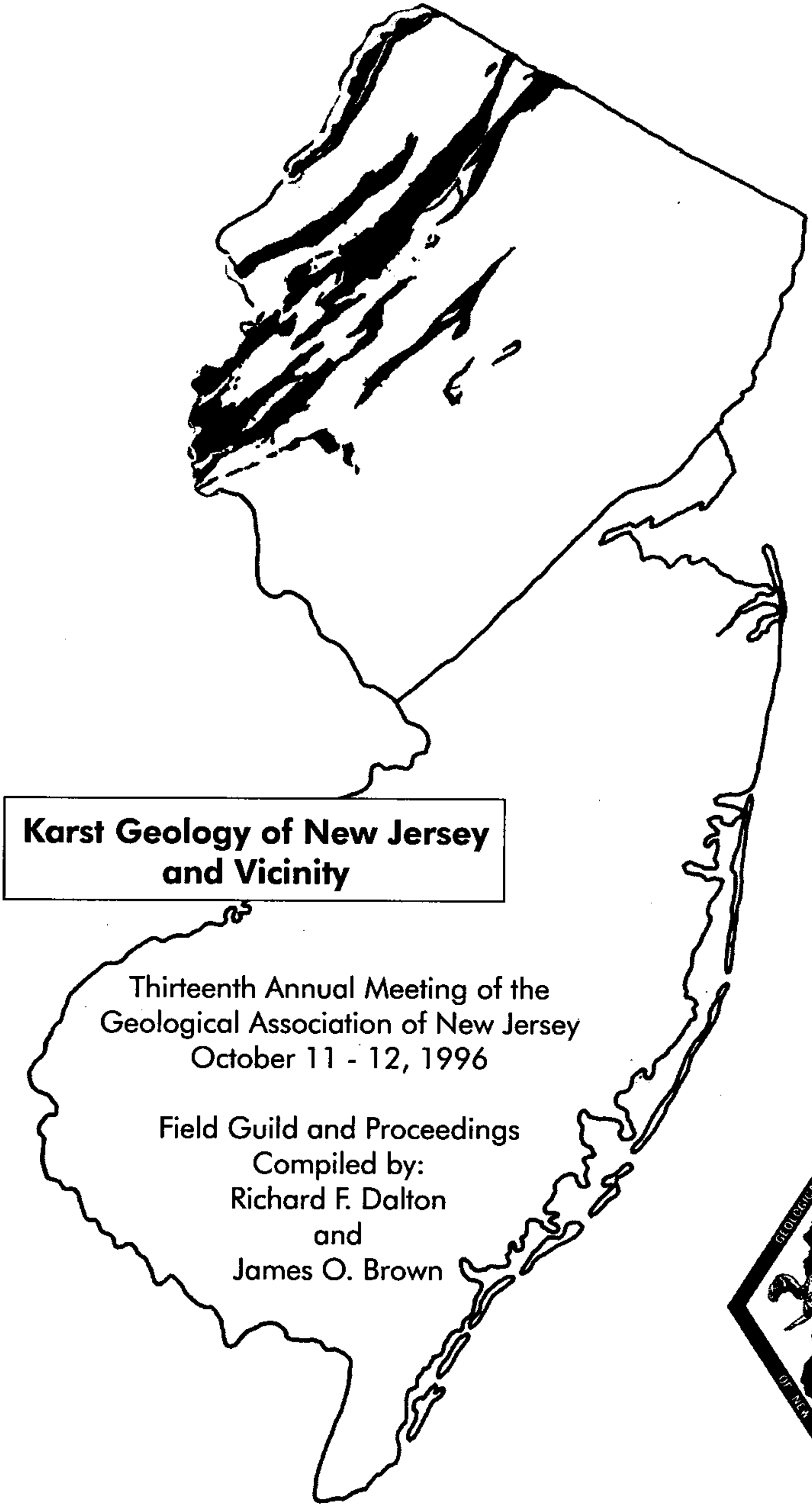

Karst Geology of New Jersey and Vicinity

Thirteenth Annual Meeting of the
Geological Association of New Jersey
October 11 - 12, 1996

Field Guild and Proceedings
Compiled by:
Richard F. Dalton
and
James O. Brown

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XIII Annual Meting

Geological Association of New Jersey

October 11 & 12, 1996

Whippany, New Jersey

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GANJ V	1988, Rider College, Lawrenceville, NJ
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GANJ IX	1992, Quality Inn, Somerset, NJ
GANJ X	1993, Ledgewood Inn, NJ
GANJ XI	1994, Quality Inn, Somerset, NJ
GANJ XII	1995, William Paterson College of NJ, Wayne, NJ

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FOREWORD

Why Karst? The reason is both one of chance and need. The chance stems from Haig Kasabach, Chief of the New Jersey Geological Survey, being one of the field trip chairman for the annual national meeting of the Association of Engineering Geologists. If you missed it, the AEG meeting was held in the last week of September in North Brunswick, New Jersey. The junior editor of this guidebook, being president of GANJ and an active AEG member, initially approached the AEG with the idea of joint meeting (if these two geologic selections are not enough, Pennsylvania's annual meeting was last week and New York is next week). Logistics and Haig having more ideas for field trips than allotted time lead to Jim Brown contacting Richard Dalton, and the rest is now GANJ the thirteenth.

The need comes from there never being a field guide for north Jersey devoted strictly to Karst geology. Some twenty years ago, geologists from the state of New Jersey ran the Annual meeting of the 42nd Field Conference of Pennsylvania Geologists and "karsification" was discussed by Richard Dalton (Markewicz et al., 1977). Subsequently, at least two previous GANJ meetings (Grossman, 1989; Kroll and Brown, 1990) had respective stratigraphic and hydrogeologic field stops in Karst terrains. The senior compiler of this field guide also contributed to both of these meetings. The following updates some of the material previously presented in these publications. In addition at our Friday October 11th afternoon seminar "new" aspects of studying karst terrains with seismic geophysical methods (Costa *et al.*, herein) and radon in caves (Umanski, herein) are presented along with other karst related papers. It is our hope that this guidebook will become a standard reference for geologists, engineers and speleologists for years to come who find themselves in Karst terrain in northern New Jersey and vicinity.

We wish to acknowledge the support of the following in helping us organize this meeting and preparing this guidebook:
the GANJ executive committee;
Haig Kasabach and the State Geologic Survey;
Mark Zdepski and the staff at JMZ Geology; and
Mike Hozik and Stockton State College (for printing).

Richard Dalton,	New Jersey Geologic Survey, Trenton
and	
James O. Brown,	JMZ Geology, Flemington and Stockton State College, Pomona

KARST TOPOGRAPHY - A GENERAL OVERVIEW

Howard R. Craig, P.G.

INTRODUCTION

New Jersey presents to the viewer a unique opportunity to experience a virtually complete spectrum of geologic time if one were to traverse the state from northwest to southeast. Structurally and paleontologically, New Jersey geology is as diverse as its formations. Rock units ranging from Precambrian gneisses and Paleozoic carbonate and clastic sedimentary sequences in the northwest are bounded by Mesozoic sedimentary redbeds, diabases and basalts. These are, in turn, bounded on the southeast by later Mesozoic and Tertiary unconsolidated deposits.

Generally, karst topography is not thought of as an important aspect of New Jersey's geologic features. Little thought is given to the underlying features and their topographic expressions of the carbonate terrains of western and northwestern regions of the state. In fact little, if anything, was written on the topic by Rogers (1840), Kitchell (1856), Cook (1868) and other early geologic writers in New Jersey. The fact remains that karst terrains in New Jersey are of great importance in the western areas of our state and that a great many features associated with karst topography can be found throughout the region underlain by carbonate rocks.

The term karst topography, to those trained in the geological sciences, embodies a complex interaction of water and rock chemistry and the mechanics of rock structure and groundwater hydrogeology. To most people, and admittedly to geologists and earth scientists, the first vision to come to mind is one of extensive cave systems and elaborate, ethereal structures. Mental images of deep interconnected passage ways, leading to rooms and chambers filled with stalactites, stalagmites, pipe organs as well as fragile and intricate drip and flow structures immediately fill the imagination. Certainly, names like Mammoth Caves in Kentucky, Luray Caverns in Virginia and Carlsbad Cavern in New Mexico and, to a lesser extent, Howe and Secret Caves in New York embody these images. These locales however, are only the final manifestations of a long term process that starts humbly in small rock joints and fractures with an almost imperceptible flow of water.

Karst topography encompasses a broad suite of geomorphological and structural features and encompasses unique hydrogeological and environmental regimes. This paper will bring these aspects together and describe them to provide the reader with a clearer picture and understanding of karst topography. The aspects of karst formation and development, surface and underground expressions and economic and environmental impacts will be discussed.

WHAT IS KARST TOPOGRAPHY

Generally, karst features can be defined as the topographic expressions of the dissolution of underlying bedrock which in most of the notable areas is carbonate. These features include sink holes, pinnacled bedrock surfaces, sinking creeks, natural tunnels, caves and various topographical expressions of the underlying bedrock surface. The term karst, which is applied as a general description of this type of terrain, comes from a region of the former Yugoslavia. This region is composed of a narrow limestone plateau in which there are numerous features which have developed as a result of bedrock dissolution. Although a great number of the terms associated with karst topography have come from this area, each region of the world, where these conditions exist, has contributed names to unique provincial features.

AREAS OF KARST DEVELOPMENT

Limestones underlie most of the karst areas of the world. Dolomites and dolomitic limestones also are common bedrock types where karst features have developed. Gypsum and rock salt are associated with karst topography to a much lesser degree, not necessarily because they are any less soluble but rather due to their limited areal extent. The presence of limestones or dolomites does not guarantee that karst topography will develop within an area. Other conditions, discussed below, must be fulfilled in order for the development of these features. Major areas of karst development within the United States can be found in the Great Valley region of Pennsylvania, Maryland, Virginia and Tennessee, a region from Indiana to Kentucky, the Florida carbonate areas and the Salem-Springfield region of Missouri (Thornbury, 1969).

Karst Formation

Karst topography forms as a result of a combination of several factors which are directly related to the physical and chemical properties of carbonate rocks. Water is the primary element in dissolution of carbonate rocks and the resulting development of karst topography. Water alone however, is not sufficient to guarantee karst development and the following conditions, as outlined by Thornbury (1969), should be met for karst topography to be well developed in an area.

- A soluble rock such as limestone or dolomite, must be present at or near the surface,
- The rock formation should be dense, highly jointed and thin bedded,
- The region should have moderate to abundant rainfall, and
- Entrenched valleys underlain by carbonate or other soluble rock units should be present to provide ready downward movement of water.

The presence of a soluble rock near the ground surface will permit the development of karst features seen at the ground surface. If the soluble rock unit is too deep then dissolution features may not be reflected at the surface. Similarly, if the soluble unit is overlain by an insoluble or less soluble rock unit, development of karst features will be retarded.

The soluble rock unit should be massive and well jointed to allow water to travel preferentially along these discontinuities. Continued action by water will result in a gradual enlargement of these pathways into well defined channels and voids which in time may be reflected in surface topography.

If a rock unit is porous with a high permeability, water will travel throughout the rock mass rather than along joints and fractures. In this case, there will be no preferential development of pathways and no karst development.

The primary means for development of karst topography is passage of precipitation through the soil column and into the groundwater regime. By virtue of this fact, moderate rainfall, at a minimum, is essential to the growth of solutional features. In arid areas, such as the southwest United States, carbonate rocks form prominent features in outcrops. They are, in the arid environment, more resistant to mechanical erosion than are clastic rocks and karst features either do not develop or are inconsequential in these areas. Those which do exist in arid regions are almost certainly relict features of previous climatic conditions.

The presence of valleys, underlain by carbonate rocks favors development of karst topography; however, this condition is not as important as the three previously discussed conditions. Upland areas underlain by relatively insoluble rocks will provide runoff to the valleys where, if the previous conditions are met, the ample supply of water will enhance the dissolution of the underlying carbonate rocks. Development of karst topography is dependent on circulating groundwater; moving water will dissolve rocks, standing water will not.

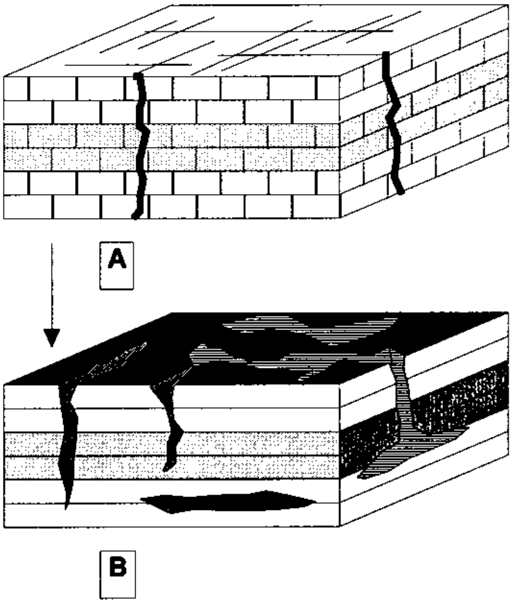

Figure 1. Development of Solutional Features;
A. Deposition of primarily horizontal carbonate rocks and the early development of joints and fractures.
B. Continued action by water along joints, fractures and bedding planes enlarges these structures into channels for continued and facilitated groundwater flow.

White et. al., (1995) have distilled the requirements for karst development into two properties; mechanical strength and chemical composition. Carbonates are resistant to physical change such as mechanical erosion; however, they are very susceptible to chemical processes. When there is a balance between the rates of physical and chemical weathering then the probability that karst topography will develop increases. If the rate of physical weathering is too rapid then rock material will be removed before there is time for chemical processes to work. In the same way, if the rate of chemical dissolution of the rocks is too rapid, then the karst features would be developed and destroyed in a short period of time.

Limestones and dolomites consist primarily of calcium carbonate with the addition of a magnesium component in the dolomites. Both limestone ($CaCO_3$) and dolomite ($CaMgCO_3$) are generally stable in pure water but with an increase in the acidity of water they become more soluble. Rain becomes more acidic as it passes through air and carbon dioxide (CO_2) is dissolved and carried with the precipitation. The normal atmospheric concentration of CO_2 is approximately 0.03 percent by volume (human activities tend to increase this percentage). Bacterial activity in soils can increase the percentage of CO_2 to ten percent or more. (White et.al., 1995) Once the acidity of water has been elevated then reaction with carbonate rocks can occur based on the following reaction.

$$\mathbf{CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3}$$

In this equation, acidified water reacts with the calcium carbonate to produce calcium and carbonic acid. This dissolution produces an irregular surface of clefts, grooves and pillars. Pinnacled bedrock surfaces is the comprehensive term used to describe these irregular surfaces, particularly where deformation of the bedrock has provided additional structures which become accentuated by dissolution. The reverse reaction can occur when the groundwater, saturated with calcium and CO_2, enters an air filled passage such as a cave. The groundwater may contain CO_2 at a higher partial pressure than the partial pressure in the cave atmosphere. Carbon dioxide will diffuse out of water entering the cave which, in turn, causes the water to become supersaturated with $CaCO_3$. The carbonate material is precipitated out of solution and is re-deposited as a result of this reaction giving rise to stalactites, stalagmites and other cave structures.

According to White et.al., (1995) a similar reaction can occur in waters rich in hydrogen sulfide (H_2S) such as those emanating from oil fields. Carbonate rocks are dissolved by sulfuric acid (H_2SO_4), produced by the mixing of the H_2S enriched waters and O_2 rich groundwater. The dissolved carbonate is then replaced by gypsum ($CaSO_4$) precipitated from the acidic groundwater. Subsequent reactions between the gypsum deposits and fresh groundwater will cause the gypsum to be dissolved leaving a series of solution channels or caves. This is illustrated by the following series of reactions.

$$\mathbf{H_2S + 2O_2 \leftrightarrow 2H^+ + SO_4^{-2}}$$

(production of sulfuric acid)

$$\mathbf{CaCO_3 + H^+ \leftrightarrow Ca^{2+} + HCO_3^-}$$

(dissolution of carbonate rock)

$$\mathbf{Ca^{2+} + SO_4^{2-} + 2H_2O \leftrightarrow CaSO_4 \bullet 2H_2O}$$

(deposition of gypsum)

As these chemical reactions proceed along joints, fractures and bedding surfaces in carbonate rocks, these planes of weakness are enlarged by continuing dissolution of rock material. If the karst forming conditions discussed previously are satisfied, then open spaces and voids will continue to be enlarged and eventually irregularities at the ground surface will develop and reflect these features. At this point an area can be said to have karst topography.

CHARACTERISTIC FEATURES OF KARST TOPOGRAPHY

The development of karst topography carries with it the formation of unique surface features which relate directly to the underlying bedrock. As discussed above, continued work by water will capitalize on planes of weakness in the bedrock. These planes eventually will be enlarged and their presence may be reflected in the development of geomorphological features such as sink holes, springs, sinking creeks and pinnacled bedrock surfaces to name a few. What follows is a discussion of the formation and features, both at and below the ground surface of the most prominent of these aspects of karst topography.

Sinkholes

The best known and most common karst feature is the sink hole. A sink hole is a topographic depression which can appear as a minor depression or can be over 100 feet in depth. The average depth however, usually does not exceed 30 feet. The horizontal extent of sinkholes, according to Thornbury (1969) ranges from a few square yards to several acres. In cross-section, sinkholes are generally funnel shaped with the broad end facing upward. Sinkholes are individual features; however, if the density of sinkholes in an area is sufficiently high, separate sinkholes will intersect and form *compound sinkholes*. A compound sinkhole will appear as a major depression over several acres with smaller sinkholes or depressions within its limit.

A sinkhole will often form a convenient avenue for surface water to enter the shallow groundwater regime. Over time, as material is washed into the depression, the sinkhole may become clogged with soil, rocks and debris. If this obstruction is sufficiently impermeable then water will cease to pass freely to the groundwater and will collect in the sinkhole. These features are called *sinkhole ponds* or *karst lakes*. (Thornbury, 1969)

The development of a sinkhole can generally be described as a function of dissolution of a carbonate rock unit, creation of a temporary void or arch in the overlying soil and eventual collapse of the soil cover. The chemical action and physical elevation of groundwater play the most important roll in the sinkhole development.

As discussed previously, carbonate rocks are dissolved by the action of acidified groundwater. This dissolution continues as an on-going process with the resulting enlargement of the voids in the bedrock. As the solution opening continues to grow, soil overlying the bedrock begins to collapse into the sinkhole. As illustrated in Figure 3, if groundwater is high enough, the soil will be supported by buoyancy and a greater soil cohesiveness. With a high groundwater level the sinkhole will develop slowly over time. If, during a dry period or drought, the water level is lowered substantially, the soil will lose water and with it cohesiveness and buoyancy. The soil will begin to pass more freely down the sinkhole and the arch developed in the soil column will collapse catastrophically forming a sinkhole, in some cases virtually within hours.

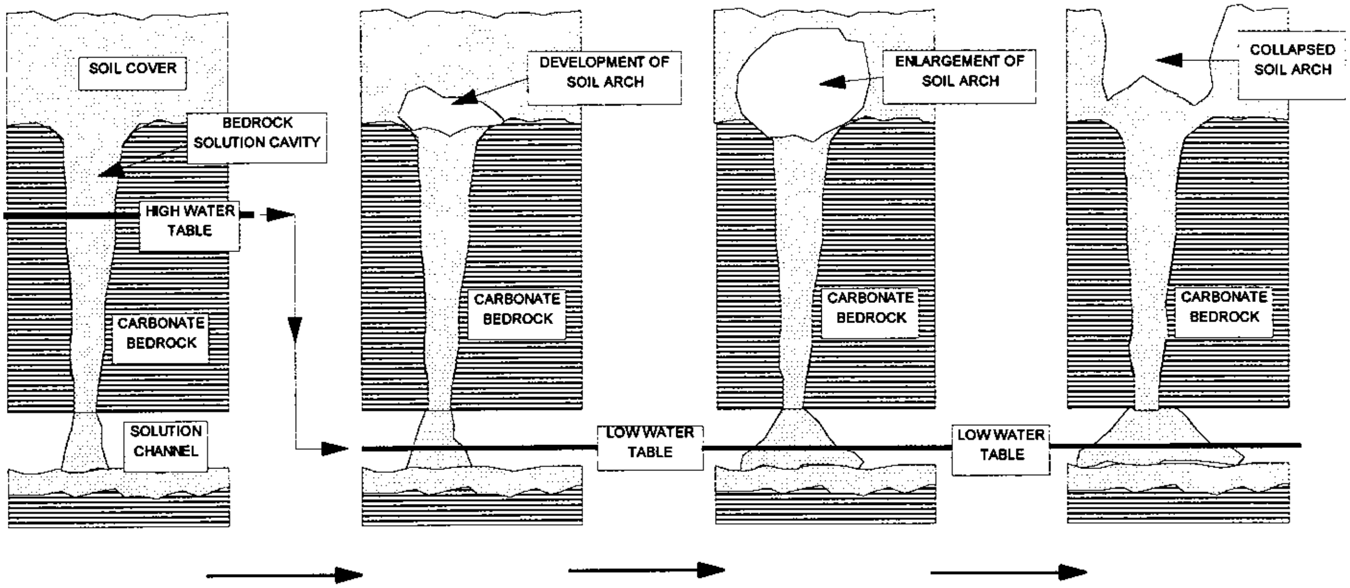

Figure 2. Development of a sinkhole with a decline in the level of groundwater and resultant soil arch collapse.

Sinking Creeks

Creeks, in a karst terrain, can often be observed to disappear into the subsurface. Large creeks, with well developed courses and a high volume of water, may continue across an area of karst features; however, smaller creeks or tributaries are more susceptible to complete loss of water to sinkholes. Generally, a sinking creek loses its water directly to a sinkhole or series of sinkholes. Sinkholes, when discussed in relation to sinking creeks are commonly termed *sinks*. In areas with thicker deposits of soil, creeks may lose water through the alluvium in their channels and the exact location of the sink or sinks cannot be determined. Sinking creeks are important in the development of karst topography as a source of rapidly moving groundwater. As discussed previously, standing water does not tend to dissolve carbonate rocks but a supply of moving water, passing along planes of weakness, will further the development of karst features.

Sinking creeks may travel for miles underground following well defined solution cavities and channels which have been enhanced sufficiently to be considered caves. These subterranean creeks may, at some point, reappear at the surface as a spring. This point of reappearance is often termed a *rise*. In most cases where a creek reappears and commences following a surface course, the exact source or sinking creek cannot be determined. Depending on the number, density and degree of interconnection of sinkholes in an area, the original sinking creek may be supplemented by numerous underground sources of water; hence their original source becomes less identifiable. It should be noted that the presence of springs in a region characterized by karst topography does not necessarily indicate the reappearance of a sinking creek. Springs may also be the result of simple gravity flow of water which moves through the carbonate bedrock and is directed to an outlet, typically in a valley wall.

So far in the discussion of sinking creeks, it has been assumed that once the creek enters a subterranean pathway, its original course is abandoned and, upon reappearing at the ground surface, the creek cuts a new channel. Features known as *natural tunnels* serve as diversion points and conduits for a stream's water. The natural tunnel consists of the same elements as a sinking creek; an upstream sink, a tunnel or conduit to direct the water and a rise. The difference between this and a sinking creek in the strict sense is that the tunnel terminates and discharges water farther downstream in the stream's natural channel. Depending on the magnitude of the stream all or some of the water may be diverted into the natural tunnel. At the rise, the diverted water may either rejoin the streams natural flow or it may be discharged into the lower portion of the stream channel, with the intervening portion of the channel between the sink and the rise occupied by water only during floods.

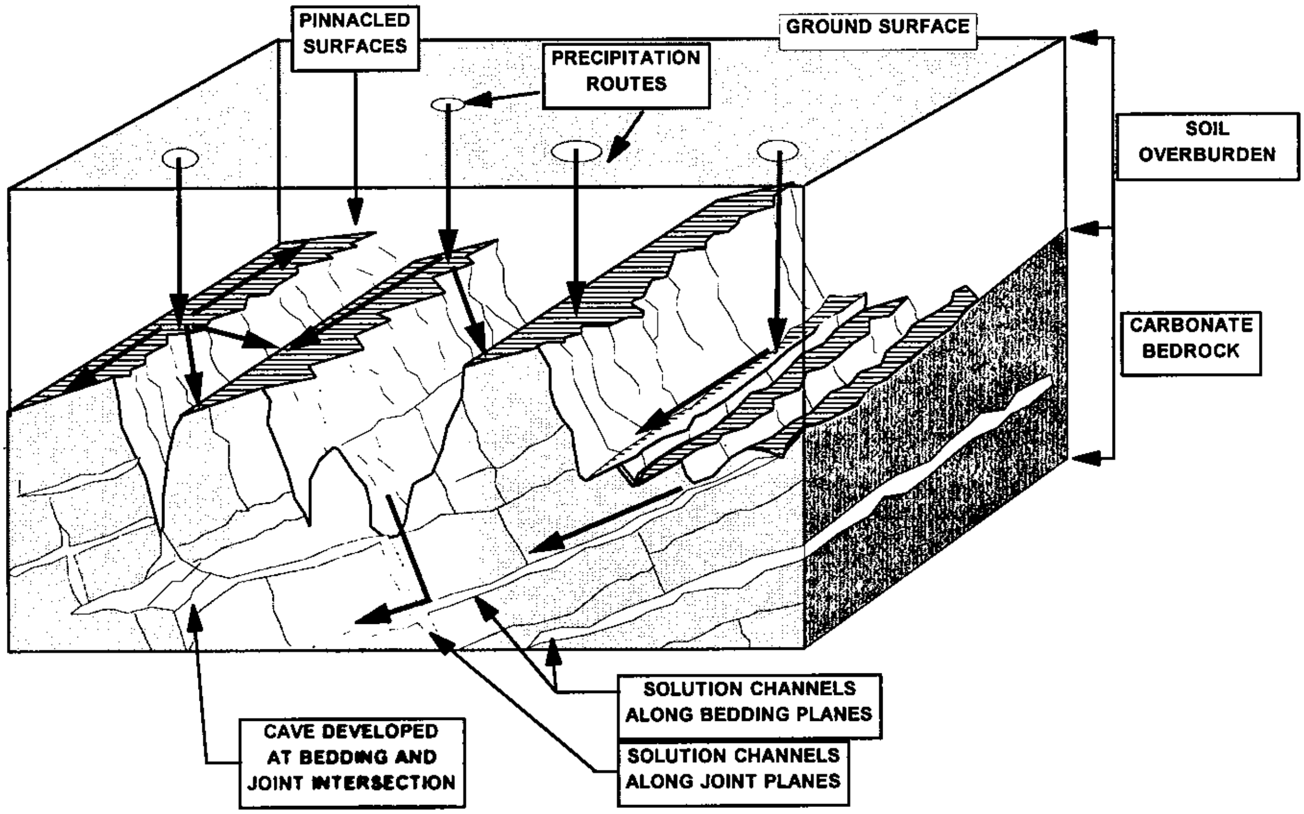

Figure 3. Conceptual illustration of pinnacled bedrock surfaces, shallow groundwater recharge flow and solution channel enlargement

Pinnacled Bedrock Surfaces

In areas underlain by deformed carbonate rock units, dissolution of the top of bedrock often results in an extremely irregular surface. These surface irregularities are governed by dissolution along bedding planes and, more importantly, along the joints and fractures resulting from deformation.

Figure 3 illustrates pinnacled surfaces and can be considered as an illustration of the final phase of the processes illustrated in Figure 1.

Commencing with a generally flat lying carbonate rock unit, joints and fractures begin developing due to normal stresses associated with loading and subsidence. These planes of weakness are further developed by subsequent deformation while additional planes of weakness are produced during deformation. In time groundwater commences to act on these features. As precipitation passes through the soil column and reaches the top of a pinnacled bedrock surface, flow will continue in any number of initial preferred directions. Flow may move along the top of a pinnacled surface if it is level and extensive enough or groundwater may flow down one of the pinnacle slopes and along a lower surface level. Eventually, precipitation reaching the bedrock will enter and flow along one or more of the solution channels developed in the bedrock.

Where erosion of the overlying soil is extensive enough to reveal bedrock, the irregular pinnacled surface will be readily evident. Depending on the orientation of the deformed bedrock, the pinnacled surface may, if exposed or close to the ground surface, create parallel linear topographic features. These features will further help to funnel and direct the flow of precipitation into the shallow groundwater and thence into the karst solution features.

Caves

Caves are the most dramatic of the features associated with karst topography. They are the final manifestation of the solutional work of groundwater as planes of weakness are exploited and enlarged. Caves form along the route of maximum groundwater flow where the rate of dissolution of bedrock is maximized. Cave development is dependent on a number of factors including temperature, flow distance, fracture width, discharge, gradient and the partial pressure of CO_2. (Palmer, 1991)

Caves can be simple or complex with structural elements ranging from a single passageway to those composed of an intricate network of interconnected passageways. The more intricate caves are extensively developed laterally as well as vertically. A cave with multiple vertical levels is termed a *galleried cave* and these can range from two to more than five interconnected levels. (Thornbury, 1969)

Palmer (1991) presents four basic cave patterns, exclusive of the simple single passage cave. The development of each cave type is governed by a lithologic or structural control which produces a unique pattern of passages. The four types are discussed below and are based on Palmer's descriptions. Figure 4 presents the generalized features of each cave type modified from the figures presented by Palmer.

Branchwork caves

These caves are characterized by passages which follow no apparent pattern and when seen in plan view resemble a river drainage system. (Figure 4) The passages, much like the tributaries of a river, appear to flow into larger passages and diminish in number with each succeeding intersection with a larger passage. These caves are formed along bedding planes. Because of this, the pattern of passages is more random than in caves which are formed along repetitive structural controls such as joints.

Network Caves

Network caves are developed along and reflect the pattern of the joints in the bedrock. The passages in these caves tend to be straight, depending on the attitude of the structural controls, narrow and with high ceilings, again depending on the persistence of the structural controls across different beds. Assuming that there is solution along more than one set of joints, then the passages developed in this type of cave will interconnect in a series of closed loops. Where two intersecting joints meet, the passage may be widened into what could be viewed as a small room. (Figure 4)

Anastomotic Caves

These caves, like the Branchwork caves, are formed along bedding planes and are therefore more random than Network caves in their pattern of development. Anastomotic caves are characterized by numerous closed loops and generally are developed along single weakness planes such as a bedding planes. (Figure 4)

Ramiform and Spongework Caves

Ramiform caves consist primarily of a main area of development with rooms and passages moving out in three dimensions. Spongework caves are characterized by random three dimensional passages commonly with interconnections. The mode of formation of Ramiform caves is along bedding planes. Spongework caves are thought to be related to intergranular solution, contrary to the normal mode of cave formation and are commonly found in association with Ramiform caves. (Figure 4)

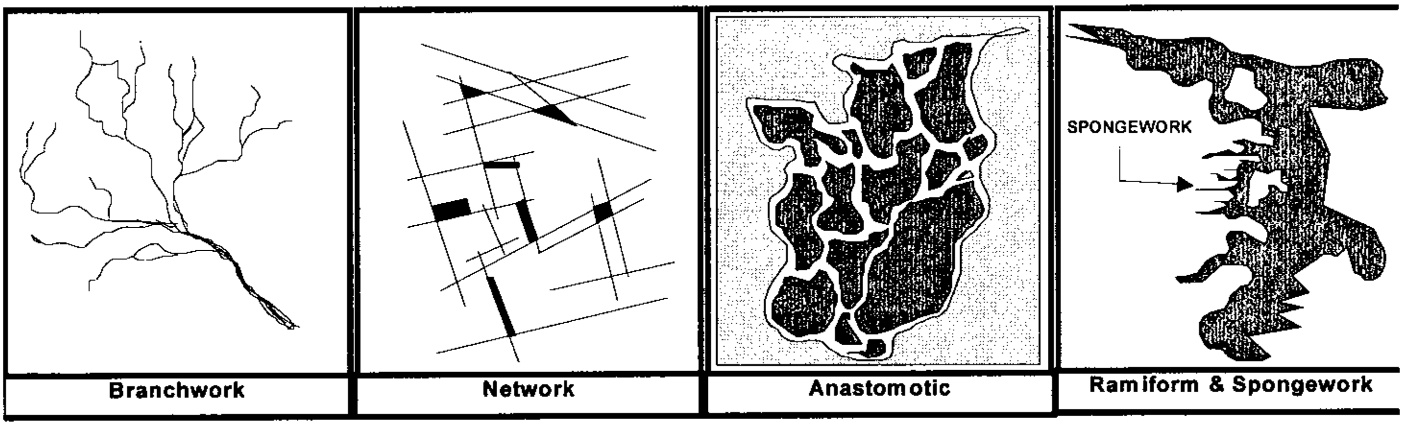

Figure 4. Illustration of common patterns of cave development (modified from Palmer, 1991)

ASPECTS OF GROUNDWATER FLOW IN AREAS OF KARST TOPOGRAPHY

The most readily available source of groundwater is from the soil overlying bedrock. This, in many areas, is the most commonly tapped source of groundwater for residences. Industrial users generally require greater supplies of water and are therefore, more likely to draw water from deeper bedrock sources. Residences in areas with very permeable soils or areas where there is little soil overlying the bedrock will, by necessity, draw groundwater from bedrock aquifer sources.

Groundwater flow in carbonate bedrock, follows bedding, joints, fractures and faults since there is very little primary porosity and permeability in lithified material. The flow along these features can be very rapid and can almost approach the flow characteristics of a river in well developed solution cavities or it can be slower due to lesser degree of development of the routes of flow. Rapid flow of water through an aquifer is termed *free flow*. White (1969) defines a free flow aquifer as one in which groundwater flow has been localized into a well integrated system of secondary flow paths or conduits with a negligible amount of groundwater flow occurring in the primary rock matrix. The flow in a free flow aquifer is thought to achieve rates of thousands of feet per day and, in some cases, can be turbulent with a sediment load.

The more quiescent flow in a carbonate aquifer is termed *diffuse flow*. White (1969) defines a diffuse flow aquifer as one in which bedrock has undergone the least amount of solution modification. Flow in this type of aquifer is laminar with little or no suspended load.

Figure 5 is a simplified representation of the potential routes of groundwater flow along bedding plane partings and two intersecting joints. Figure 5A shows bedding dipping to the west and joints dipping to the east and northwest. One can assume that groundwater will flow easily along each of these pathways if sufficient dissolution has taken place. Figure 5B illustrates that, in addition to the three planar pathways for groundwater flow, the intersections of each of these planes will form a potential location for enhanced dissolution of the carbonate aquifer and an added pathway for groundwater flow. Flow and dissolution along these pathways illustrated in Figure 5 will develop a network pattern of enlarged joints and caves as illustrated in Figure 4. Flow along the pathways developed at the intersections of structural features may be in directions different from the planar pathways. For example, the intersection of the northwest and east dipping joints will form a linear feature with a bearing and plunge to the northeast. Potentially, a well developed solution channel may exist which will act as a conduit for groundwater flow in this direction adding to the complexity of the groundwater regime.

There is very little primary or inter-granular porosity in carbonates therefore, most of the groundwater flow is along these elements of secondary porosity. Because of this, the ability of a carbonate aquifer to store water within inter-granular interstices is low. As water is removed from the secondary features it cannot be replaced from the rock itself but must be replenished by flow along routes of secondary porosity.

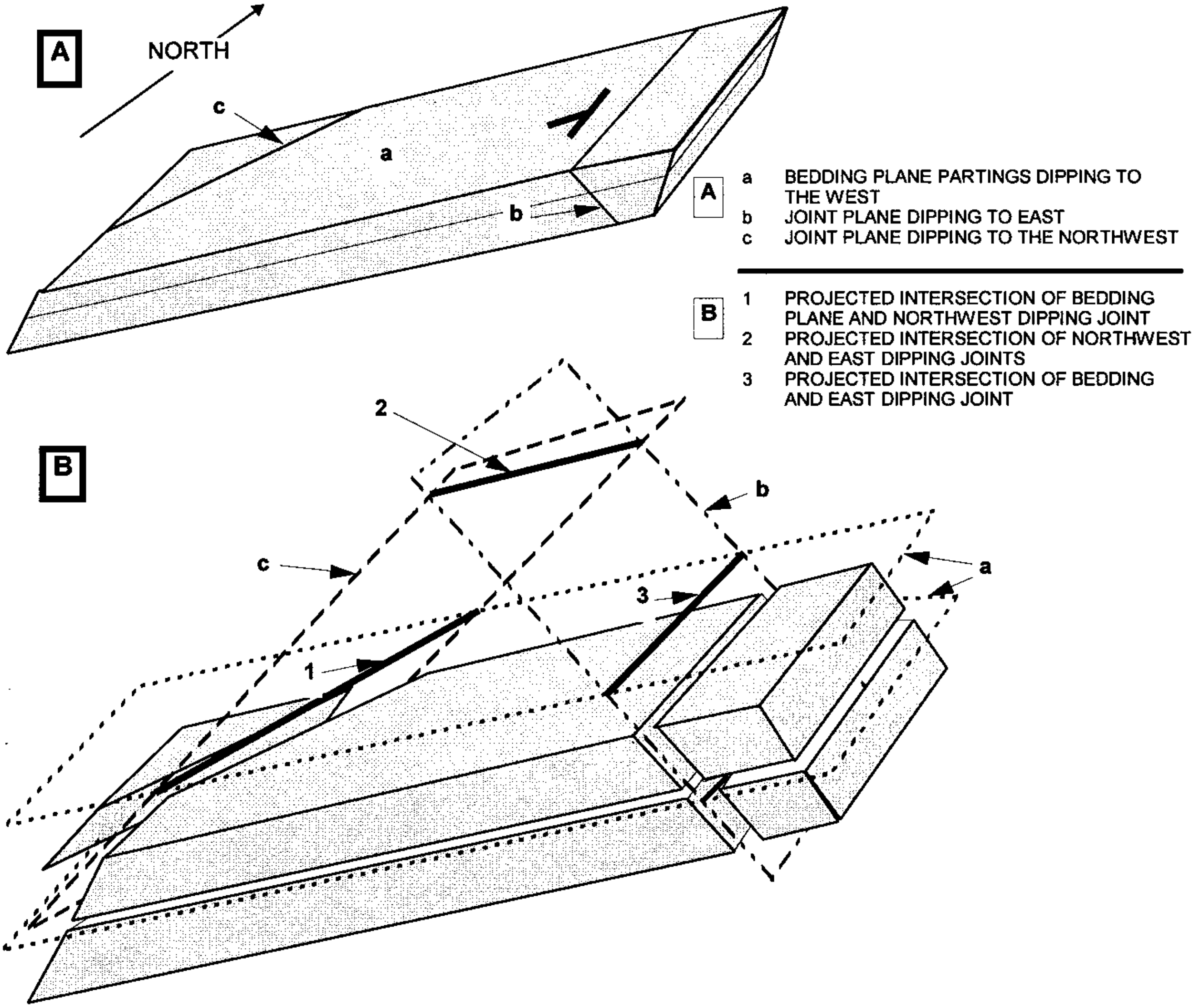

Figure 5. Development of Potential Groundwater flow path planes and enhanced development along planar intersections.

Substantial groundwater supplies can be obtained from karst features; however, there are certain limiting conditions. Since there is very little primary porosity in carbonate aquifers and most of the available water is stored in solution features, the effects of withdrawal of water through wells can be transmitted rapidly over a wide area. This is especially true in diffuse aquifers where the flow is from a system of pathways which have undergone a lesser amount of solution modification. The effects of a well withdrawing large amounts of water will be seen in surrounding wells by a lowering of their respective water levels. In a free flow aquifer, these effects will be masked by the sheer volume of water available and the solutionally enhanced avenues of flow. If two wells are located on the same joint or bedding plane however, the well which is upgradient or withdrawing water from a higher or upslope location, may tend to impact the well which is downgradient.

One additional aspect of groundwater flow in areas of karst features is that due to the low storage capacity and rapid flow along solutionally enlarged planes, carbonate aquifers tend to respond quickly to extended periods of drought. This is unlike other bedrock aquifers where, in the case of permeable rocks such as some sandstones, water is stored in the interstices between grains as well as flowing along secondary permeability features. When precipitation and recharge to the aquifer are low the aquifer can still supply water from the porous and permeable matrix. In the case of relatively impermeable and insoluble rocks such as shales and metamorphic rocks, the effects of a drought are not as readily apparent since the flow along secondary permeability pathways is substantially slower than that of carbonate aquifers. The water resides for a longer period of time and is therefore, available for withdrawal for a longer term.

A BRIEF OUTLINE OF KARST AREAS IN NEW JERSEY

Western New Jersey, particularly the counties of Warren, Sussex and Hunterdon are partially underlain by lower Paleozoic carbonate rocks. These regions form the area known for karst topography in New Jersey. To a lesser extent the region underlain by the Franklin Limestone (marble) can also be included in the karst region however, the un-metamorphosed carbonates both in New Jersey and in adjoining Pennsylvania, present the best illustrations of karst topography.

For a complete discussion of these formations and their karst characteristics, see Dalton, this volume. Generally, the formations consist of a series of dolomites with a lesser number of pure limestone units ranging in age from Cambrian through the lower Devonian. Table 1 presents a summary overview of these formations and their lithologic and groundwater bearing characteristics. As a general description, the Cambro-Ordovician carbonate units consist of massive dolomites, the colors of which range from black to light grey on fresh surfaces. Throughout most of the units there are conspicuous intervals of white to black chert which stand out in relief on weathered surfaces. (Markewicz et.al., 1981) The Silurian and Devonian rocks in New Jersey are characterized by nearly pure limestones and sandy to shaly limestones. Chert is common in the younger limestones of the state and the rock colors range from light to dark grey and dark blue to nearly black.

The carbonate regions of New Jersey are marked by a great many typical karst features. Most of those discussed previously have been documented to be present in New Jersey in previous investigations and reports. Most of the carbonate units have been deformed to some degree and the resultant surfaces are, in most cases, pinnacled. The pinnacles range from irregular, blocky surfaces to those forming parallel ridges and valleys. (see Figure 3) Solution cavities (Figure 1 and Plate 1) are prominent feature and can be seen in a number of exposures along roads and rail lines. Generally they are vertical and controlled by jointing and fracturing of the bedrock.

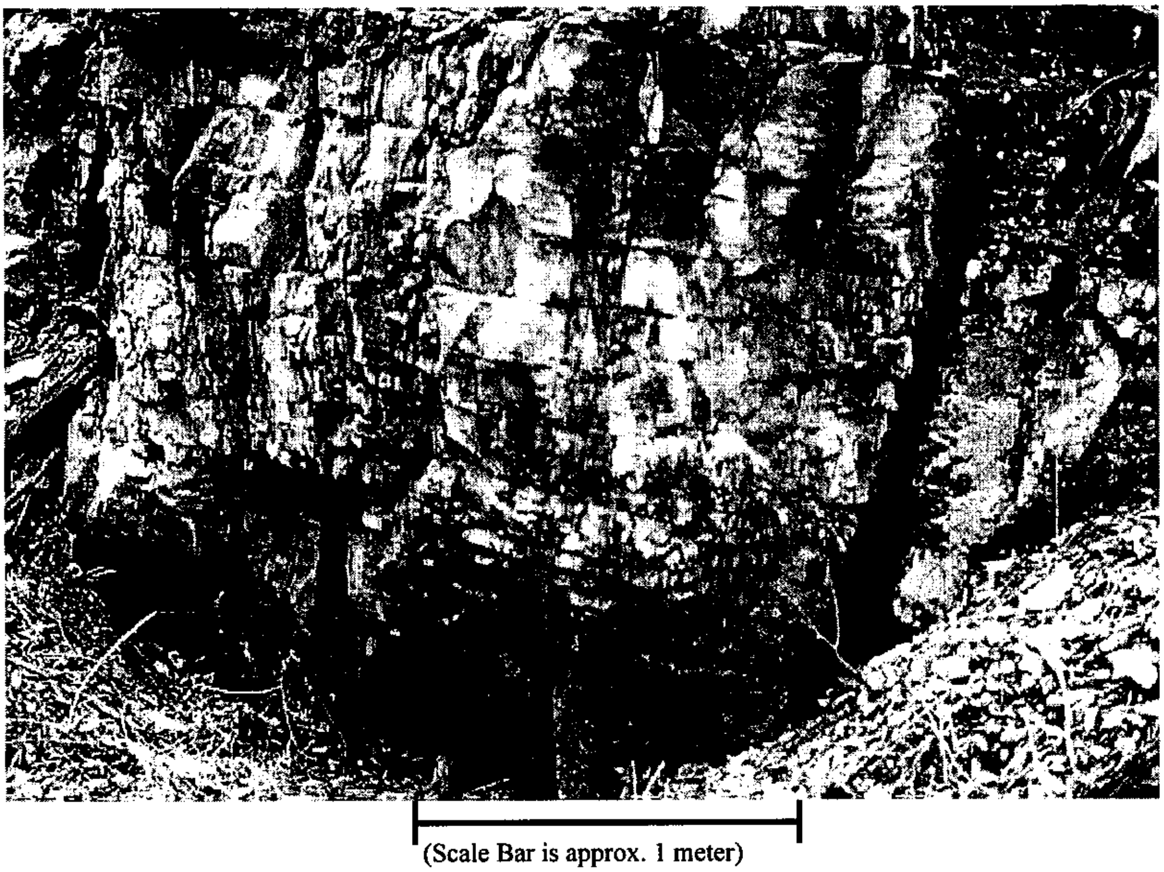

Plate 1 Enlargement of joints by solution in Ontelaunee Formation railroad cut near Alpha, NJ, Stop number 5, 1989 GANJ Meeting

Sinkholes and sinkhole ponds appear throughout the carbonate terrains of New Jersey and are easily identified on both topographic and geologic maps of the western areas of the state. (Plate 2) Sinkholes appear as circular depressions, either alone or in clusters, and may be water filled. The map section below, from the USGS 7.5 minute Bangor, New Jersey quadrangle illustrates a small area which contains several sinkholes. These lie within the Rickenbach Formation and are detailed on the topographic map as being water filled.

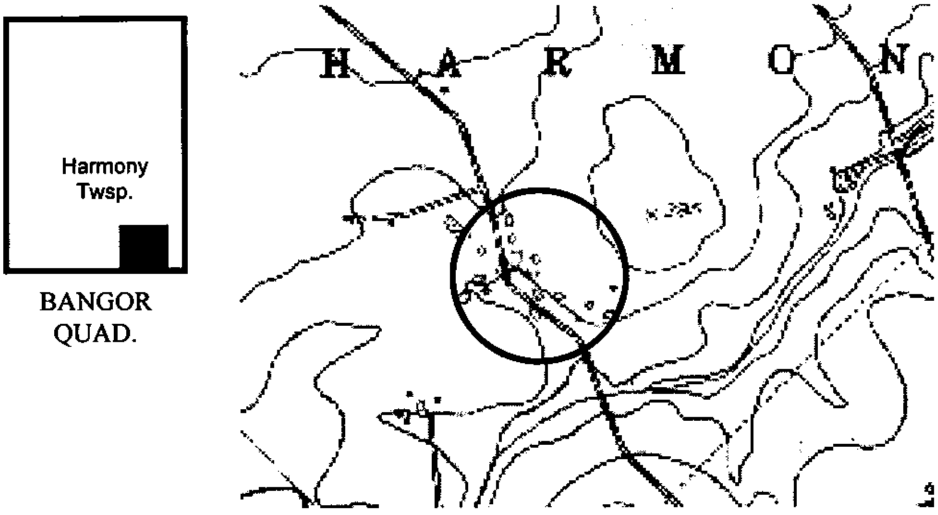

Plate 2. Section of the Bangor USGS 7.5 minute topographic map illustrating sinkhole ponds

Although not generally known, New Jersey is also home to a great many caves. Not all of the caves in the state lie within the carbonate belt; however, the preponderance of caves and the most extensive of these can be found within the dolomites, limestones and marbles of western New Jersey. The majority of the caves in this state fall into three of the aforementioned categories, single passage, branchwork and network caves. (Dalton 1976) According to information presented by Dalton (1976) there are approximately 132 known caves or cave-like features reported from the Paleozoic and Precambrian carbonate formations of New Jersey.

FORMATION	# of CAVES
Onondaga	3
Oriskany	3
Coeymans	1
Jacksonburg	2
Ontelaunee	3
Epler	49
Rickenbach	6
Allentown	28
Leithsville	11
Franklin	26

The preponderance of these occur in the Epler Formation followed by the Allentown Formation and the Franklin Limestone. The following is a summary of the cave bearing carbonate formations and the approximate number of reported caves in each unit. The number of caves reportedly found in a given formation provides an indication of the suitability of that rock unit to produce karst features. The one exception to this is the Franklin Limestone. A number of the reported caves in this formation were discovered during operations at the Sterling Hill mine. These caves do not approach the ground surface and most probably would not result in surface indications of their existence or in the development of karst features

TABLE 1

SUMMARY OF CARBONATE FORMATIONS AND THEIR CHARACTERISTICS IN WESTERN NEW JERSEY

GEOLOGIC PERIOD	FORMATION NAME	APPROXIMATE THICKNESS	GENERAL LITHOLOGICAL CHARACTERISTICS	GROUNDWATER POTENTIAL
DEVONIAN	Onondaga Limestone	200 ± ft.	Dark grey cherty limestone, shaly limestone and limy shale.	Yields ranging from 1 gpm to 70 gpm
	Oriskany Formation	170 ft	Sandy limestone grading to sandstone to the south.	L. Devonian formations range from 2 to 80 gpm (avg yield of 18 gpm)
	Becraft Limestone	20 ft	Hard grey cherty limestone, fossiliferous.	
	New Scotland Formation	160 ft	Hard cherty limestone and limy shale.	
	Coeymans Limestone	40 ft	Light grey limestone, pure to sandy, highly fossiliferous	
SILURIAN	Manlius Formation	35 ft	Thin bedded dark blue to nearly black fossiliferous limestone.	Silurian formations range from 2 to 80 gpm with an avg yield of 18 gpm.
	Rondout Formation	39 ft	Limestone at base with alternating beds of shale and dolomite with a bed of silty dolomite at the top.	
	Decker Ferry Limestone	52 ft	Thin beds of limestone and shale becoming sandy to the south.	
	Bossardville Limestone	12 to 100 ft	Banded fine grained bluish grey limestone.	
ORDOVICIAN	Jacksonburg Limestone	125 to 300 ft	Dark blue. grey or black fossiliferous limestone, thin layers of calcareous shale are interbedded with limestone and become thicker and more abundant near the top.	Few wells are completed in this formation. Data not available
	Ontelaunee Formation	370 to 440 ft	Grey to black fine grained, dense, fetid, cherty dolomite. Fossiliferous in some areas.	Yields ranging from 3 gpm to 50 gpm
	Epler Formation	230 to 550 ft	Light to dark grey, fine to medium grained to cryptogranular impure dolomite with interbedded units of banded to lenticular limestone and cherty zones.	Yields ranging from 3 gpm to 20 gpm
	Rickenbach Formation	400 to 525 ft	Upper beds fine grained, less crystalline, lighter colored, more thinly bedded than lower beds. Lower beds grey to dark grey, fine to coarse crystalline sparkly on fresh surfaces. Basal beds separated by thin shaly partings and discontinuous chert beds.	Yields ranging from 3 gpm to 200 gpm
CAMBRIAN	Allentown Formation	1,400 to 1,900 ft	Thick rhythmically bedded ligght ot dark grey, fine to medium grained, crystalline impure dolomite.	Yields ranging from 3 gpm to 1,000 gpm
	Leithsville Formation	525 to 750 ft	Massive medium to fine grained, impure calcareous dolomite weathering to grey to light grey in basal units and lighter in upper units.	Yields ranging from <10 gpm to 2,000 gpm

Modified from Markewicz et. al. 1981 and from Miller 1973

ENVIRONMENTAL CONCERNS IN AREAS OF KARST TOPOGRAPHY

Dissolution of bedrock and the resulting subsurface conditions present interesting problems and limiting conditions for human habitation. Reliable supplies of water for domestic or industrial use, water quality especially with regard to pollution and its potential to migrate long distances and considerations of subsurface conditions and their effects on structural requirements for building development are but a few of the aspects which need to be addressed in karst areas. The following is a brief overview of some of these topics and their potential impacts to families and businesses located in karst regions.

The majority of homes or industries which are not connected to municipal water supplies or services either get their potable water from surface water bodies such as lakes and rivers or from supplies of groundwater. Of these two sources, the vast majority of water is obtained from the groundwater regime for a number of reasons. Groundwater, as compared to surface water, is a more reliable source of water. Not all residences or businesses are located within a reasonable distance from a stream or lake but groundwater supplies are always available. Groundwater levels may exhibit seasonal fluctuations; however, in general it is a more constant source of potable water than are surface water supplies which can be dramatically affected by droughts. During periods of high precipitation, rivers and streams are subject to floods which can create conditions of high turbidity, rendering the water unusable without treatment. In addition, the presence of bacteria in surface water supplies generally requires some form of treatment in order to make the water suitable for drinking. Groundwater is, for the most part, unaffected by these factors. Periods of high precipitation may raise the level of the groundwater; however, there is not necessarily a corresponding increase in turbidity. Bacteria are not generally a health concern in groundwater supplies assuming that recharge to the aquifer is not through a direct conduit such as a sinkhole or from a septic system directly overlying a bedrock surface. As water passes through the mantle of soil overlying bedrock there is a natural filtering process which removes harmful bacteria.

As discussed previously, karst aquifers generally provide substantial supplies of water for any application. Groundwater yields in some of the New Jersey karst aquifers range from approximately three to ten gallons per minute on the low side to a reported high of 2,000 gallons per minute (Markewicz, 1981).

Since the carbonate rocks contain little primary porosity, a well drilled into a massive unit may not supply sufficient water even for domestic use. A well, on the other hand which intersects a conduit may yield sufficient quantities of water to supply a community. This makes the selection of a location for well installation of paramount importance. Two methods have been used successfully to determine the optimum placement for water supply wells; surface geomorphic features and shallow geophysical surveys.

Through the use of topographic maps and, more importantly, aerial photographs, surface expressions of the underlying bedrock can be identified and exploited in determining well placement. Linear features such as alignment of soils and vegetation types or drainage features such as stream and river channels can be used effectively to predict the presence of fractures in the bedrock. This information, when used in conjunction with detailed information on the geology of an area will indicate whether a well will probably intersect a zone with a high water yield. Placement of a supply well, so that intersection of one of these subsurface features is virtually guaranteed will increase the likelihood that a sufficient water supply will be tapped.

Shallow geophysical survey techniques such as seismic reflection or refraction and ground penetrating radar will produce a visual representation of the subsurface. These methods may be used to identify the discontinuities formed by dissolution of bedrock into groundwater flow conduits. A more complete discussion of geophysical survey techniques and the results of surveys of this type are presented in Costa et.al., this volume.

Aside from determining the placement of a well to maximize the amount of water available, consideration must be given to impacts to surrounding wells. Two wells, withdrawing water from the same conduit, may begin to interfere with each others effectiveness. As discussed in the general section on groundwater and illustrated in Figure 5, groundwater will tend to flow along well defined planes and conduits. In a free flow aquifer, the quantity of water may be sufficient so that two wells drawing from the same conduit will not interfere with each other and withdrawals from one well will not cause surrounding wells to experience a loss in water or, in the extreme instance, cause other wells to go dry. In a diffuse flow aquifer, where the rate of water flow is lower, well placement becomes more important. Use of geophysical methods and reviews of available geological and geomorphological information will help in determining where probable water bearing zones can be located and assist in placement of wells in non-interfering arrays.

As discussed above, groundwater is generally a more reliable source of potable water than are surface water supplies. The natural filtering action of sediments will remove bacterial pollution from most percolating water and yields from wells will remain constant with little variation in turbidity or chemical content. Human activities can alter this delicate balance and the impacts can be felt rapidly and can reach far beyond the area of origin, particularly in regions underlain by carbonate rocks. Impacts to groundwater quality can come from highly publicized catastrophic sources such as chemical spills Longer-termed sources such as leaking underground storage tanks can contribute any number of contaminants but most commonly are sources of petroleum contaminants such as gasoline or oils. Pollution to groundwater supplies can also come from less well known sources including agricultural operations where fertilizers and pesticides can be transmitted to groundwater and domestic waste from improperly installed septic systems.

Generally, groundwater flows rapidly in karst areas. Spills or leakage of contaminants into groundwater can travel long distances in a relatively short period of time and can become manifest in water supply wells virtually overnight. As water migrates into a carbonate aquifer, it may travel for a distance over the surface of the bedrock before entering the groundwater regime as noted in the previous discussion of pinnacled bedrock surfaces and in Figure 3. Additionally, due to the interconnections of groundwater flow conduits in carbonate aquifers (Figure 5) it is also difficult to track contaminant spread and to predict what areas will be impacted by releases into the groundwater regime.

The conditions discussed throughout this paper are of paramount importance in the development of areas underlain by carbonate rocks. The relationship of the soil cover to the underlying bedrock characteristics must be examined more closely in carbonate terrains than in those underlain by other rock types. The most obvious aspect of karst bedrock which would be of concern in development of an area is the presence of soil filled solution voids which, if natural conditions are altered, can fail with a resultant collapse and formation of a sinkhole. The presence of pinnacled bedrock surfaces can, if mantled by a thin veneer of soil, cause problems or even failure of building foundations. Even common construction practices such as dewatering during excavation can precipitate changes in the relationship of soil to bedrock with catastrophic development of karst features.

During construction of a building a soil filled solution cavity may go undetected if it is sufficiently deep and bedrock is not examined prior to construction. This feature may continue to support the foundation of the structure with no adverse impacts. If a well is installed to supply water to the building, the groundwater level may be lowered over time which may result in a change in the conditions which supported the soil in the solution cavity. The changed conditions may, over time, cause the soil to collapse into the solution cavity thereby creating a sinkhole (Figure 2) which may impact the foundation of the building or, in a worst case, undermine the building sufficiently to cause the building to collapse.

Pinnacled bedrock surfaces can create conditions which will provide uneven support for a buildings foundation. Pinnacles, as shown in Figure 3, form highs in the bedrock surface and the intervening lows are soil filled. The pinnacles and the soil filled troughs will provide uneven support for a foundation. In addition, there is the potential for soil to be lost to solution features in the troughs which will further serve to create variable support for a building. The potential then exists for uneven settlement and eventual damage to the foundation of the building.

Prior to commencing development in karst terrains, the same measures discussed for placement of water supply wells need to be considered. Use of topographic and geologic information, aerial photographs and a program of exploratory drilling or a geophysical survey will minimize impacts to development from karst features.

SUMMARY

This paper was intended to provide the reader with a basic understanding of some of the complexities of karst terrains and to this end has presented a generalized discussion of their common features and modes of development, aspects of groundwater flow and issues related to human habitation of these areas. In summary, areas underlain by carbonate rocks present a set of complex relationships between the bedrock, soil and groundwater. Continued dissolution of limestones and dolomites by groundwater creates topographic features unique to karst terrains, many of which can be found in the carbonate regions of western New Jersey.

The development of karst topography is dependent on a number of factors; however, the most important of these is groundwater flowing along planes of weakness. The carbonates of New Jersey have been deformed and, as such, display a well developed pattern of joints and fractures which, through the action of groundwater, become enlarged forming conduits for enhanced flow. As these conduits grow, evidence of these processes can be observed at the ground surface in the development of sinkholes, sinkhole ponds, sinking creeks, caves and pinnacled surfaces. All of these features give indications of the nature of the underlying bedrock and the resultant work of groundwater. Of these features developed as a result of dissolution of carbonate rocks, caves offer perhaps the best insight into the character of the bedrock. By examining and mapping cave routes in a region, a determination can be made whether groundwater has exploited avenues developed along bedding or whether joints and fractures have provided the preferred route for groundwater flow.

There is very little primary porosity in carbonate rocks and groundwater flow in these aquifers is primarily through these secondary planes and conduits formed along structural elements. Flow in New Jersey carbonates can range from a few gallons per minute to thousands of gallons per minute and can supply a wide range of human endeavors from domestic and municipal use to agricultural and industrial applications. Due to the complex nature of groundwater flow in carbonate rocks and the high rates at which groundwater can flow, extreme care must be exercised to protect the quality of this source of water. Contaminants which enter carbonate aquifers can be carried rapidly over a wide area and can impact groundwater users virtually overnight. In addition, development in areas with karst features faces a unique set of difficulties. Activities of construction and water withdrawal can precipitate changes in the relationships of soil, groundwater and the underlying bedrock, sometimes with rapid and far reaching effects.

REFERENCES

Dalton, Richard F., 1976, **Caves of New Jersey**, NJ Geological Survey, Bureau of Geology and Topography, Bulletin 70
_____________ , 1989, **Stratigraphy of the "Kittatinny Limestone"** in Paleozoic Geology of the Kittatinny Valley and Southwest Highlands Area, NJ; I.G.Grossman ed; 6th Annual Meeting of the Geologic Association of New Jersey, Oct. 20-21, 1989.

Drake Jr., Avery Ala, 1967, **Precambrian and Lower Paleozoic Geology of the Delaware Valley, New Jersey-Pennsylvania** in Seymour Subitzky, ed., Geology of Selected Areas in NJ and Eastern PA; GSA Annual Meeting November 1969.
_______________, 1965, **Carbonate Rocks of Cambrian and Ordovician Age Northampton and Bucks Counties, Eastern Pennsylvania and Warren and Hunterdon Counties, Western New Jersey**, United States Geological Survey, Contributions to Stratigraphy, Bulletin 1194-L.

Herman, Gregory C., 1988, **Paleozoic Geology and Related Geohydrologic Aspects of New Jersey**, in Geology and Hydrogeology of New Jersey, Rutgers University and Cook College; Sept. 14 & 15, 1988

Hobson, J.P., 1963, **Stratigraphy of the Beekmantown Group in Southeastern PA**, Pennsylvania Geological Survey, 4th Series, General Geology Series Report 37.

Lucey, Carol S., 1971, **Geology of Warren County in Brief**, New Jersey Geological Survey, County in Brief Series.

Markewicz, Frank J., and Dalton, Richard; 1980; **Lower Paleozoic Carbonates: Great Valley**, in Warren Manspeizer ed, Field Studies of New Jersey Geology and Guide to Field Trips; 52nd Annual Meeting of the New York State Geological Association, Rutgers University.

Markewicz, Frank J.;Dalton, Richard; Canace, Robert, 1981, **Stratigraphy, Engineering and Geohydrologic Characteristics of the Lower Paleozoic Carbonate Formations of Northern New Jersey**, in Proceedings of Design and Construction of Foundations on the Carbonate Formations of New jersey and Pennsylvania, New Jersey Institute of Technology, March 27, 1981.

Miller, Benjamin LeRoy, 1925, **Limestones of Pennsylvania**, Pennsylvania Geological Survey, Fourth Series, Bulletin M-7 and 1934 Edition Bulletin M-20.
_________, 1939, **Northampton County, Pennsylvania**, Pennsylvania Geological Survey, Fourth Series, County Report 48

Miller, Benjamin LeRoy, 1941, **Lehigh County, Geology and Geography**, Pennsylvania Geological Survey, Fourth Series, Bulletin C-39

Miller Jr., Joseph W., 1974, **Geology and Groundwater Resources of the Sussex County and Warren County Portion of the Tocks Island Impact Area**, New Jersey Geological Survey, Bureau of Geology and Topography, Bulletin 73.

Palmer, Arthur N., 1991, **Origin and Morphology of Limestone Caves**, Geological Society of America Bulletin Volume 103, Number 1, January 1991.

Thornbury, William D., **Principles of Geomorphology**, Second Edition; John Wiley and Sons, Inc.

White, W. B. et al, 1995, **Karst Lands**, American Scientist, Volume 83, September-October 1995.
_________ 1969, **Conceptual Models for Carbonate Aquifers**, Groundwater, Volume 7 Number 3 in Gregory C. Herman, 1988.

Karst Geology of New Jersey and Vicinity

by

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INTRODUCTION

Karst is a type of topography which forms on soluble bedrock. It is characterized by sinkholes, sinking streams, and underground drainage. Distinctive features of karst terrain may include exposed bands of bedrock (karren) which are cut by soil or clay filled enlarged joints (cutters), sometimes the exposed rock surface is dissected by a myriad of close spaced cross fractures which have weathered to form small ridges and hollows a few inches deep (lapies).

Karst areas in New Jersey occur in the northern part of the state and are underlain by carbonate bedrock. These areas total more than 225 square miles (fig. 1) and range in age from the Precambrian to Devonian (Dalton and Markewicz, 1972, p. 115). The most extensive carbonate areas are underlain by rocks of the Cambrian-Ordovician Kittatinny Supergroup, and the Precambrian Franklin Marble.

This field trip will examine karst features in Precambrian, Cambrian-Ordovician, and Devonian rocks. Three stops are in New Jersey and the fourth is in southern New York State, a few miles north of the border.

The New York site was chosen because it is an excellent example of sinkhole development in the Silurian-Devonian rocks which are also found in New Jersey.

ACKNOWLEDGEMENTS

The field trip committee is grateful to the Geological Association of New Jersey for its guidance, cooperation and overall supervision of this field trip and meeting.

Special acknowledgement is given to State Geologist Haig Kasabach for his support of the project and for providing the time and assistance of staff. The guidebook from this trip and meeting should become a standard reference on karst and sinkholes in the New Jersey area.

Thanks is given to Thomas Seckler, William Graff and Josephine Valencia of the Bureau of Geology and Topography for providing editing, cartographic and word processing assistance.

Thanks is also given to the various land owners who have allowed access to their properties for this field trip.

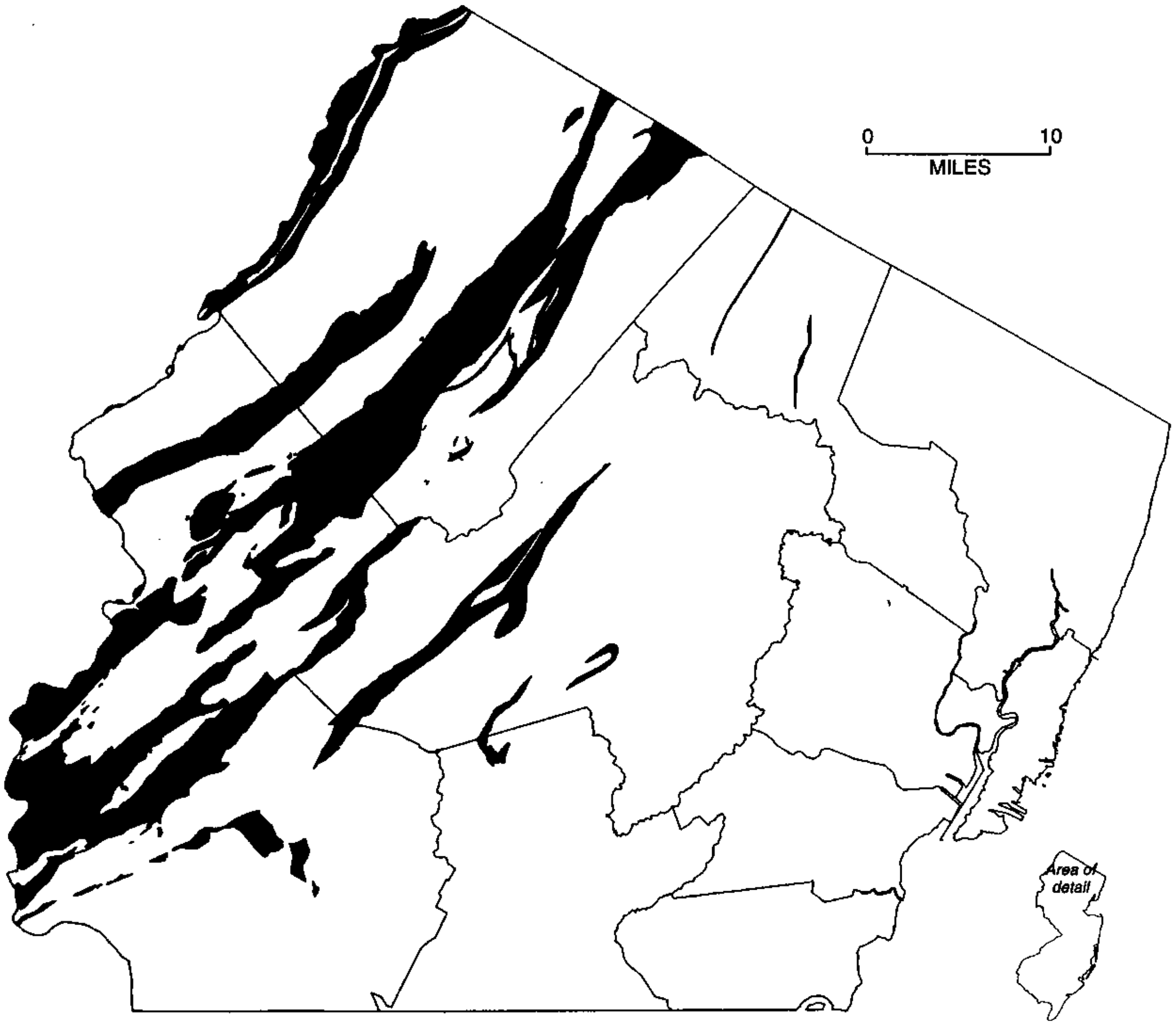

Figure 1.-- Carbonate rocks of New Jersey generalized from New Jersey atlas sheet series geologic overlays.

STRATIGRAPHY

New Jersey carbonate rock units range in age from the Precambrian to the Paleocene. Table 1 identifies the late Precambrian and Lower Paleozoic carbonate rocks which may have areas prone to the development of sinkholes. The oldest carbonate rocks in the state, the Precambrian Franklin Marble (Drake and others 1995) is a white- to light-gray weathering, white, grayish-white, or less commonly pinkish-orange, very coarse to locally fine crystalline, calcitic to occasionally dolomitic marble. Common accessory minerals consist of graphite, phlogopite, chondrodite, clinopyroxene and serpentine. In the Franklin-Sterling Hill area of Sussex County the Franklin Marble has been divided into three separate bands (Hague and others, 1956) which are interbedded with gneiss. The upper band, known as the Wildcat Marble, is approximately 300 feet thick. The lower two bands, collectively called the Franklin Marble, are separated by a 300 foot discontinuous gneiss called the Median Gneiss. Due to the complex structure the total thickness is not known, although the portion above the Median Gneiss is about 1500 feet thick. Over 26 caves and numerous sinkholes are found in the Franklin Marble.

The Cambrian-Ordovician Kittatinny Supergroup subdivision into 5 mappable formations (Markewicz and Dalton, 1977) is used in this paper rather than the more informal subdivision used by Drake and others, (1995). The difference concerns the breakdown of the Ordovician portion of the sequence. Both publications agree on the Leithsville and the Allentown.

The Leithsville Formation, of Lower to Middle Cambrian age, consists of three mappable members; the Califon, Hamburg and Wallkill. The Califon is a medium- to dark-gray, silty weathering, medium- to coarse-grained, medium- to massive-bedded, rubbly, undulating locally sandy dolomite with scattered white dolomite clots and crystals. Frequent discontinuous large masses and lenses of pyrite and other sulphides can be present in the lower part.

The Hamburg Member is a buff to medium-gray-weathering interbedded sequence of medium-gray, very-fine to fine-grained, thin- to medium-bedded dolomite, shaly dolomite and varicolored quartz sandstone, siltstone and shale. The unit is very cyclic. The Wallkill Member is a medium- to dark-gray, fine- to medium-grained, medium- to massive-bedded, pitted dolomite. Knots and lenses of chert can be present.

The Leithsville ranges from 500 to 800 feet in thickness and generally underlies the lowest topography. Where it is present above the swamp and lake levels, sinkholes can be fairly common except on the middle member which forms a hogback ridge. There are 10 caves known in the Leithsville, including several considered large by New Jersey standards.

The Allentown Formation of Upper Cambrian to earliest Ordovician age consists of two members, the Limeport and the upper member. The Limeport Member is an cyclic sequence of cream- to light-gray and dark-gray-weathering, fine- to medium-grained, thin- to medium-bedded dolomite interbedded with shaly dolomite. Ripple marks, cross beds, edgewise conglomerate, mud cracks, oolites, and algal structures are common. The upper member is a cream-weathering, fine- to medium-grained, locally coarse, medium- to massive-bedded dolomite. Some minor orthoquartzite and thin shaly- to silty-laminae present, as are occasional edgewise conglomerate, oolites, ripple marks, mud cracks, and algal structures. At the top are two sequences of steel-gray, thin-bedded quartzite and discontinuous dark-gray chert lenses.

The Allentown Formation is approximately 1800 feet thick. The Limeport Member forms a prominent bench above the Leithsville lowland and the upper member forms a rugged topographic high with numerous troughs and ridges. Sinkholes tend to be larger in the Limeport than the upper member. The Allentown contains 25 known caves including the longest in the state.

The Beekmantown Group of Lower Ordovician age as used here consists of the Rickenbach, Epler, and Ontelaunee (Markewicz and Dalton 1977).

The Rickenbach has two members, the lower and the Hope, as well as a distinct mappable facies, the Crooked Swamp facies. The lower member consists of cream- to light-gray-weathering, thin- to medium-bedded, fine- to medium-grained dolomite with many stringers of sand. The unit looks similar to the upper part of the Limeport Member of the Allentown and produces a similar topography. The Hope Member consists of a light- to medium-gray, silty weathering, medium- to dark-gray, aphanitic to coarse grained, medium-bedded dolomite. Some beds contain floating quartz sand to sand stringers at the base. There are two zones of thin black chert beds, knots and stringers. The upper contact with the Epler can consist of a massive chert horizon. There can be some beds of a light-gray, medium- to very-coarse-grained, massive-bedded dolomite with the dolomite grains being very euhedral and surrounded by a clay-like material. This latter lithology is the Crooked Swamp facies which can thicken from a few feet to over a hundred feet along strike.

The Rickenbach ranges in thickness from 150 to 300 feet and generally underlies a low swampy, subdued topography. The Crooked Swamp facies when 50 or more feet thick forms a prominent ridge. Sinkholes of all sizes are common, with some of the largest found in New Jersey occurring in the Hope Member. There are 7 known caves in the Rickenbach.

The Epler Formation contains three members, the Branchville, Big Springs, and Lafayette. The Branchville member is a light-brown or grayish-yellow-orange-weathering, very-fine- to medium-grained, massive, laminated dolomite. The Big Springs is a laterally variable, olive-gray, light-brown, or dark-yellowish-orange-weathering, dark-gray, aphanitic- to fine-grained, thin-bedded dolomite or siliceous dolomite with thin up to 2" silicious or shaly ribs that weather in relief. This unit can grade into lenticular, light-bluish-gray-weathering, aphanitic- to fine-grained massive laminated to ribbed limestone. The Lafayette member is a very-fine- to fine-grained, massive, laminated dolomite very similar to the Branchville.

The Epler ranges in thickness from 350 to 500 feet and generally underlies a high terrain which contains narrow to wide linear ridges. Sinkholes are scarce and tend to be small. There are 35 small caves known.

The Ontelaunee has two members, the Beaver Run and Harmonyvale. The Beaver Run is a light- to medium-gray-weathering, medium- to dark-gray, medium- to very-coarse-grained, massive dolomite which contains a large amount irregularly bedded and rugose chert. The Harmonyvale is a light- to medium-gray or yellowish-gray-weathering medium- to dark-gray, very-fine- to medium-grained, thin- to massive-bedded dolomite containing scattered chert zones.

The Ontelaunee, which ranges from 0 to over 350 feet thick, tends to form a rugged topography due to the large amount of chert. Very few small sinkholes occur. There are 5 small and one moderate size caves known.

The Middle Ordovician Jacksonburg Formation consists of a lower "cement limestone" and upper "cement rock". The "cement limestone" is a light- to dark-gray-weathering, medium- to dark-gray, fine- to coarse-crystalline, fossiliferous, locally high-calcium limestone. A thin- to very-thick dolomite cobble conglomerate and less abundant limestone clast conglomerate can also be present. The "cement rock" is a dark-gray to black, fine-grained, argillaceous limestone with occasional coarse-crystalline limestone beds. The "cement rock" usually has a pronounced cleavage.

The Jacksonburg, which ranges from 100 to over 600 feet in thickness, forms a prominent bench between the underlying units and the Martinsburg Formation. Occasional small to large sinkholes are present. Streams which flow off the Martinsburg tend to sink in the lower part near the contact with the Ontelaunee Formation. There are two known caves, one of which is an old stream course. The stream cave is the moderate sized cave included in the Ontelaunee. The other consists of several large rooms and is the largest cave in terms of volume in the state.

The Jutland klippe sequence, Lower to Middle Ordovician age, is largely shale and sandstone but contains lesser amounts of thin-bedded, fine-grained to aphanitic limestone, dolomite, and pebble conglomerate. The thickness is at least 1500 feet. There are a few small sinkholes but no known caves in New Jersey. In eastern Pennsylvania, this unit contains many caves including the famous Crystal Cave, as well as numerous sinkholes.

The Poxono Island Formation of Upper Silurian age, is a greenish-gray- to yellowish-gray, very-fine-grained, thin- to medium-bedded, flaggy dolomite with discontinuous lenses of rounded quartz sand, with local quartz sandstone and argillaceous dolomite beds. The thickness can range up to 600 feet in the Delaware Valley and up to 275 feet in the Green Pond Mountain region. There are no known caves or sinkholes. Borings for the Tocks Island Dam study intersected many weathered zones with pits and cavities, but they did not seem to be interconnected.

The Bossardville Limestone, which overlies the Poxono Island in the Delaware Valley, consists of a light-gray- to yellowish-gray-weathering, gray- to medium-dark-gray, very-fine-grained, laminated to thin-bedded limestone to argillaceous limestone. Desiccation columns 6 feet or more high occur in the southwest. This formation ranges in thickness from 10 feet at the New York boundary, to over 100 feet in the southwest. It has no known caves or sinkholes.

The Decker Formation, of Upper Silurian age, is a light-gray to yellowish-gray-weathering, light- to medium-dark-gray, flaggy to massive, medium- to coarse-grained, fossiliferous limestone to the northeast of Hainesville. Southwest from Hainesville, it consists of yellowish-gray to grayish-orange, calcareous, quartz-pebble conglomerate, fine- to coarse-grained calcareous sandstone, to siltstone, and arenaceous limestone. Some medium-gray, very-fine-grained dolomite beds also can be present. The Decker ranges from 50 to 80 feet in thickness and contains no known caves and few if any sinkholes.

The Berkshire Valley Formation, in the Green Pond Mountain region, is equivalent to the Decker Formation in the Delawqre Valley. It is a yellowish-gray-weathering, medium-gray to pinkish-gray, very-thin-bedded, fossiliferous limestone, interbedded with a greenish-gray calcareous siltstone and silty dolomite, and less abundant quartz-pebble and limestone-pebble conglomerate. This thickness is 90 to 125 feet and there are no known caves.

The Rondout Formation of Upper Silurian to Lower Devonian age, varies vertically from a lower, medium- to dark-gray, very-fine- to medium-grained, medium-bedded limestone, to a middle, medium-gray, laminated to medium-bedded, argillaceous dolomite, to an upper, medium-dark-gray, fine-grained, medium-bedded, argillaceous limestone to calcareous shale. The total thickness is about 40 feet and it has no known caves or sinkholes.

The Manlius Limestone, of uppermost Silurian age, is included in the Helderburg Group (Epstein and others 1967). Weller (1903) separated it out of the Helderberg based on its gradual contact with the underlying Rondout. It consists of a medium-gray-weathering, medium-gray- to dark-bluish-black, thin- to uneven-bedded, flaggy to massive limestone, and local medium-grained limestone with yellowish-gray shale partings. The thickness ranges from 15 to 45 feet and there are no known caves or sinkholes in the formation in New Jersey, although there are caves in Pennsylvania and New York.

The Coeymans Limestone is of Lower Devonian age, and is the basal member of the Helderburg Group by Weller's (1903) usage. It is a medium-gray-weathering, medium-dark-gray, fine- to coarsely-crystalline, medium- to massive-bedded limestone containing crinoid stems, brachiopods and some chert. The Coeymans has a maximum thickness of 40 feet. There is one known small cave found in New Jersey. A few miles across the river in Pennsylvania there is a small cave, and 3 small and one very large cave (1.5 miles long) in New York within 15 miles of the border. Sinkholes can be rare to very common.

The Stormville Formation - Kalkberg Limestone consists of a light-gray quartz-pebble conglomerate, calcareous to limonitic sandstone, to a medium-gray, fine- to medium-grained fossiliferous limestone. The name Stormville is used to the southwest into Pennslylvania for the sandstones which interfingers with the limestones of the Kalkberg of New York. In New Jersey, northeast of Hainsville a thin finger of the Stormville overlies the Kalkberg; but a few miles into New York it is gone. The thickness ranges up to about 30 feet. There are no known caves or sinkholes.

The New Scotland Formation consists of a lower, medium-gray, fine-grained argillaceous, highly fossiliferous limestone, with chert lenses, knots and irregular beds and an upper dark-gray, very-fine-grained, laminated to thin-bedded, siliceous to slightly calcareous shale containing pods of very-fine-grained limestone and scattered thin beds and lenses of fine-grained argillaceous limestone with some small chert nodules. According to Epstein and others (1972) the New Scotland Formation has a thickness of about 75 feet; Weller (1903) gives a thickness 160 feet. There are no known caves or sinkholes.

The Minisink (Becraft) Limestone is a light-medium-gray-weathering, medium-gray, fine-grained, medium-to massive-bedded argillaceous limestone, fossiliferous and cherty, with lenses of purer limestone. The thickness is about 20 feet and there are no known caves or sinkholes.

The Port Ewen Shale, the top of the Helderburg Group, is a medium-gray-weathering, medium-bedded calcareous siltstone, shale, and silty shale. It is about 150 feet thick and contains no known caves or sinkholes.

The Oriskany Group consists of the Glenarie Formation, Shiver Chert and Ridgely Sandstone. The Glenarie; a medium-gray-weathering, medium- to dark-gray, fine-grained, thin- to medium-bedded, silty limestone with local chert, ranges in thickness from 55 to 170 feet. The Shiver Chert; a medium- to dark-gray-weathering, dark-gray- to-black, medium- to thick-bedded siltstone and shale containing interbedded cherty limestone and chert, ranges in thickness from 0 to 30 feet. The Ridgely Sandstone; a white-weathering, medium-gray, medium- to thick-bedded calcareous, quartz-pebble conglomerate and sandstone, ranges in thickness from 0 to 32 feet. It interfingers laterally with the Glenarie Formation to the northeast.

Glenarie Formation of the Oriskany Group contains the famous Beavan Rock House and two other small caves. There are no known sinkholes.

The Schoharie Formation is a yellowish-gray to pale-olive-weathering, medium- to dark-gray, medium- to thick-bedded calcareous siltstone and some silty limestone with local ribs or pods of black chert. The thickness is 175 feet and there are no known caves or sinkholes.

The Onondaga (Buttermilk Falls) Limestone is a light-gray-weathering, medium-gray, fine-grained, thin- to medium-bedded limestone with nodular and bedded black chert. The name Onondaga is used to the northeast of Millville and Buttermilk Falls to the southwest. The unit is about 150 feet thick and there are two known caves and occasional sinkholes.

The Triassic-Jurassic rocks of the Newark Basin contain rare limestone beds which are a few feet thick, as well as some massive limestone clast conglomerates. There is one known small cave in a thin limestone bed and no sinkholes.

The Vincentown Formation of Paleocene age, in the Coastal Plain, can contain up to 95% calcium carbonate but because it is mainly a loose sand with occasional thin limestone ledges there are no caves or sinkholes present.

KARST

Karst is the type of topography which forms on soluble bedrock and is attributable to solution by ground and surface water. The most common soluble rocks are limestone and dolomite. Other soluble rock types include gypsum and anhydrite and much less commonly halite or rock salt deposits. A unique karst occurs on Mount Sedom, Israel, in the exposed head of a salt diapir (Frumkin, 1994). Solution features in this area take only hundreds of years to form, rather than the thousands of years such features take to form on other soluble rock types.

The main cause of karst land forms is the solution of the bedrock by surface and groundwater, creating voids on and in the bedrock. Howard (1963, p. 46) states "Karst landscapes may be considered composed mainly of three forms: cutters (karren), sinks, and caves."

These solutional or negative features can leave positive features such as pinnacles, karren, lapiés, tower or cone karst, and others. All of these features can be modified by other erosion and or depositional processes. Most karst is characterized by underground drainage and numerous resurgences. Surface streams can be less common than in adjacent non karst areas.

The chemical process of solution on carbonate rocks is well understood. As rain water percolates through the soil zone it can become charged with carbon dioxide from the biological activity in the soil; this forms a weak carbonic acid solution which will slowly dissolve the carbonate rock. In the soil zone and unconsolidated and/or weakly consolidated formations the flow is intergranular through the primary porosity, but in the consolidated rocks the flow is dictated by the secondary porosity, that is, joints, fractures and bedding or foliation planes. When the slightly acidic water comes in contact with carbonate rock it can slowly dissolve the rock away. Over time, joints or fractures will gradually enlarge and become primary conduits for the ground water flow system.

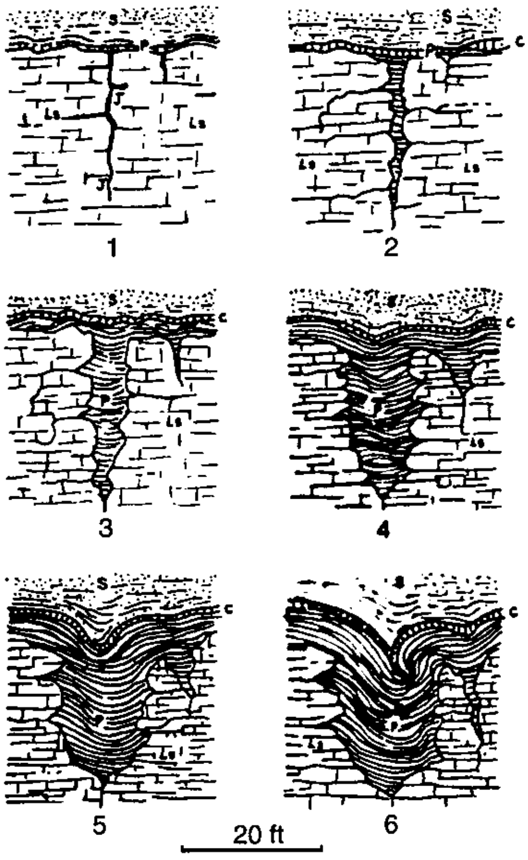

Figure 2.-- The development of cutters (from Hook, 1915). S- soil; Ls- limestone; C- clay seam; J- jointing; P- phosphate

The weakly acidic ground water will slowly dissolve the rock until the water becomes saturated with calcium carbonate. If the saturated ground water is carried away by the flow system the dissolution of the rock will continue and the openings in the rock will become larger. This process can occur both at the rock soil interface as well as deeper in the rock.

As the ground water dissolves the carbonate bedrock, insoluble mineral grains are left behind. Most of the insoluble minerals consist of clay and fine quartz grains. This material forms the residual soils at the surface and the clay fillings in the solution enlarged joints, fractures or bedding openings.

The main negative solution features are cutters, sinkholes, and caves. Cutters (fig. 2) are solution enlarged joints or fractures and are near vertical, regardless of the dip of bedding. They narrow downward and are

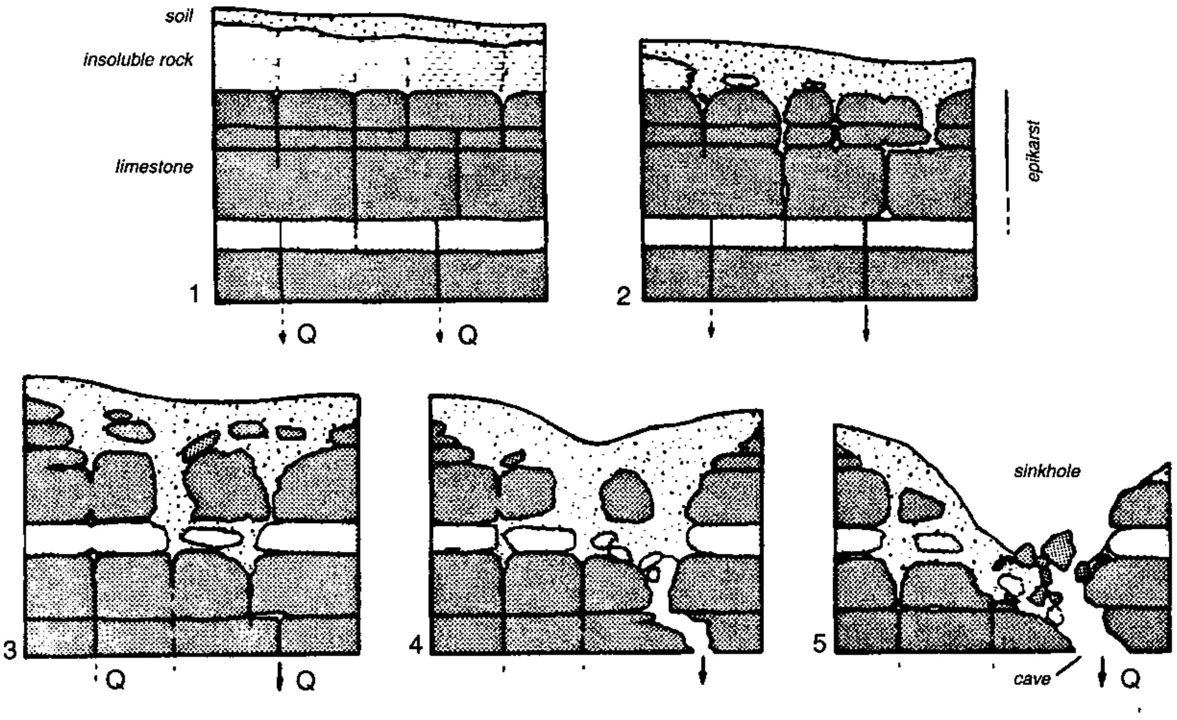

Figure 3.-- Evolution of the epikarst and a typical solutional sinkhole (from Palmer, 1991). The lightly shaded bed is a visual aid in comparing stages. Q indicates ground water flow.

usually clay filled. As the cutters enlarge the bedrock surface becomes very irregular with a series of ridges and/or knobs left between the cutters. These are called pinnacles, and if they are exposed at the surface in long bands they are called karren.

Lapies, according to Howard (1963, p. 47) are small scale ridge and valley type features which form on bedrock at the surface. Bretz (1956, p. 22) applies this term to vertical grooving on cave walls, especially in dome pits, as well as for the ridge and valley grooves which are exposed at the surface. Other workers such as White (1976, p. 13) use the term lapies interchangeably with karren. In this paper, lapies are defined as the smaller scale features formed on exposed bedrock surfaces as described by Howard (1963).

Sinkholes or dolines (as some authors use) can form in several ways: by solution only, by solution collapse and by soil collapse. Solution of the bedrock is required for all forms of sinkholes. The solution sinkhole generally forms along or at intersections of joints or fractures where the soil water can percolate into the underlying bedrock. As this water comes in contact with the rock it can dissolve the carbonate rock and form conical or elongate depressions in it (fig. 3). As more water flows into the depression it will deepen and the residual soil mantel will mimic the shape of the bedrock depression. The general stratigraphy of a solution sinkhole is shown in figure 4 (from Hall, 1976). Figure 5 (Markewicz and Dalton, 1977) is a generalized section of a paleosolution system preserved below the Knox-Beekmantown unconformity in northwestern New

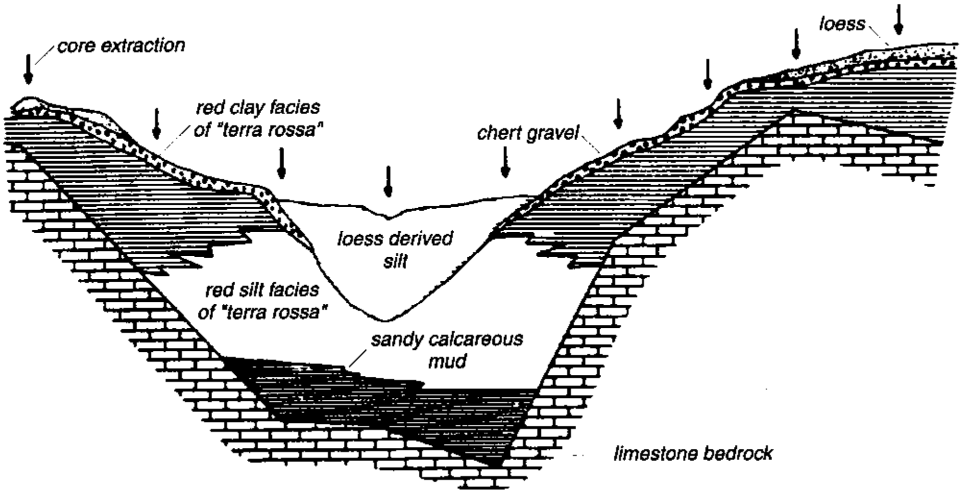

Figure 4.-- Modern sinkhole stratigraphy: south central Indiana (modified from Hall, 1976).

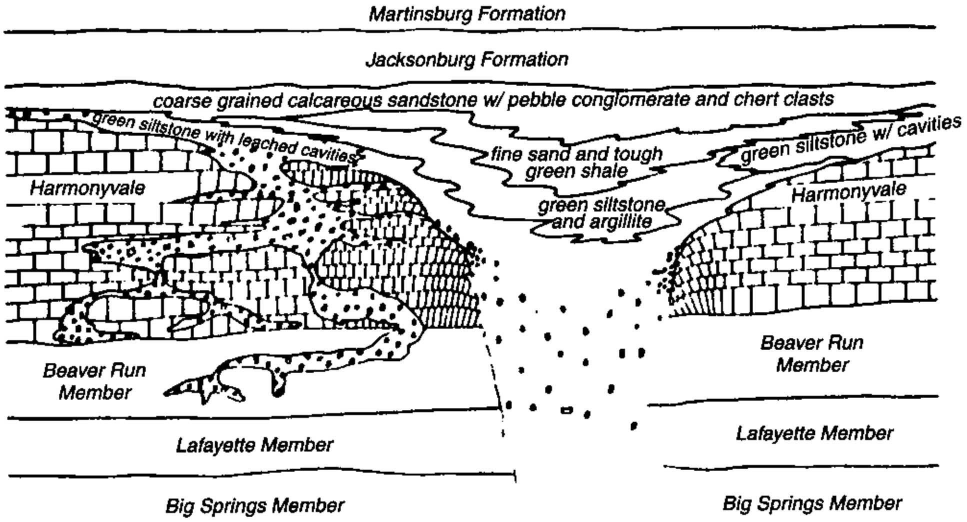

Figure 5.-- Paleo-sinkhole filling near Hamburg, New Jersey (modified from Markewicz and Dalton, 1977).

Jersey. Notice the similarities of the stratigraphy between the two fillings even though the sinkholes formed almost 480 million years apart. This indicates that the processes which formed both are essentially the same.

Solution collapse sinkholes occur when an underground void or cavern is near enough to the surface, and large enough that the rock roof of the void cannot support the weight above it. Stresses

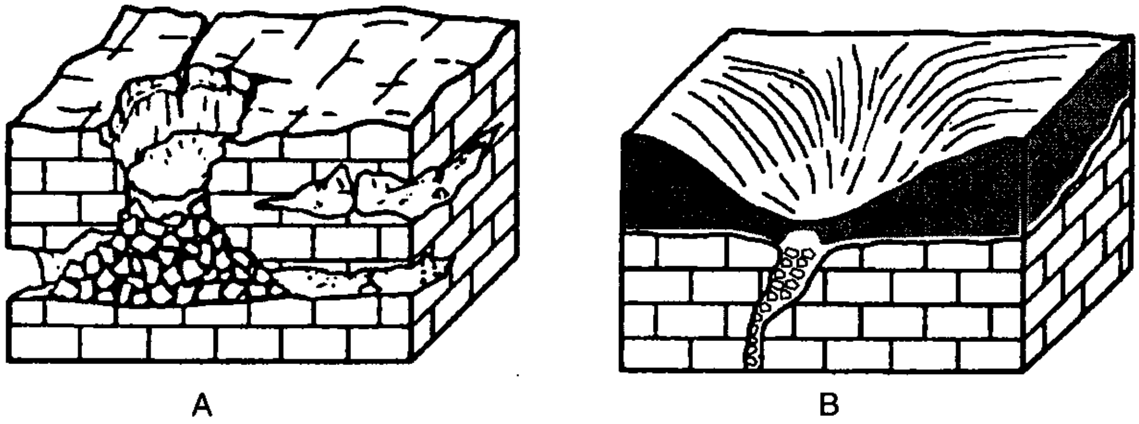

Figure 6.-- Block diagrams of (A) bedrock collapse sinkhole and (B) soil collapse sinkhole (modified from Jennings, 1971).

build up in the rock and blocks of the ceiling rock (breakdowns) fall to the floor of the void. Eventually the entire column of rock to the surface will collapse into the cave or void (fig. 6A). Sinkholes of this type are characterized by exposed vertical rock walls, and the floor will usually contain a jumble of soil and rock. Over time, erosion will gradually cause the sides to become more sloping, like a solution sinkhole, but there will likely be numerous outcroppings of the bedrock on the sides of the sink. In late stage of development it might be difficult to differentiate between a solution and collapse sink.

Soil collapse sinkholes occur when there is a moderate to thick mantle of soil overlying bedrock which has interconnected solution openings. If some of the voids intersect the soil-rock interface they can provide conduits for the soil to be carried into the bedrock voids. As the soil is carried down, a void can form in the soil zone (fig. 6B). Changing soil moisture conditions can cause the soil void to enlarge and stope its way toward the surface. When the soil arch over the void no longer support the weight above, it will suddenly collapse into the void forming a vertical sided depression at the surface. The steep sides of the depression will rapidly (days to months) erode; forming a funnel shaped feature.

If the solution voids become large enough and accessible to human exploration, they are called caves. Caves can range from simple tubes a few feet long to complex networks such as Mammoth Cave, Kentucky which has over 350 miles of mapped passages. In New Jersey, caves range up to 1200 feet in length.

Karst terranes can develop a complex drainage systems. The recharge from rainfall is rapidly transmitted to the groundwater system through sinkholes which are invariably connected to the network of voids in the bedrock (fig. 7). Water flowing over the land and into streams can also enter the groundwater system by sinking streams. A swallow hole is a sinkhole in a stream bed

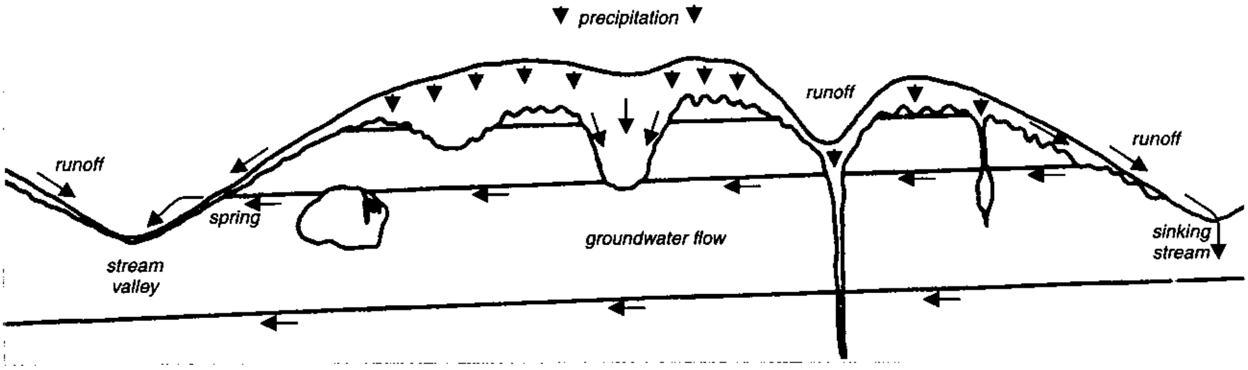

Figure 7.-- Generalized model of movement of water in karst regions from precipitation to the subsurface (modified from Fellows, 1965).

which receives the surface water. There may be no discrete sinkhole where the stream disappears, or it might flow directly into a cave opening.

Karst terranes can also be characterized by box valleys or dry stream valleys which abruptly end. "Rock towers" which result from highly enlarged cutters leaving small, straight-sided towers of bedrock detached from the main outcropping may be present.

The solution action of surface and ground water is not the only modifier of the landscape developed on carbonate bedrock. Sediment can be deposited on top of the bedrock by wind, water, or ice. In New Jersey these types of deposits can mask the true nature of the landscape. Sometimes soil collapse sinks occur in these deposits. If the deposits are too thick, it is likely that no sinkholes are present, although there can be well developed subsurface drainage.

Glacial moraine and outwash deposits can form a pseudo karst topography. Kame and kettle topography results from the melting of buried ice blocks, which cause soil collapse features that look like sinkholes. There are extensive areas of this type of topography on both carbonate and non carbonate bedrock. Sometimes true sinkholes are found within the kame and kettle topography.

Sinkholes in New Jersey range from a few feet across to huge solution collapse features measuring several hundred feet across and over forty feet deep. Some of the features look like long segments of collapsed cave roofs. These can be several hundred feet across and a thousand or more feet long and are similar to the "gulfs" of Missouri (see Field Trip Stop 4).

Many of the sinkholes found in New Jersey were formed by a combination of processes. In the areas north of the terminal moraine, much of the original karst landscape was removed by the glaciers. Then the bedrock was covered by varying thicknesses of glacial deposits, up to several hundred feet thick. Sometimes the solution openings were filled with glacial material. If the underlying voids are open; the glacial deposits are not too thick (50 feet or less) and the water table is deep enough, soil collapse sinks can occur. Palmquist and others (1976) indicate that most sinkhole development occurs in areas where glacial drift is 25 feet or less. There are some documented sinkholes in glacial deposits near Franklin that are 15 to 25 feet deep.

South of the terminal moraine there are some very limited areas of earlier glacial deposits, but most of the sinkholess are found in the original saprolitic soils. There are no identifiable large scale solution collapse features present. South of Phillipsburg near the Delaware River there are several hundred foot wide conical sinks which could be either straight solution sinks or late stage soil collapse sinkholes.

Palmquist and others (1976) also compared sinkhole densities in Iowa to the age of three erosion surfaces, based on the age of the tills. The sinkhole densities were:

Nebraskan - 45 per square mile
Iowan - 10 per square mile
Late Wisconsinan - 4.6 per square mile.

One of their conclusions is that sinkholes begin forming 5,000 to 6,000 years after the surface formed and would continue at a high rate for about 250,000 years.

Warren County was examined to see if there were similar sinkhole densities in New Jersey both north and south of the terminal moraine. The results are as follows:

older than Late Wisconsinan - 9.76 per square mile
Late Wisconsinan - 6.5 per square mile.

There is fairly good agreement between the densities for the late Wisconsinan areas, but the older areas south of the terminal moraine are more problematic since some of the tills there are older than Iowan.

Human activity is one of the main causes of sinkhole formation in an area. Anything that changes the surface-ground water flow system can cause sinkholes to form. The sinkholes that concern people most are the soil collapse sinks, because true solution sinkholes take thousands of years to form. The solution collapse sink is generally not a concern in New Jersey, although if rock is blasted above a cave, the roof can collapse into the void below. The only documentation of this happening in New Jersey occurred at Peapack Quarry during operations in 1958. Following a blast, approximately 600 tons of rock collapsed into a large cave.

White (1976 p. 13), in discussing some of the activities which can cause sinkholes, indicates that "Paving of sinkhole areas leads to concentrated runoff and intensive erosion of soils and weathering and weakening of bedrock where the drainage from parking lots, streets, and roofs is discharged into limestone". This implies that the discharge of runoff into the limestone can cause rapid weathering or solution of the bedrock.

An example of very rapid solution of limestone is discussed by Fink (1945) when a leaky dam foundation in Tennessee was grouted with an intersecting barrier of grout holes. Several intersecting holes cored over a year apart showed the effects of solution and allowed a rate to be calculated. Based on one boring, he estimated about 0.1 inch of solution per year on a high calcium limestone with free water circulation. Fink cites an earlier work by Fox (1941) which yielded about 0.5 inches in 25 years (0.02 inches per year) on a different, but less soluble, limestone also in Tennessee. Solution, even at the higher rate of Fink (1945), would take tens to hundreds of years to produce voids large enough to cause sinkholes in competent rocks like those found in New Jersey; whereas, in areas of less competent rocks that may not be the case.

The prime concern in New Jersey is the development of the soil collapse sinkholes. These can form immediately after or even during construction. There are cases of sinkholes occurring during the drilling of a well or corehole, that resulted in drill rigs being upset. In Washington, New Jersey, a well pump house collapsed and about a half acre became potmarked with sinkholes while a well was being developed.

Water main and/or sewer line leakage has resulted in some spectacular sinkholes in the state. The famous Thomas Street sinkhole in Phillipsburg which swallowed a house, was the result of a water main break. The collapse of the Route 78 bypass around Phillipsburg, just before it was opened, was the result of leaking storm sewer joints. The Route 78 bypass continues to develop numerous sinkholes. Every year, extensive grouting operations are undertaken along this stretch of road. A proper geological investigation prior to the selection of the right-of-way could have saved millions of dollars in repairs which are continually needed to rectify the problem.

REFERENCES

Bretz, J.H., 1956, Caves of Missouri: Missouri Division of Geological Survey and Water Resources, 2nd ser., v. 39, 490 p.

Dalton, R.F. 1976, Caves of New Jersey: New Jersey Geological Survey, Bulletin 70, 51 p.

Dalton, R.F. and Markewicz, F.J.; 1972 Stratigraphy of and characteristics of cavern development in the carbonate rocks of New Jersey: National Speleological Society Bulletin v. 34, No. 4, p. 115-128

Drake, A.A., Jr., Volkert, R.A., Monteverde, D.H., Herman, G.C., Houghton, H.F., Parker, R.A., and Dalton, R.F., 1995, Geologic map of New Jersey: Northern Bedrock Sheet: U.S. Geological Survey Miscellaneous Investigation Series Map I-2540-A, scale 1:100,000.

Epstein, A.G., Epstein, J.B., Spink, W.J., and Jennings, D.S., 1967, Upper Silurian and Lower Devonian stratigraphy of northern Pennsylvania and New Jersey, and southeasternmost New York: U.S. Geological Survey Bulletin 1243, p. 74.

Fellows, L.D., 1965, Cutters and pinnacles in Greene County, Missouri: National Speleological Society, Bulletin v. 27, No.4, p. 143-150.

Frink, J.W., 1945, Solution of limestone beneath Hales Bar Dam: The Journal of Geology, v. 53, No.2, p. 137-139.

Frumkin, A., 1994, Morphology and development of salt caves: National Speleological Society, Bulletin v. 56, No.2, p. 82-95.

Hall, R.D., 1976, Investigations of sinkhole stratigraphy and hydrology, south-central Indiana: National Speleological Society, Bulletin v. 27, No.4, p. 88-93.

Hague, J.M., Baum, J.L., Herman, L.A., and Pickering, R.J., 1956, Geology and structure of the Franklin-Sterling area, New Jersey: Geological Society of America Bulletin, v. 67, p. 435-474.

Hook, J.S., 1915, The brown and blue phosphate rock deposits of south-central Tennessee, v. 4, p. 50-86.

Howard, A.D., 1963, The development of karst features: National Speleological Society, Bulletin v. 25, part 2, p. 53-65.

Markewicz, F.J., and Dalton, Richard, 1977, Stratigraphy and applied geology of the Lower Paleozoic carbonates in northwestern New Jersey: in 42nd Annual Field Conference of Pennsylvania Geologists Guidebook, Harrisburg, Pennsylvania, p. 117.

Palmer, A.N., 1991, Origin and morphology of limestone caves: Geological Society of America, Bulletin, v.103, No.1, p. 1-21.

Palmqurst, R.C., and others. 1976. Doline densities in northeastern Iowa: National Speleological Society, Bulletin v. 38, No.3, p. 57-67.

Weller, Stuart, 1903, The Paleozoic faunas: New Jersey Geological Survey Report on Palenontology, v.III, p. 426.

White, W.B., ed, 1976, Geology and biology of Pennsylvania caves: Pennsylvania Geological Survey, 4th ser., General Geology Report 66, p. 103.

GLOSSARY

Breakdown - Rock fragments and blocks of rock which have fallen from the ceiling.

Cave - A natural opening of size permitting human exploration and extending into a region of sharply reduced or no light.

Conekarst - Karst, usually tropical, dominated by its projecting residual relief rather than by its closed depressions.

Cutters - Solution enlarged, near verticle joints which can intersect the surface.

Dip - The angle of intersection of a passage or bedding with a horizontal plane, measured in a vertical plane from the horizontal downward and at right angles to the direction of the line of intersection.

Doline - See sinkhole.

Dome Pit - An opening extending upward into the ceiling of a cave. Formed by water moving in a vertical plane.

Fissure Passage - A passage that is many times higher than wide. It can be due to solution along joints or fractures in a soluble rock; voids due to contraction in an igneous rock or open fractures in any rock type.

Karren - Exposed bands of bedrock on the surface as long rows.

Karst - A type of topography formed by solution of the bedrock characterized by sinkholes.

Kettle - A depression in glacial outwash and tills formed by the melting of buried ice blocks.

Keyhole Passage - A tube type passage with a fissure at the base.

Lapies - Small scale, sharp crested ridge and valley type features which forms at the surface and are usually a few inches to several feet in height.

Pillar - A bedrock column, from roof to floor, left by removal of surrounding rock.

Pit - A hole in the floor of a passage formed by water moving in a vertical plane.

Resurgence - The point where subsurface waters come to the surface.

Salt Diapir - A mass or dome of rock salt which has pierced up through overlying rocks.

Sinkhole (Doline) - A closed depression at the surface, in areas underlain by soluble bedrock which can be formed either by solution of the bedrock or by collapse of the soil or rock into a deeper void.

Strike - An imaginary line formed by the intersection of the bedding in the rock with a horizontal plane.

Swallow Hole - A closed depression or doline into which all or part of a stream disappears underground.

Towerkarst - Conekarst in which the residual hills have very steep to overhanging lower slopes. There may be alluvial plains between the towers and flat-floored depressions within them.

Vadose Streams - Streams which flow in the vadose zone.

Vadose Zone - The region below the surface and above the water table.

KARST SITE INVESTIGATIONS:
New Jersey & Pennsylvania Sinkhole Formation and Its Influence on Site Investigation

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ABSTRACT

Sinkhole formation in the Cambrian-Ordovician-aged carbonate rocks of the northeastern United States generally results from mechanisms markedly different than those occurring in the younger and softer carbonates of the southeastern United States and Caribbean. Besides the northeastern rocks being older and stronger, the effects of a long and violent tectonic history have impacted the typical vagaries of long-term subsurface solutioning.

Site investigation can be the result of a need for basic hazard identification or it can be development-driven. Both types of site study are initiated in the same manner. The geotechnically oriented investigation goes perhaps one step further in that both hazard and risk need to be identified.

The major sinkhole formation mechanism in the northeast seems to be the ravelling of soils into existing cavities within the bedrock. Cave roof collapse also occurs, though is of lesser concern except where heavy construction loads are anticipated. Thus, in identifying existing hazards or potential risks, the concerns are, in most cases, a soil (or soil mechanics) problem, not a rock problem. Rock mechanics likely enters the picture only if the investigation is directed toward supporting heavy structures in areas of more flat-lying bedding.

As a result, subsurface investigation in the karst terrane of New Jersey and Pennsylvania is directed toward identifying sinkhole occurrence as it relates to existing subsurface conditions over time periods measured in decades not millennia. Many ingredients go into assessing both hazard and risk; soil/rock type and condition, tectonic history, bedding dip, history of sinkhole occurrence, topography, surface water flows, and type of construction, to name a few.

A multi-phased "geotechnical" investigation program for the identification of sinkhole hazards and for the evaluation of potential sinkhole formation as well as for other construction-related concerns is described. The procedures are directed toward highlighting the site specific mechanisms and characteristics that influence sinkhole occurrence and the associated variations in physical properties of both soil and rock.

INTRODUCTION

To many, this paper may seem like preaching to the choir. However, reviews of professional documents over recent years and experience at numerous karst sites throughout New Jersey and Pennsylvania has revealed what appears to be a wide-spread ignorance of the nature of northeastern U.S. karst and its possible effects on engineered construction. For instance, in a discussion concerning the cause of building settlement, an architect related that an engineer indicated "the problem with limestone is the rapid rate that it dissolves after construction" and that this was likely causing subsurface holes at the site. One geologist testified that cavities in carbonates get bigger with depth and unless you excavated thirty feet or so into rock you might not see sinkholes at the site in question (that was without having looked at aerial photographs of the site). Finally, a lawyer indicated that remediation for a limestone site only costs about $1,000 per known (preconstruction) sinkhole. This information was apparently sound to him as his cost data came from an excavator who had filled a sinkhole with concrete.

New Jersey and Pennsylvania have hard rock karst which is found in or near Appalachian Valleys, generally in Cambrian-Ordovician-aged sediments. Also, a number of ancient solution features have been found in local Proterozoic marbles. The occurrence, effects and remediation of sinkholes in these rocks is quite different than in the softer, more porous limestones of Florida and the Caribbean.

In addition, the solutioning and near-surface competency of some of these hard, more northerly rocks have been affected by glaciation which stripped any incompetent surficial rock, and some 20 thousand years ago, provided a protective cover. These affects have both geologic and engineering significance. These same rocks have been folded and stressed by a series of major tectonic events. Generally, in northwestern New Jersey/Eastern Pennsylvania, this has resulted in steeply dipping beds (Figure 1A), not flat-lying beds as in text book renderings (Figure 1B), as well as enhanced solutioning.

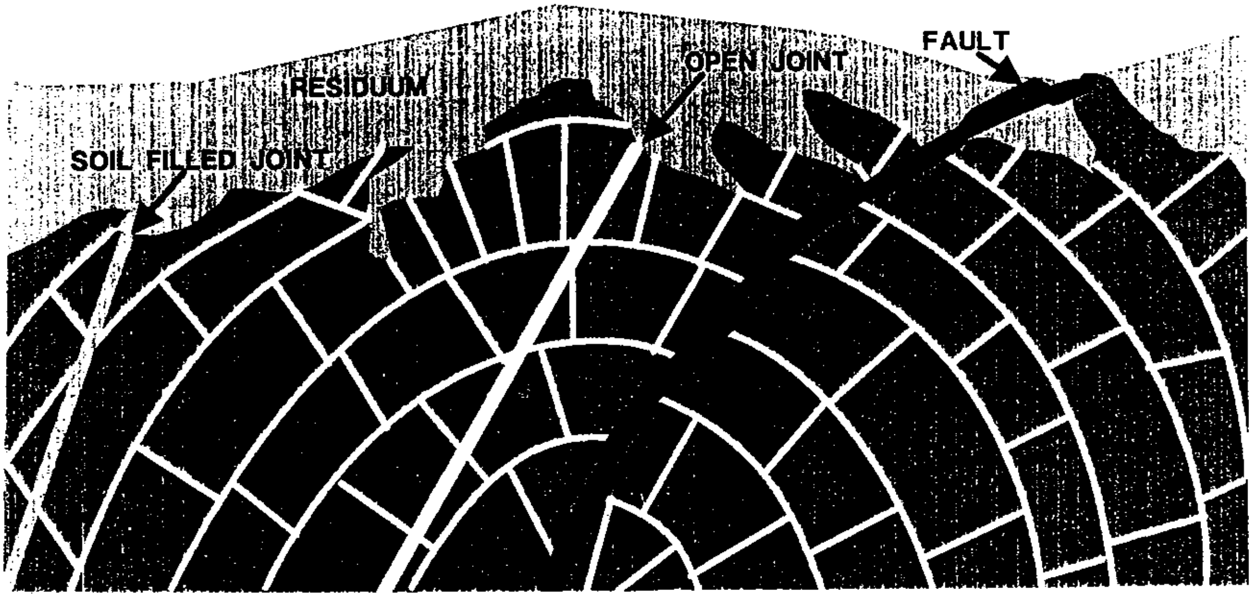

Figure 1A - Typical Folded Rock Section

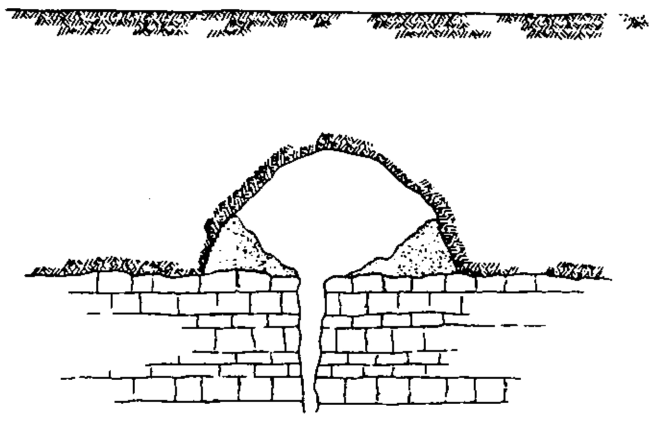

Figure 1B - Typical Textbook Flat Rock Section
From: Reitz & Eskridge (1977)

As a result of many geologic factors, it is difficult to predict variations in subsurface conditions, not only from one site to another, but from location to location across a particular site. For example, Figures 2A and 2B show a prospective development site in Bethlehem Township, New Jersey (presently in COAH arbitration hearings). Aside from the number of formations shown on Figure 2A (each with their own range of characteristics), past tectonic events (as evidenced by faulting and the repeated sequence of formations) have further complicated the already confounding nature of a karst site. Fortunately, as a result of carbonate rock studies by both Pennsylvania and New Jersey State agencies, much information is available to the engineering geologist and geotechnical engineer who must provide a useful (and of course cost-effective) evaluation of such complex subsurface conditions.

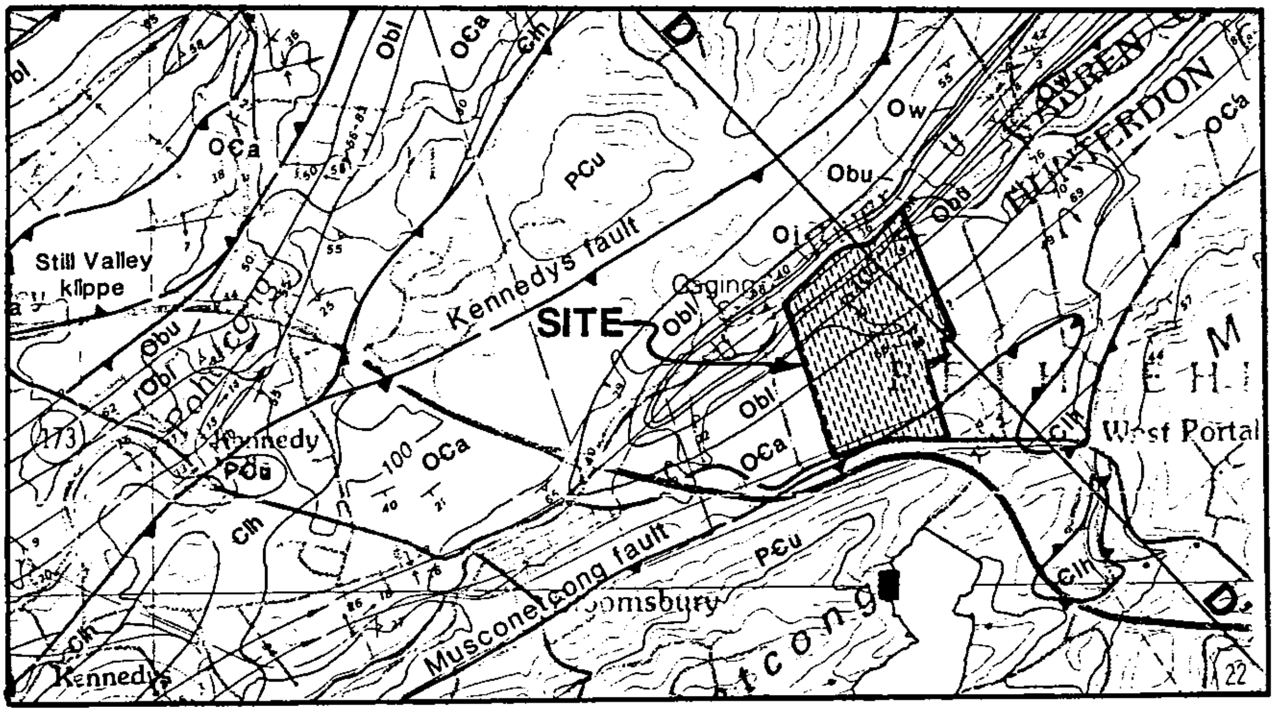

Figure 2A - Bethlehem Township Area Geologic Map
From: Herman and Monteverde (1989)

In the harder, northeastern carbonates, sinkhole occurrence is generally of two types, ravel (or solution) and collapse (see Figure 3A and 3B). Of the two, ravelling sinkholes are the most prevalent. In a sinkhole conference proceedings preamble, Beck (1984) defines ravelling or "subsidence" sinkholes as forming "by the piping of unconsolidated overburden into karstic openings in the underlying soluble bedrock", and "collapse sinkholes arise when the roof of a bedrock cavern collapses; such incidents are rare". Karst sinkholes (or dolines) are not the same as what the New Jersey Department of Environmental Protection refers to as subsidence pit collapse which are also sinkholes to the media.

The authors have performed investigations from differing perspectives, both research and geotechnically driven. However, the need to understand the subsurface is equally important whether one maps an area for basic geologic purposes or for eventual site development. Once the geotechnical engineer has a sound geologic data base, he should proceed in developing planning and design recommendations. The layout of a development in karst, as well as facility design, can only be predicated upon a reasonable (and unfortunately never complete) understanding of the subsurface.

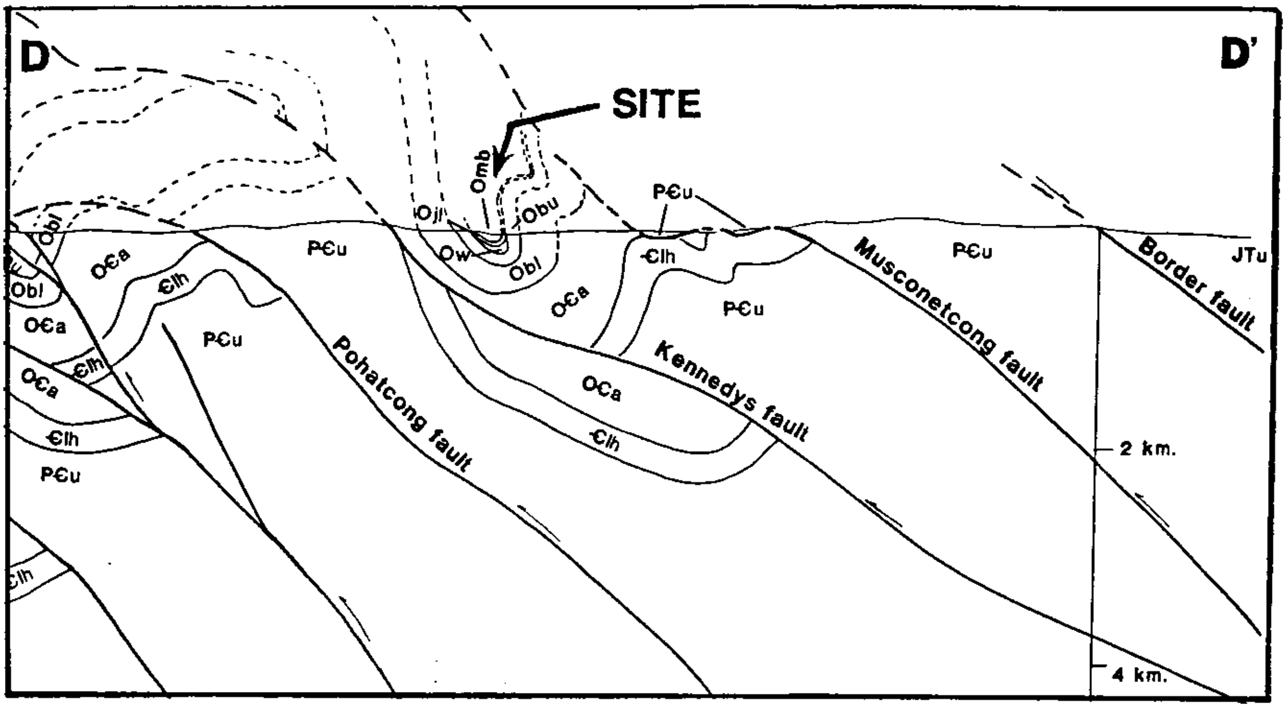

Figure 2B - Bethlehem Township Area Cross-Section
From: Herman and Monteverde (1989)

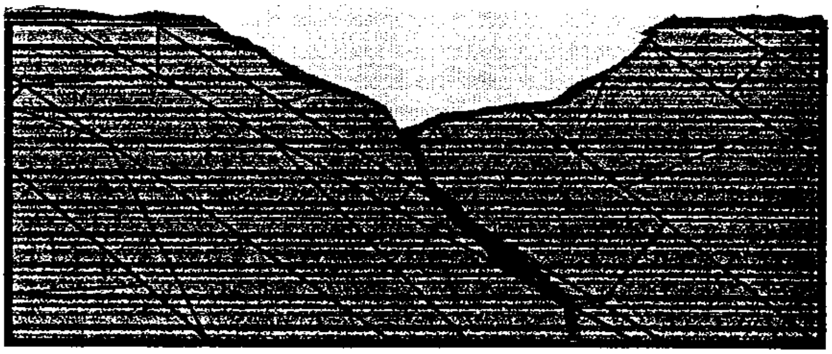

Figure 3A - Ravel (Solution) Sinkhole

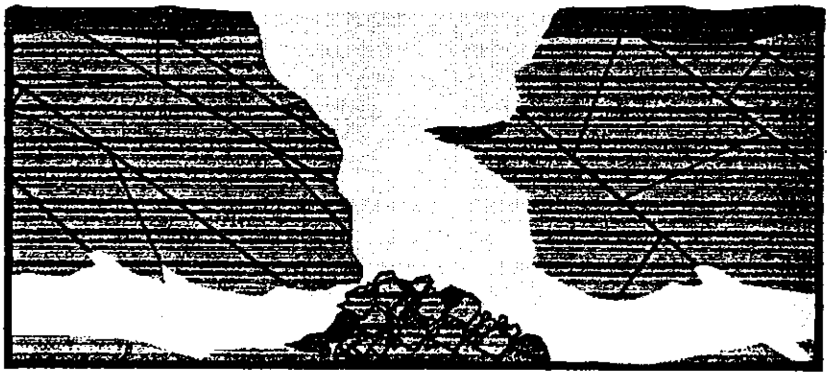

Figure 3B - Cave Collapse Sinkhole

In our experience, almost any investigation is driven by economics with the full understanding that one cannot define all possible subsurface variations at a karst site. The additional step in a study driven by planning and engineering considerations is the necessity to evaluate the effects of these variations upon any planned construction. Locally, one generally starts under the premise that the rocks are folded and faulted; that they rarely exhibit horizontal bedding; that different formations (and different beds within the same member or formation) weather differently; that stressing can enhance weathering; that some fault zones are relatively open while others have been recemented to varying degrees; that water infiltration rate and acidity affect weathering; that topography affects weathering; and that glacial activity may have either exacerbated solutioning or provided an effective soil cover (after stripping weathered rock and near-surface cavities), but only for some few million years. All of these variables affect investigation and interpretation.

SINKHOLE FORMATION

The carbonate rocks of New Jersey and Pennsylvania are susceptible to solutioning. Generally, it is assumed that acidic water converts calcium carbonate into soluble calcium bicarbonate. A weak carbonic acid can be formed from rain water with the addition of carbon dioxide. Thus, precipitation can become acidic as it percolates through decomposing organic matter in the vadose zone.

The effectiveness of the acidic water in dissolving carbonates is greatest when it first comes into contact with the rock. The acidity of the solution decreases as the water becomes increasingly saturated with dissolved material. The susceptibility of the rock to solutioning may vary with grain-size, composition, number of openings (passages through which the acidic water flows) and the level of stress to which the rock has been exposed. Protection from solutioning can be provided by the deposition of solutional residue as well as the thickness and permeability of the overburden soils.

Figure 4 depicts a typical karst subsurface for an area of dipping bedding and it can be seen how the continued movement of water carrying soil into the underlying solutioned zones results in a slowly growing soil arch above a soil void. Erosion of soil through downward percolating water is the conventional assumption of ravelling type sinkhole formation (e.g., Jennings, 1965 and Fischer and Greene, 1984). However, Reits and Eskridge (1977) postulated a surging effect from underground, upward ground water flow enlarging soil voids. While not currently accepted as the primary cause of ravelling sinkholes, this possible influence in soil erosion over cavernous rocks should not be discounted if the appropriate geohydrological conditions exist. No matter what the source of the water, increased flow increases the rate of soil movement. The downward percolation of acidic water could continue to dissolve the rocks below. However, the rate of dissolution is generally much slower than the movement of new soil into existing voids, particularly when man alters the flow of water by construction. These alterations include increasing runoff with impervious cover and funneling storm water into existing or constructed depressions or low spots (often called detention basins). In addition, construction operations may remove or reduce soil arch thickness through excavation or increase the load on the arch by areal fills or the placement of "engineered" construction. Thus, in our attempt to predict future performance (i.e., risk), a soil-related problem develops which was created by the existing solutioned rock conditions

A cavern collapse phenomenon is more likely to occur when bedding is more flat-lying. Dissolution or increased loading removes or weakens the roof of a previously solutioned zone. The cavern roof collapses and the soils above enter the underlying void quickly at first, then more slowly with the inflow of surface water. As in any type of sinkhole, water is a concern, but a natural or man-made loading is the likely cause of the collapse.

In performing a geotechnical site investigation the concern is ordinarily with the prospect of future sinkhole formation. However, the problems of the typically great irregularity in rock surface elevation as well as the large, erratic changes in the properties of both the rock and residual soils over short horizontal and vertical distances also arise. While sinkholes may be the most graphic geotechnical risk, the irregular subsurface can often be as costly a penalty in constructing in karst terrane. Thus, site investigation is complex and many conventional

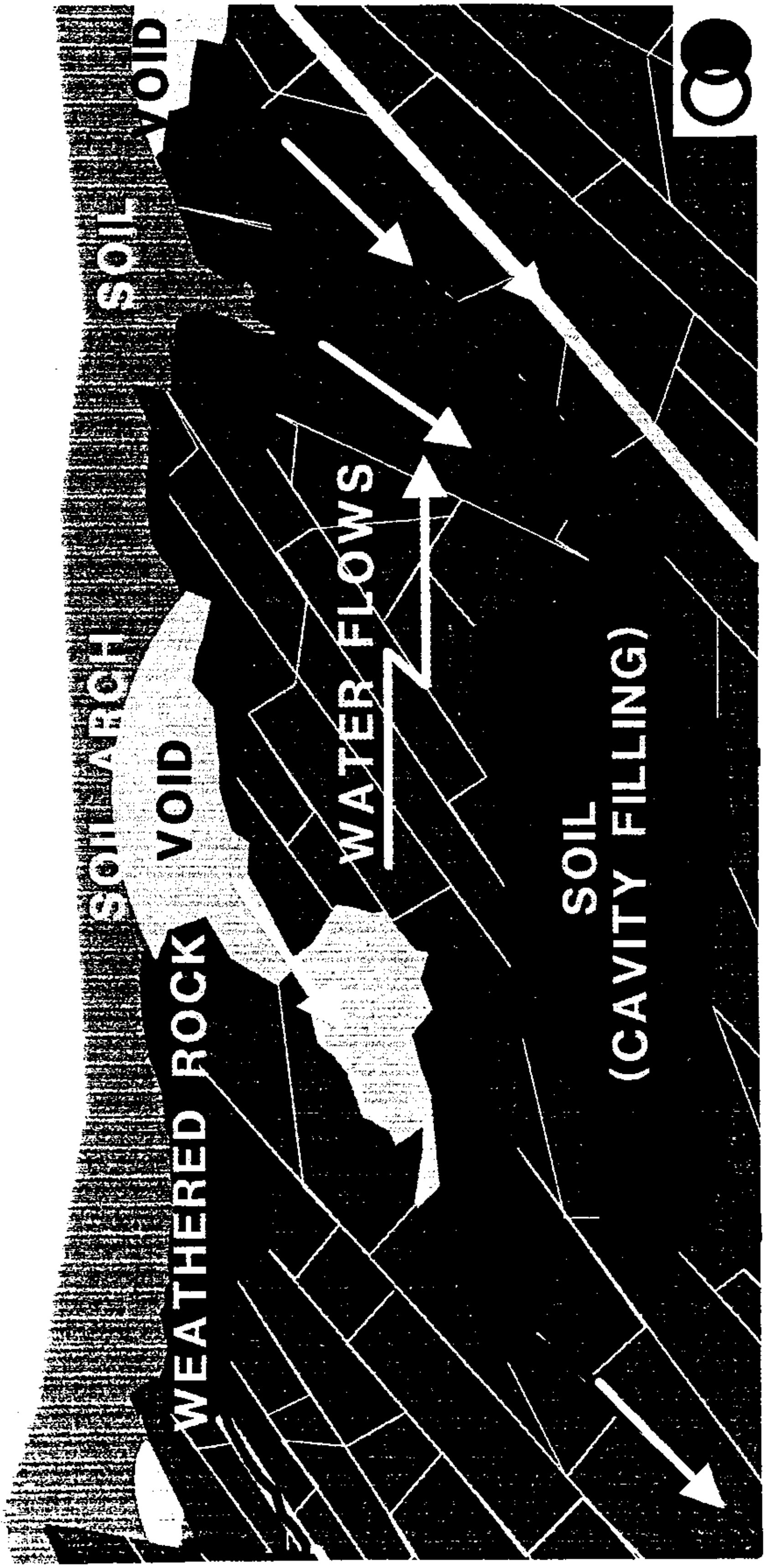

Figure 4 - Typical Karst Cross-Section

geotechnical investigation and evaluation techniques are not applicable to predicting future risks and estimating construction costs.

SITE INVESTIGATION

Until recently, commercial and home development in metropolitan New York and New Jersey has mostly taken place in areas where the subsurface was relatively consistent. With the apparent population shift trending westward to and beyond the Delaware River, more karst sites are being developed. At first, most developers approached sites in areas of carbonate rocks in a conventional manner. With little exception, the awareness of the difficulties in constructing in karst areas have only become apparent through the institution of "limestone" ordinances by more and more municipalities and by media reports of sinkhole occurrences. Therefore, many developers and their engineers are experiencing the problems inherent in constructing in karst only as they build or shortly after construction is complete.

Assuming that no geotechnically oriented investigation will be funded at a level that allows a complete picture of the karst subsurface, site studies are generally performed in phases and with a strong emphasis on obtaining "geologic" data rather than trying to define the actual physical parameters of the soils or rock below each loaded area. A multi-phased approach has been developed with the understanding that data will even be obtained during the construction phase and incorporated into final design. The concepts were developed through both geologic research and geotechnical studies. The field procedures were developed as a result of the combined experience of a number of geological, geotechnical and drilling personnel.

The "model ordinance" developed by the North Jersey Resource Conservation and Development Council's Limestone Committee essentially uses this multi-phased approach to geotechnical investigation, allowing a development design team to become more familiar with the site subsurface conditions as the program progresses from phase to phase.

PHASE 1 - SITE INVESTIGATION

In any "limestone" investigation, the greatest return on investment is possible during the initial (Phase 1) stage of any site study. The first step is to review the data available from federal and state sources. Aerial photography of the site, taken over a period of at least a decade, should be obtained as karst features may develop over time. Annual cycles of precipitation and drought can highlight different features at different times. Features visible in early photographs may be obscured later by man's activities. Persistent lineaments and circular shapes are particularly suspicious when they are observed on a number of photographs taken over extended time periods. Photographs taken after periods of high precipitation can reveal interesting patterns of subsurface and near-surface water movement which can aid in developing a preliminary geologic model of the area in question. "Home-flown" oblique photographs taken at low sun angles and after precipitation events can be particularly effective in delineating areas requiring ground-truthing.

Aerial photography (and sometimes satellite imagery) in combination with the available geologic information are used as the bases for a reconnaissance of the site and surrounding locale. Areas that farmers avoid during cultivation often represent rock pinnacles or persistent sinkholes. Forested areas in otherwise fully-farmed lands generally indicate areas of shallow rock or possibly intense sinkhole activity. Changes in vegetation from photo to photo sometimes indicate incipient sinkhole activity. Obviously, photo-lineaments, depressions, possible sinkholes, disappearing streams, springs, wetlands, etc. must be investigated on-site. One of the observations usually made in a site reconnaissance is that ground surface elevation variations across an area underlain by carbonates is generally greater than they appear from a distance. These variations usually represent stratigraphic differences or geologic structure that has been emphasized by differential solutioning or weathering.

A geologic reconnaissance using the readily available data is a necessary step in any investigation of a karst site. In a geologic hazard evaluation such as a New Jersey or Pennsylvania Geological Survey project, it may often be the last step as these agencies are usually called in only after a problem is recognized. A geotechnically oriented study provides the opportunity to confirm the data developed to this point and the necessary ground work for the next phase of the work.

The amount of useful information that can be developed by an experienced engineering geologist from this preliminary phase is surprisingly large. The findings usually allow a number of decisions to be made in a geotechnical investigation. From a planning or construction standpoint, the simplest approach may be to remove the site from further construction considerations. This conclusion is often valid. Alternately, if only a portion of the site can be developed economically, site planning may be able to account for the carbonate rock concerns or the purchaser of the site may find it's time to reevaluate its' worth.

PHASE 2 - GEOTECHNICAL INVESTIGATION

The results of the preliminary survey and the needs of proposed construction will likely lead to additional site study for an important development project. A Phase 2 investigation is mostly used to confirm and expand Phase 1 findings through direct subsurface investigation which generally includes a number of test pits and borings at key locations. This phase of the investigation should be used to further explore geologically suspect areas identified in Phase 1 as well as critical facility areas and storm water detention/retention areas in a typical development. The emphasis of a Phase 2 investigation is to provide both hard data and allow, at least conceptually, for structures, roadways, utilities, and other facilities to be located and designed in a manner appropriate for the subsurface conditions likely to be encountered throughout the site (not just at the locations drilled or excavated). However, so as not to escalate the cost of this phase, much extrapolation is necessary to expand the limited information gathered to this point into a loose but coherent geologic model of the whole site. One must also recognize that the variations that can occur over short distances will usually preclude the development of an all encompassing geologic model.

Test pits can be performed with conventional equipment and are obviously quite informative, particularly when a comparatively large area of rock is revealed in the pit bottom. The undulating or even disappearing rock surface is a surprise to many investigators. Often, 10 foot long test pits have encountered shallow rock at one end and none at the other. Soil characteristics are also diagnostic. Is there a simple pattern of weathering in the pit side; or is there evidence of leaching or ground water movement; or an old, filled sinkhole; or soil voids; is the bedding dip identifiable in residual soils? Backfill in test pits should always be compacted to densities essentially the same as the in situ materials. Very often, soil log test pits become new sinkholes because poorly placed backfill allowed water to erode soils into an existing, underlying cavity.

Test borings should be drilled with rotary wash drilling procedures without the addition of drilling "muds" to allow water loss depths and quantities to be monitored. Drill water is often lost above the top of the rock indicating ground water flow had previously carried the generally clayey residual soils into a nearby (but not necessarily directly below) cavity within the rock. Often, water losses occur well above the rock (tens of feet) indicating large cavity formation, sometimes partially- or fully-filled with soft, sticky soils. Sampling is usually accomplished with a conventional split spoon, although the softer materials are sometimes difficult to retain even with a split spoon using the appropriate trap.

Encountering rock is always an adventure. Is it sound, broken, weathered (to what degree), and what sort of angle is the rock surface at? Numerous roller bits and drill rods remain in the ground as testimony to the difficulty of attempting to advance a hole in creviced or pinnacled limestone.

Rock core should be extracted with a double- or triple-tube, split core barrel. This equipment takes no longer to advance in the borehole and perhaps only an extra minute or two to extract the core. The information gleaned from a core run lying in the split barrel, not "hammered" out of a conventional barrel, is invaluable. Conventionally, numerous fractures, some open, some soil-filled, are evidenced. Often, cavity fill materials are recovered. Sometimes there is little in the core barrel when the softer or looser soils filling a cavity wash away during drilling. Ten to twenty foot runs with a five foot core barrel are not uncommon. Making a five foot core run in competent material is rare in New Jersey and Pennsylvania karst terranes. Obviously, an experienced driller is a must.

Many indirect procedures have been advanced for the detection of subsurface cavities and rock contours which have not yet become surface features (depressions, outcrops or dolines). A host of geophysical techniques have been suggested as suitable, including seismic reflection and refraction, electrical resistivity and conductivity, self potential, ground penetrating radar, and gravity surveys. If one is aware of the nature of the subsurface target and the resolution available with most commercial equipment, it is difficult to visualize how these geophysical prospecting procedures can be considered any more than marginally useful in karstic areas. They function only in an auxiliary role to the performance of direct measurements of subsurface parameters. Pinnacled rock, large floating boulders, the sometimes limited size and nature of soil voids, clayey soils, and the lack of a coherent ground water table compromise the use of geophysical surveys in most karst engineering applications in the northeast.

It is valuable to recognize, however, that at times such indirect methods can be effectively combined with direct methods of investigation such as test borings and test pits.

However, geophysical methods cannot be substituted for carefully drilled test borings, qualified full-time inspection, experienced and professional drillers, and large diameter (Nx-sized or larger) double- or triple-tube split barrel coring. There is invaluable information to be gained through examining water-softened soils immediately above the rock surface, noting drilling water losses at various depths, observing clay-filled seams within the rock, transported soils, stained joints, and/or weathered cavity or joint sides in a full 5-foot run laid out in the core barrel, or watching the drill rods fall through a 2-inch seam or a 10-foot void and into soft cavity fills.

Pneumatic probes can be quite valuable when used in conjunction with test borings because of an air-track's mobility, speed of drilling and relative economy, at least at shallow depths (less than about 40 feet). Although no core is extracted, rock depths and qualitative competency can be estimated. With an experienced operator, it is possible to see or feel major changes in the stiffness of the overburden soils as well as measuring penetration rate differences in variable quality rock. Noting the depths that air loss is experienced also aids in understanding the subsurface. Observing air returns from a previously drilled probe hole after noting its disappearance from the hole in progress can be quite informative.

Aside from the soil and rock data available from test borings and pneumatic probes, grouting (or attempting to grout) the borehole is informative. A conventional, lean cement, water, bentonite grout can be used. The quantities of grout placed downhole should be measured. However, after several tens of cubic feet of grout have been introduced into a 1½ cubic foot borehole, it is often necessary to employ unconventional means to plug the hole so as to prevent water infiltration and possible future sinkhole occurrence.

PHASE 3 - GEOTECHNICAL INVESTIGATIONS

Phase 3 takes the conclusions drawn from all of the work to this point, considers the proposed development layout, and performs more detailed subsurface investigations (as necessary) to further expand the information in critical areas. The investigation can be performed in a single field program or as a long-term program as the site is being developed. For example, if a number of homes with basements have been planned for an area identified as likely having shallow rock, test pits at each major facility location may be appropriate to help in estimating whether rock will be encountered and whether it is "rippable" or will require blasting. In addition, signs of past or incipient sinkhole formation may be observed from the ground surface in the test pit wall. If heavily loaded or settlement sensitive facilities are proposed, then drilling below the proposed locations or even at each column location may be warranted.

Sometimes, the Phase 3 investigations can include remedial grouting such as suggested in Fischer and Fischer (1995). An exploration/grouting program is generally quite cost-effective at this stage (prior to construction), rather than after failure has occurred. Although remediation can be accomplished in a number of ways, downhole tremie grouting and shallow excavation with sinkhole (rock) throat closure are generally the most economical.

SUMMARY AND CONCLUSION

There is a relatively large amount of karst terrane in New Jersey and Pennsylvania. Fortunately, both the public and professionals are beginning to realize that solutioned carbonate rocks can spell trouble both from potential ground water contamination and facility safety standpoint. The manner in which the subsurface in karst areas is investigated differs somewhat from conventional engineering geologic/soil mechanics investigations. The need for special procedures and equipment is easily understood when one recognizes the nature of our local karst. No amount of geotechnical investigation can precisely predict all variations across a site, hence, a geologic understanding of the likely heterogeneity of the subsurface is the primary prerequisite in performing an adequate, cost-effective evaluation of a karst site.

REFERENCES

Beck, B.F., 1984, Sinkhole Terminology. In Sinkholes: Their Geology, Engineering & Environmental Impact, A.A. Balkema, Boston, MA.

Fischer, J.A. & J.J. Fischer, 1995, Karst Site Remediation. In Karst Geohazards, A.A. Balkema, Boston, MA.

Fischer, J.A. & R.W. Greene, 1984, New Jersey Sinkholes - Distribution, Formation, Effects, Geotechnical Engineering. In Proc. of 1st Multidisciplinary Conf. on Sinkholes, Orlando FL.

Herman, G.C. & D.H. Monteverde, 1989, Tectonic Framework of Paleozoic Rocks of Northwestern New Jersey; Bedrock Structure and Balanced Cross-Sections of the Valley and Ridge Province and Southwest Highlands Area. In Paleozoic Geology of the Kittatinny Valley and Southwest Highlands Area, NJ, Lafayette College, Easton, PA.

Jennings, J.E., A.B.A. Brink, A. Louw, & G.D. Gowan, 1965, Sinkholes and Subsidence in the Transvaal Dolomite of South Africa. In Proc. of 6th Int. Conf. on Soil Mechanics and Foundation Engineering, Montreal, Canada.

Reitz, H.M. & D.S. Eskridge, 1977, Construction Methods Which Recognize the Mechanics of Sinkhole Development. In Hydrologic Problems in Karst Regions, Western Kentucky Univ., KY.

Underground Radon in New Jersey: A Case Study

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ABSTRACT

The United States Geological Survey and New Jersey Geological Survey measured Radon concentrations exceeding 20,000 picocuries per liter in the carbonate rocks in the Clinton, Hunterdon County, New Jersey area. Recognition of the health hazards that result from the inhalation of radon prompted monitoring of one of New Jersey's largest and most visited caves in this area. The cave is situated in a unique geologic environment which exposes a Northwest striking thrust fault with Precambrian granite overlying Cambrian dolomite. Radon concentrations in the cave were measured via both activated charcoal and alpha track detectors during various seasons with exposure times ranging from 2 to 4 days up to 7 months. Concentrations measured ranged from 0.8 to 316 picocuries per liter. Currently there are no enforceable radon regulations for residential environments just a guidance value of 4 picocuries per liter. Enforceable maximum limit radon concentrations for the occupational environment are promulgated by State and Federal regulations at four Working Level Months per year. Applying the occupational radon regulations for a limited number of visits to the cave indicates that recreational use of the cave is within acceptable radon exposure limits.

INTRODUCTION

The purpose of this paper is to describe and evaluate the levels of radon found in a cave environment and assess the risk posed by periodic visitation.

Increased awareness of possible health problems associated with indoor radon in homes prompted an investigation toward understanding the govermental radon regulations, guidelines and the concentration, and distribution of radon in one of New Jersey's largest caves. This paper is intended to provide the methodology and results, as well as the regulations that apply to radon.

Radon measurements were made during eight separate visits to the cave. During the first two visits in 1986, two activated charcoal canister measurement devices were placed in the largest room and lowest elevation portion of the cave and their location was mapped. The canisters remained in place for four days and were subsequently removed for analysis. Concentrations of radon detected at the largest room in the cave were 190 and 220 picocuries per liter (piC/L).

In the spring of 1994, ten activated charcoal canisters and one alpha track detection device were placed at various locations throughout the cave to estimate the horizontal and vertical radon distribution within the cave. The charcoal detectors remained in place for two days prior their removal. The first alpha track detector was placed at the base of a vertical pit and remained in place for approximately four months.

Finally, during the fall of 1994, a second alpha track detector was installed in the same location as the first alpha detector and subsequently remained in place for three months prior to analyses. Each device was subsequently analyzed by DMA Radtech, Inc. of Chester, New Jersey.

PHYSIOGRAPHIC AND GEOLOGIC SETTING

The studied cave is one of New Jersey's largest caves and is located near Clinton, Hunterdon County, within the Highlands Physiographic Province also known as the Reading Prong. The elevation in the area of the cave ranges from 300 to 550 feet above sea level. The cave is located in a rural area at a former quarry.

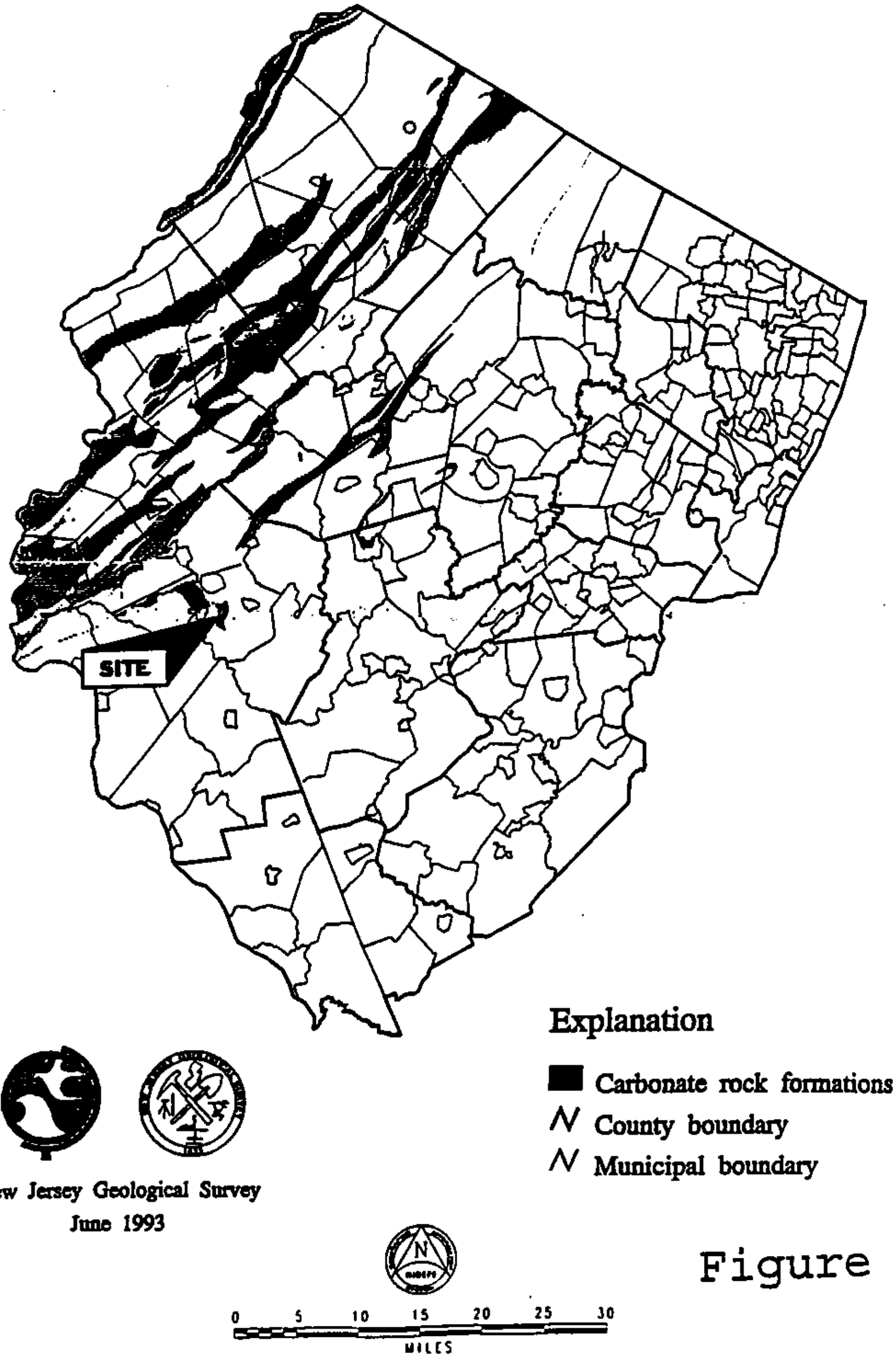
In the area of the cave, the Highlands Province contains Precambrian granitic rocks of the Byram Intrusive Suite, the Losee Metamorphic suite and includes minor Paleozoic outcrops of Cambrian sandstone and Ordovician dolomites. Within one-half mile west of the cave are Triassic sedimentary rocks and to the east Jurassic Diabase and sedimentary rocks. A generalized stratigraphic table of the rock units in the area is presented in Table 1.

The dissected geology resulting from complex faulting in the Clinton area, including the Jutland klippe, may be the result of strike slip duplex formation during the early Mesozoic rifting of Pangea. Left-lateral movement along the Ramapo Border Fault in this vicinity during the early stages of the rifting of the Newark basin may have developed a right step-over fault offset at a restraining bend in the main fault strand. The section of the main strand in the study area extends generally from Spruce Run Reservoir southwest to the Delaware River. The offset strand extends from Round Valley Reservoir northeast to near Gladstone. Fractures or ramps connected these two fault segments resulting in a contractional duplex (Woodcock and Fischer, 1985). Horses within the contractional duplex were shuffled vertically and rotated along reverse, oblique, and normal faults between the main boundary fault strands resulting in the outcrop puzzle preserved today (Laney and Gates, 1996) Stresses causing strike slip faulting rotated to result in oblique and normal movements dominating along the Border fault later during the extensional history. Intrabasinal faults, including the Flemington Fault, formed toward the end of basin rifting. (Schlische, 1992).

The cave is located in a structurally complex, highly faulted area at the border of the Piedmont Province and the Highlands Province (Figure 2). In the study area, the northeast trending Flemington Fault forms the boundary between Precambrian and Paleozoic rocks of the Highlands and Mesozoic rocks of the Piedmont. A minor northwest trending thrust fault approximately one-half mile long (on outcrop) is bounded to the east by the Flemington Fault and to the west by an unnamed Paleozoic normal fault (personal communication with Rich Volkert). The Flemington

Carbonate Rocks of New Jersey

Generalized from the New Jersey Atlas Sheet Series Geologic Overlays



Explanation

■ Carbonate rock formations

County boundary

Municipal boundary

New Jersey Geological Survey
June 1993

Figure 1

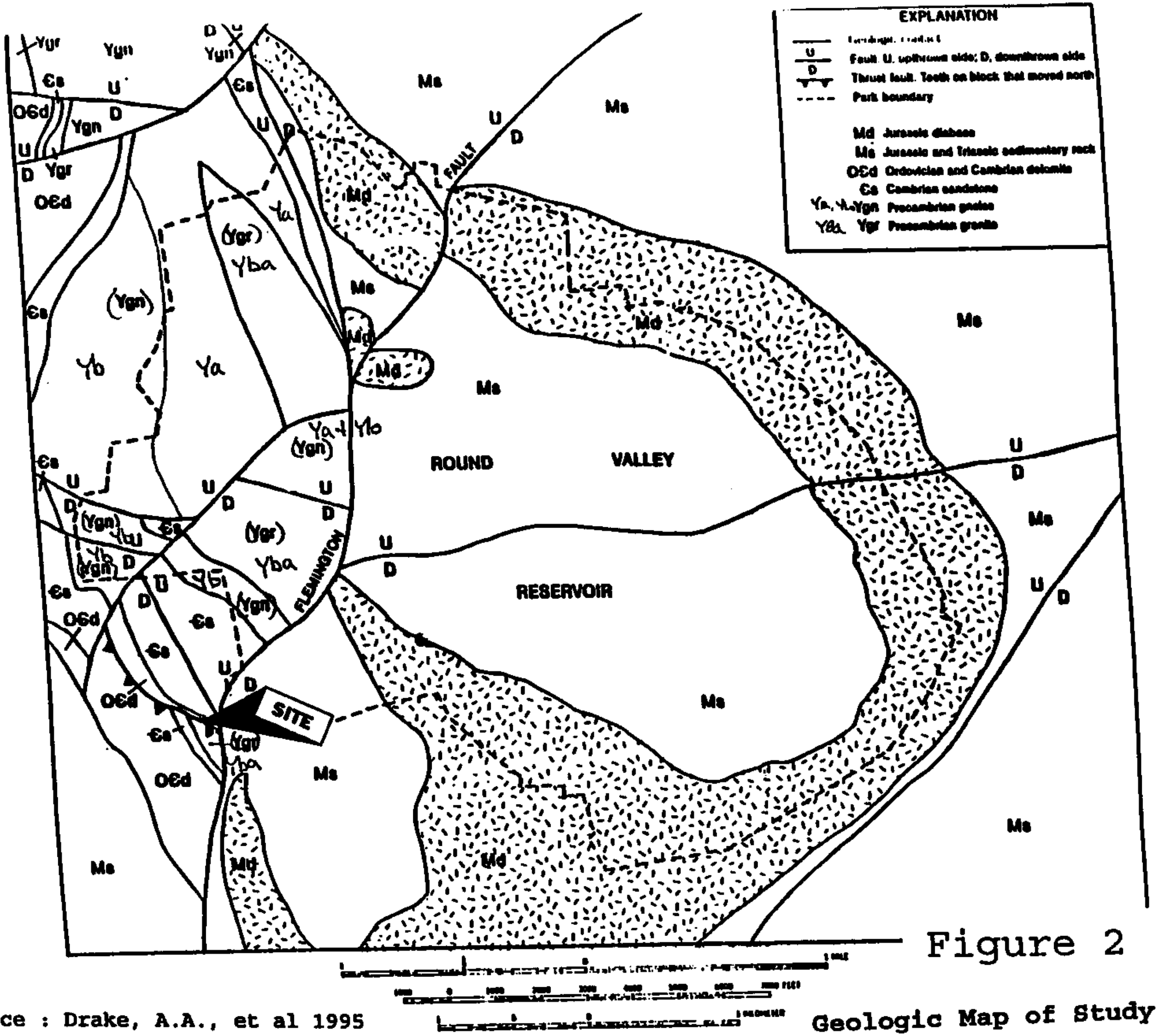


Figure 2

Source : Drake, A.A., et al 1995

Geologic Map of Study Area

Fault truncates the thrust fault. South of the study area, the Flemington Fault separates the Triassic Stockton Formation from the Jurassic Diabase and Passaic Formation.

The cave is located at the contact of the thrust fault which exposes PreCambrian granite of the Byram Intrusive Suite over Middle Cambrian dolomite of the Leithsville Formation. This thrust fault is older than the Flemington Fault based upon cross-cutting relationships. The Flemington Fault is younger than the Mesozoic rocks, because these rocks are affected by the faults. Many of the older faults in the area were reactivated during the Mesozoic (Volkert, in press).

The Flemington Fault is a northeast trending normal fault which merges into splays of the Border Fault also known as the Ramapo Fault. In the area of the cave the normal and reverse faults have strikes that trend both NE and NW. The block on the west or north side of the normal fault moved upward, while the block on the east or south side dropped downward. The exception is the reverse fault at the cave, in which the Precambrian rocks on the south side of the fault were thrust upward over the Paleozoic rocks on the north side (Volkert, in press).

Table 1
Generalized Stratigraphic Table of the Area

ERA	SYSTEM	STRATIGRAPHIC UNIT
Mesozoic	Jurassic	Intrusive Diabase
	Jurassic-Triassic	Passaic Formation
	Triassic	Stockton Formation
Paleozoic	Middle Cambrian	Leithsville Formation
	Lower Cambrian	Hardyston Formation
Proterozoic	Byram Intrusive Suite	PreCambrian Granite
	Losee Metamorphic Suite	PreCambrian Gneiss

Possibly four major deformation periods juxtaposed these geologic units into their present positions. Generally the Grenville Orogeny folded the basement rocks, the Paleozoic rocks were folded and thrust faulted during the Taconic and Alleghenian Orogenies. Mesozoic extensional rifting also affected the rocks in the area with the intrusion of the diabase Cushetunk Mountain.

CAVE GEOLOGY AND DESCRIPTION

The area of the cave is not typical of karst terrain. A thin slice of Paleozoic dolomite and sandstone was thrust in place between Precambrian and Mesozoic rocks. The cave is located in the Leithsville Formation, which is of Middle Cambrian age and Precambrian rocks of the Byram Intrusive Suite (Volkert, in press). The Precambrian granite unconformably overlies the Cambrian dolomite at the contact of the thrust fault. The Leithsville Formation is a light medium gray, fine to medium grained dolomite. The Precambrian rocks consist of microperthite alaskite (Dalton 1976). The existence of the cave is primarily due to a combination of the Northwest trending thrust fault, as well as lithologic and hydrochemical factors.

In the quarry, where the two cave entrances are, the thrust fault is exposed at the surface and exhibits an undulose character dipping approximately 20°SW. The cave passages are controlled by the fault. The most distant point from the entrance is also the lowest portion of the cave at approximately 50 feet below the level of the cave entrance. Throughout the cave the ceiling is predominantly Precambrian granite while the floor and walls of the cave are Paleozoic dolomite. Numerous slickenslides, and fault gouge are also present in the cave. Karst cave features such as stalactites are not present because the insoluble Precambrian ceiling does not provide a source of calcium carbonate to precipitate. However many pits occur within the dolomite floor. Most of the pits are approximately 20 feet deep, with the largest at 45 feet in the dome pit room. The pits are aligned with the fracture sets intersecting the Precambrian roof.

The cave is probably the largest cave in New Jersey in terms of total underground volume and contains over 800 feet of passages. The general plan of the cave indicates that it was formed below the water table (Dalton, 1976). Currently, the cave is located within the vadose zone.

RADON OCCURRENCE IN THE CLINTON AREA

Radon-222 is found virtually everywhere in soil and water (EPA 1992). In the Precambrian crystalline rocks of the Reading Prong and in adjacent Paleozoic carbonate rocks, radon occurrences are associated with the uranium-rich hornblende granites and alaskites. In the Clinton area during 1986, the New Jersey Geological Survey discovered extremely high radon data. Radon concentrations were measured as high as 20,000 piC/L. These data were collected from charcoal canisters placed in soil borings (Muessig, 1988).

PHYSICAL PROPERTIES OF RADON

Radon is a product of the decay of the naturally occurring isotopes of uranium 238 (238 U) and thorium 232 (232 Th). Radon is a naturally occurring, chemically inert, radioactive gas. Radon is the heaviest known gas with a density of gas 9.73 grams per liter. Radon is also odorless, invisible and without taste; thus, it cannot be detected with the human senses. Twenty isotopes of radon are known (Weast, 1974)

RADON DATA FROM THE CAVE

Grab samples of radon were collected using the two most common types of detectors, charcoal and alpha track canisters. Charcoal canisters are simply cans filled with activated charcoal. The charcoal detectors are short term monitoring devices exposed between 2 and 4 days. Charcoal detectors are passive devices permitting radon in air to diffuse into the canister which is adsorbed onto charcoal.

The second type of detector used was the alpha track particle etch detector. These devices require typically two or more months of exposure. This device consists of a film material that sustains damage along the track of an alpha particle. As radon diffuses through the filter into the container, alpha particles emitted by radon and its daughter decay products strike the detector and produce submicroscopic damage tracks. At the end of the measurement period, the detectors are returned to the laboratory. The film material is placed in a caustic solution that accentuates the damaged tracks so they can be counted using a microscope. The number of tracks per area is correlated to the radon concentration in air. This type of detector is sensitive to dust and electrostatic charges which make the alpha track detectors susceptible to error. Portions of the cave contain dust which is present with traffic from cavers.

Two Alpha track monitors were placed at the same location within the cave and monitored radon from 6/16/94 to 9/10/94 and then 9/10/94 to 4/27/95. The first monitor recorded 67 (piC/L) during the summer months and over the winter the second unit measured 21 (piC/L).

Table 2
Horizontal and Vertical Radon Distribution Measurements

Radon Concentration (piC/L)	Depth Below Entrance (feet)	Horizontal Distance From Entrance (feet)	Detector Type
1	0	5	Charcoal
170	17	95	Charcoal
135	20	21	Charcoal
100	25	85	Charcoal
316	29	34	Charcoal
200	30	52	Charcoal
172	42	101	Charcoal
134	45	70	Charcoal
167	47	82	Charcoal
165	55	95	Charcoal
67	25	10	Alpha Track
21	25	10	Alpha Track

Radon data from the Cave are presented in several ways with the concentration units in piC/L. The data are shown in a plan view map of the cave in Figure 3 and in a cross-section map as Figure 4. The vertical distance of the detectors measured from the depth below the upper cave entrance versus the radon concentrations is presented in a graph in Figure 5. The placement of the detectors measured horizontally from the cave entrance versus the radon concentrations measured is graphed and shown in Figure 6. The radon concentrations, type of detector and vertical and horizontal distances from the cave entrance are shown in Table 2. No apparent trend was evident in the graphs. The alpha track data are not included in the graphs.

RADON MEASUREMENT UNITS

Radon gas concentrations are expressed with various units, the most common are; picocuries per liter (piC/L), working level (WL) and Working Level Month (WLM). One piC/L is equivalent to 2.2 disintegrations per minute of a radioactive material per liter. A concentration of 1 piC/L translates to approximately 0.005 WL. One WL is equivalent to the concentration of short lived radon decays that will result in 130,000 million electron volts of potential alpha particle decay energy per liter of air. The conversion from piC/l to WL is 200 piC/L is equivalent to 1 WL. Cumulative exposure is measured by the Working Level Month (WLM), defined as the exposure received from breathing air at one WL concentration for 170 hours working per month (40 hours/week), or other combinations of concentration and time. The WLM was developed to describe exposures sustained by miners during the average number of hours spent underground.

The maximum annual cumulative time allowed for an average radon concentration can be determined by the following equation.

Maximum Time in Hours = (170 Hours * 4 WLM) / Average Radon Concentration in WL

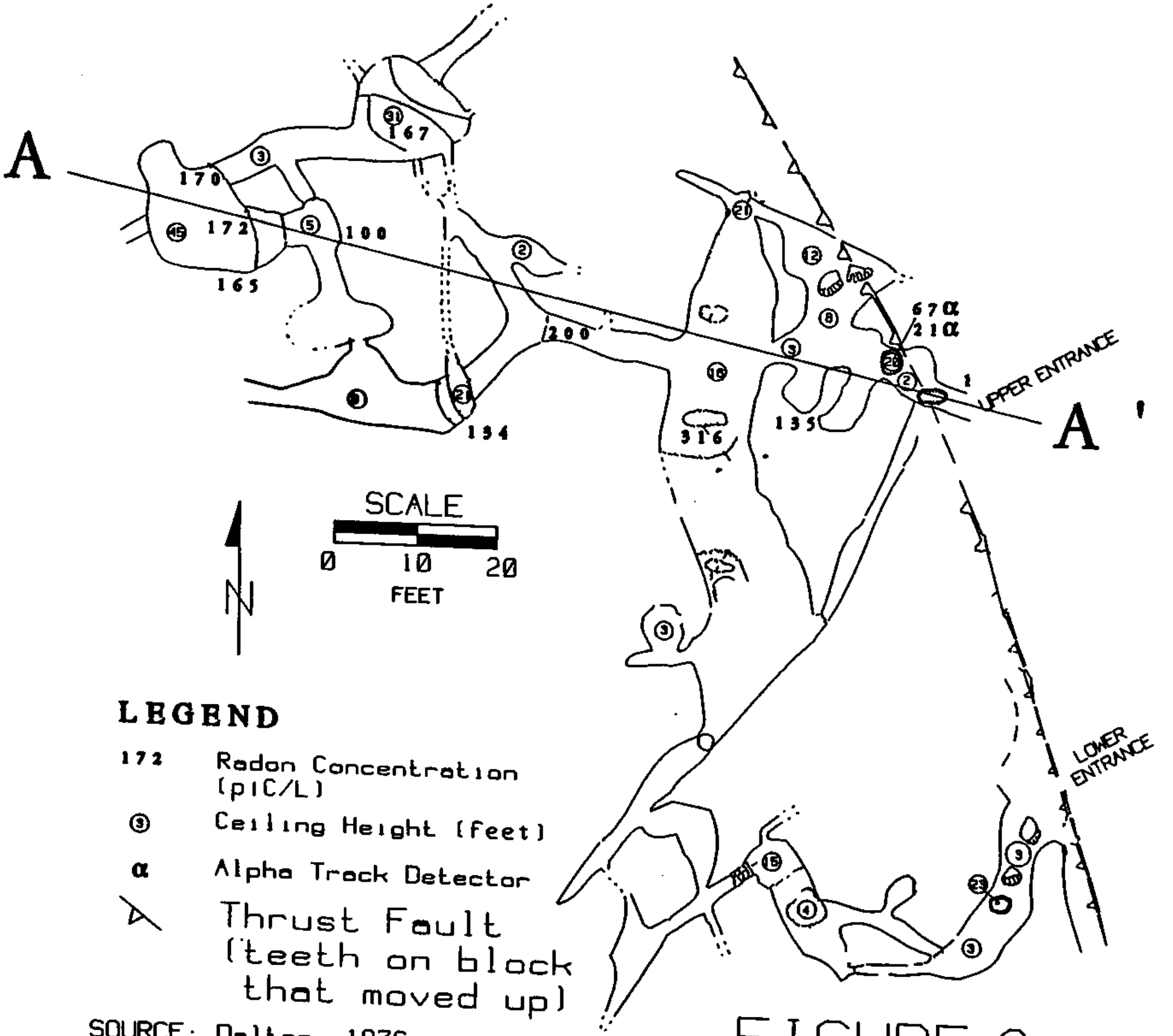
CLASSIFICATION

Radon is classified as a known carcinogen (Group A) based upon data from epidemiological studies of underground uranium miners (EPA 1992).

STANDARDS AND REGULATIONS

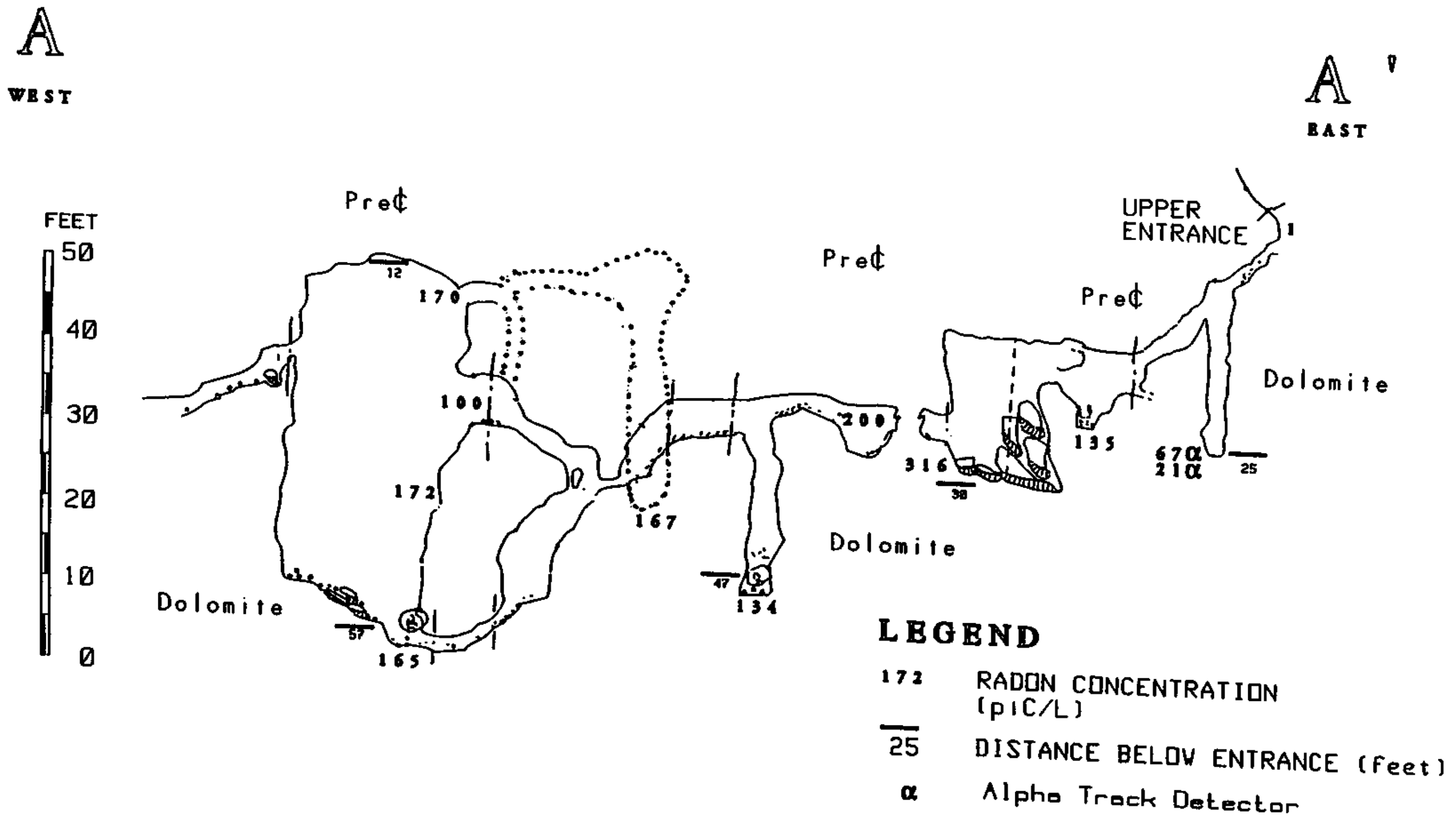
Currently, no regulations mandate specific radon levels for indoor residential environments. There are only guideline recommendations which the EPA and NJDEP encourage action to reduce levels to less than four picocuries per liter. For the working or occupational environment, Federal and New Jersey State regulations limit the maximum cumulative radon exposure to 4 WLM per year.

In October 1988, the Indoor Radon Abatement Act was passed. This Act states that the national long term goal is to recommend a radon concentration of four piC/l or less for an indoor residential and school environment with mitigation suggested above 4 piC/l.



SOURCE: Dalton, 1976

FIGURE 3
Radon Distribution in Plan View



SOURCE: Dalton, 1976

Radon Distribution in Cross Section View

FIGURE 4

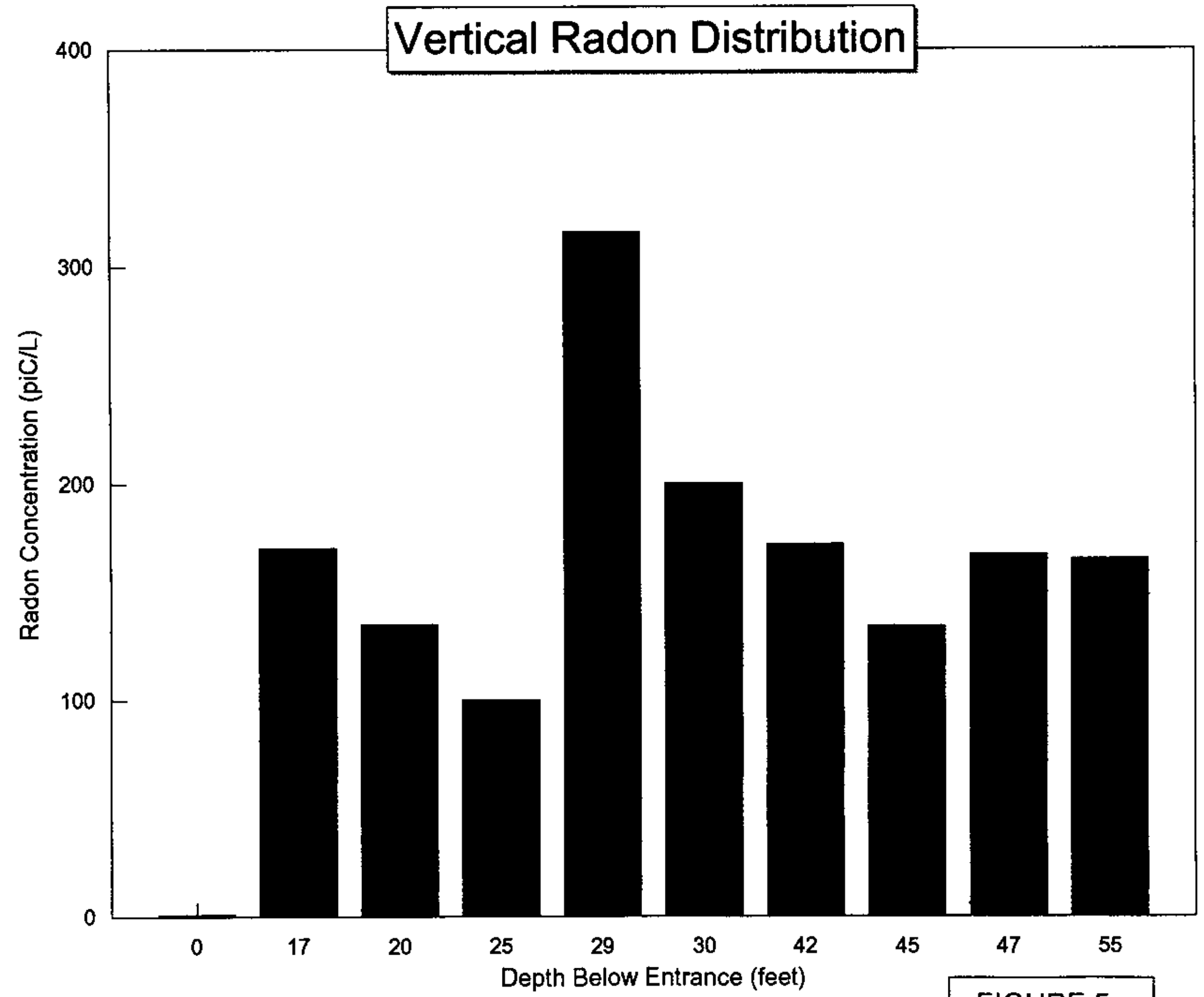

Vertical Radon Distribution
Radon Concentration (piC/L)
400
300
200
100
0
0
17
20
25
29
30
42
45
47
55
Depth Below Entrance (feet)

FIGURE 5

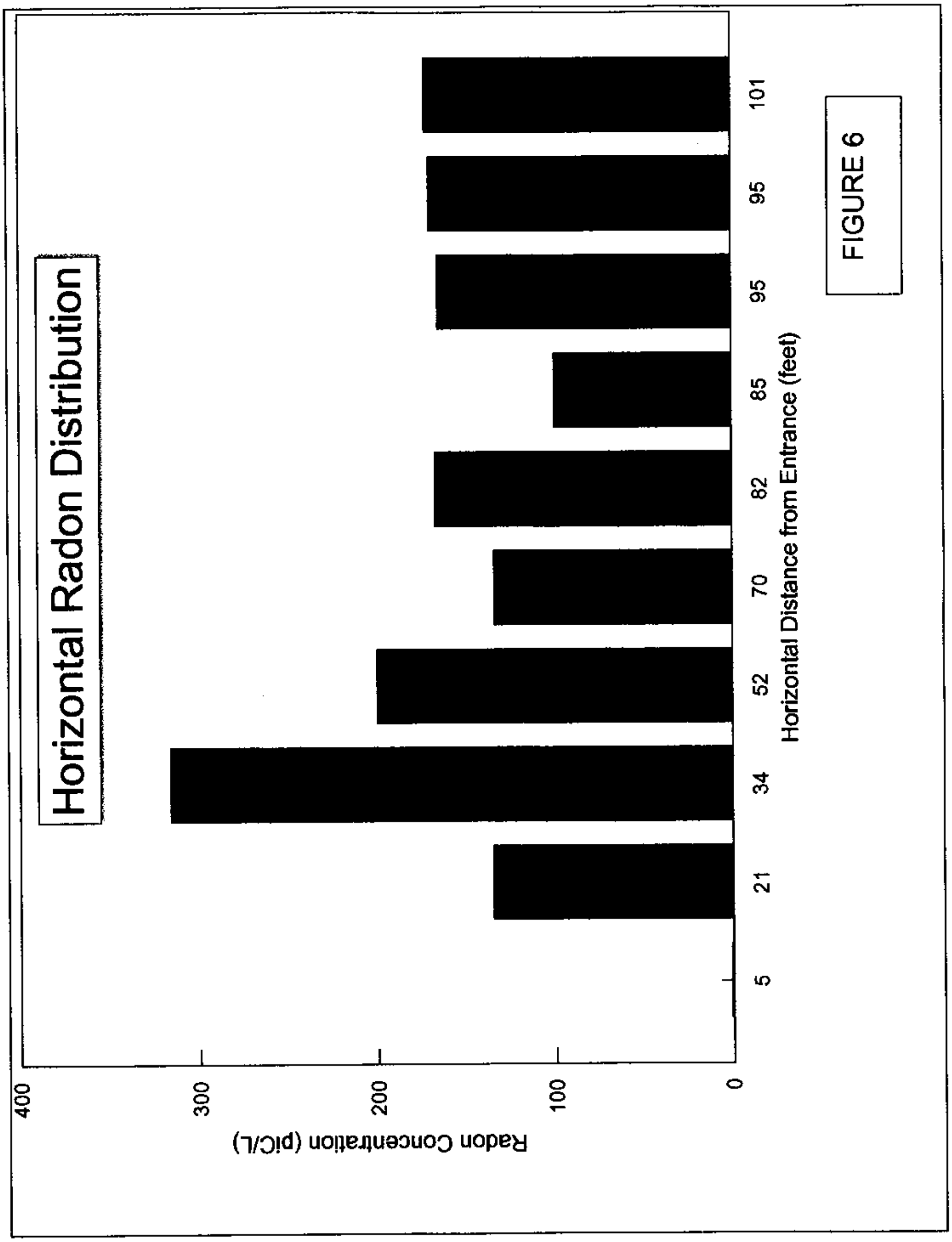

Horizontal Radon Distribution
Radon Concentration (piC/L)
0
100
200
300
400
Horizontal Distance from Entrance (feet)
5
21
34
52
70
82
85
95
95
101

FIGURE 6

Specific regulations apply to the occupational aspects of radon. The Occupational Safety and Health Administration (OSHA) and the Mine Safety and Health Administration (MSHA) regulate radon exposure to a cumulative level of 4 WLM/yr. The National Institute for Occupational Safety and Health (NIOSH) advises an exposure limit of 1 WLM/yr. OSHA has not established a permissible exposure limit (PEL) for radon.

NEW JERSEY RADON REGULATIONS

As of May 13, 1991 with the NJDEP Radon Certification Program, anyone testing or mitigatiting for radon in New Jersey must be certified by the NJDEP. Certification is mandatory pursuant to NJSA 26:2D-70. NJDEP has basically adopted the EPA's residential action level of four piC/L and for an occupational situation a maximum cumulative exposure of four WLM/yr.

DISCUSSION AND CONCLUSION

Results of this study show that a variation of radon concentrations exist within the cave. Varying radon levels in the cave maybe related to geological circumstances such as the ratio of surface area of PreCambrian rocks versus dolomite in a given sampling area or factors such as dust and humidity. Other factors such as the placement of the detector with respect to the vertical or horizontal distance from the cave entrance shows no correlation. Ventilation and permeability of the rock may also affect radon concentrations.

Although there are no explicit regulations requiring or limiting radon exposure to the general public, a guideline of four picocuries per liter is recommended in residential environments. Federal and State regulations require that occupational exposure to radon shall be controlled so that no indivual will receive no more than four Working Level Months in any calendar year, no such regulations exist for naturally occuring radon in caves.

Because most persons spend much more than 170 hours on a monthly basis in their homes a Working Level standard is inappropriate for residential environments. Thus, if one assumes that 70 % of time (6,000 hours) is spent at home, a 1 WL concentration (200 piC/l would yield an exposure of 3 WLM monthly or 36 WLM annually (Samet 1989). This annual cummulative exposure would exceed the occupational criteria by a factor of 9. Similarly, if one were to use the occupational regulations and apply the maximum annual cummulative exposure of 4 WLM to the periodic visits to this cave, it is possible to determine the maximum annual exposure time. If it is assumed that 200 piC/L or 1 WL is the average radon concentration in the cave and each caving event is 8 hours long than the maximum number of days, annually, a person should be in the cave is 85 days. The calculation is as follows:

680 Hours is the Maximum Time = (170 Hours * 4 WLM) / Radon Concentration of 1 WL
680 hours/8 hours per day = 85 days

Exposure to radon in the cave may exceed residential guidelines however, using occupational criteria, it is unlikely that any person will exceed the annual cummulative exposure of 4 Working Level Months. The radon concentrations within the cave, appears to be a minimal risk to the caving community at this cave. The radon within the cave should not be used as a means to discourage use of the cave. It is highly unlikely any person will exceed an annual exposure of 4 WLM.

A registration program is established requiring persons to sign a release form prior to each visit to the Cave. These records are maintained on a yearly basis. The records can be reviewed as an audit to estimate total individual average exposure time.

REFERENCES

Dalton, R.F., 1976, Caves of New Jersey, New Jersey Geological Survey, Bulletin 70.

Drake, A.A., Jr., Volkert, R.A., Monteverde, D.H., Herman, G.C., Houghton, H.F., Parker, R.A., and Dalton, R.F., 1995, Geologic Map of New Jersey: Northern Bedrock Sheet: U.S. Geological Survey Miscellaneous Investigation Series Map I-2540-A, scale1:100,000.

EPA 1992, Environmental Protection Agency, Technical Support Document for the 1992 Citizens guide to Radon, May 1992.

Laney, S.E. and Gates, A.E., 1996. Three-dimensional shuffling of horses in a strike-slip duplex: An example from the Lambertville sill, New Jersey.
Tectonophysics, vol. 258, p.53-70.

Muessig, K. and Bell, C., 1988, Northeastern Environmental Science Vol 7, No. 1, p 45-51.

Samet J.M., 1989, Journal of the National Cancer Institute
Vol. 81 No. 10, May 22, 1989.

Schlische, R.W., 1992. Structural and stratigraphic development of the Newark extensional basin, eastern North America: Evidence for the growth of the basin and its bounding structures, G.S.A. Bull., vol. 104, p. 1246-1263.

Volkert, R.A., in press, The Geology of Round Valley Recreation Area: New Jersey Geological Survey Geological Report Series, 18p.

Weast R.C., 1974, Handbook of Physics and Chemistry, CRC Press.

Woodcock, N.H. and Fischer, M., 1985. Strike-slip duplexes, J. Struc. Geol., vol. 8, p.725-735.

A PARTNERSHIP APPROACH IN MARKETING LAND USE REGULATIONS FOR KARST AREAS

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ABSTRACT

In New Jersey, the land development industry advocates more predictable government regulations and, in general, less red tape. In a state as litigious as New Jersey, local officials, most of whom are lay volunteers, often avoid "aggressive" land use planning and regulation that may be challenged in court. Likewise, they often shy away from imposing techniques that may be perceived as costly to implement. As a result of these concerns, proactive land use strategies to prevent structural collapse and/or ground water contamination in karst areas have historically been few and far between. This reluctance toward proactive planning is a product of a fundamental lack of knowledge within both the regulatory and development communities about the impacts of building in carbonate areas.

Faced with such challenges, how does an organization promote more practical government regulations that prevent potential loss of life, property damage and expensive law suits? This paper highlights the strategies used to "market" karst land use regulations, foster appropriate site design techniques, and heighten awareness of development impacts in karst areas among public and private sectors alike.

INTRODUCTION

The sinkhole-prone Paleozoic-aged carbonate rocks that underlie the valleys of the Appalachian Mountains extend into northwestern New Jersey and eastern Pennsylvania. Some 74 communities in northern New Jersey are located within this carbonate region. Significant problems and property damage have occurred both in New Jersey and neighboring communities in Pennsylvania as a result of inappropriate land development activities which have hastened the process of sinkhole formation in the region. As recently as five years ago, only one community in New Jersey, Clinton Township, had in place a comprehensive performance-based ordinance to ensure that the appropriate data-gathering, construction and site design measures were used in the development review and approval processes. (see Fischer and Lechner, 1989).

In 1991, the North Jersey Resource Conservation and Development Council (RC&D) formed the Limestone Resource Committee, comprised of representatives from the New Jersey Geological Survey, county planning departments, geotechnical consultants, elected officials, consulting planners, environmental groups and interested citizens. The Committee has since developed a package of educational materials, implemented an aggressive outreach effort, and provides ongoing support services for governmental officials, developers, engineers and other interested parties.

Many of the products and programs organized by the Committee are described below. The degree of success in raising public awareness and action stems not only from the availability and dissemination of information, but also from the marketing techniques used. Therefore, the discussion includes practical suggestions on how to structure educational outreach efforts.

PUBLIC EDUCATION AND OUTREACH; PROGRAMS, MATERIALS, TECHNIQUES

The Committee recognized early on that it had to deal with several issues. First, it had to present a highly technical and complex topic in a way that lay people could readily understand. Second, it needed to target a variety of players, each with markedly different interests or motivations. Therefore, a "canned" approach was not possible; rather, public education materials and workshops had to be tailored to specific audiences. Third, it had to design a comprehensive marketing strategy, particularly in the initial outreach stages, to attract interest and attention. Word is beginning to get out, so that professionals, government officials, and land owners are learning who to contact with questions or concerns.

A. Published Documents

Initially, the Committee wrote and published a brochure on karst directed toward public officials. Entitled "Limestone... A Primer for Public Officials", this easy-to-read document complete with text, photos and graphics was used as the first outreach piece to create some general awareness about the presence of karst. The brochure presents in simple terms the importance of appropriate planning and engineering methods in karst areas. An important component of the brochure is a map, prepared by the New Jersey Geological Survey, indicating the generalized locations of karst areas in New Jersey. The Committee mailed the brochure to municipal planning boards, environmental commissions, mayors, county planning boards and engineering departments, local boards of health, county health departments, professional planners and engineers. In total, roughly 1500 were mailed at the outset. Brochures continue to be distributed at public forums and in response to requests for information. This piece has proven to be a very successful attention-getter.

The Committee wrote several articles on planning in karst terrain, each directed toward different audiences. It prepared an article for the New Jersey Chapter of the American Planning Association which discussed planning in karst regions. An article directed toward municipal officials was published in the New Jersey League of Municipalities' magazine, New Jersey Municipalities, and later reprinted in Current Municipal Problems, published by Clark, Boardman, and Callaghan. The article presented case studies of development issues within the northern New Jersey and eastern Pennsylvania areas, local perspectives on the need for proactive planning to minimize costly remediation and litigation; and lessons learned as a result of improper planning, engineering and site design. Publication in the League magazine occurred shortly after completion of a model ordinance, providing the perfect opportunity to not only discuss karst management problems, but also present viable solutions and preventive actions. Additionally, Land & Water (a magazine directed toward land contractors and firms specializing in soil erosion control) published an article describing RC&D's efforts in rural farm areas. Members of the Committee presented a paper on its karst model ordinance at the Fourth Multidisciplinary Conference on Sinkholes in 1993 and at the 1995 Karst GeoHazards Conference.

The RC&D Limestone Committee maintains a library which contains ordinances compiled from throughout the country, research papers, newspaper and magazine articles, reports and geologic maps. The public can access the library during regular working hours or request copies of material by phone.

B. Model Karst Ordinance

Over the course of two years, the Committee prepared a model ordinance for land development activity in karst areas that addresses both groundwater protection and prevention of structural collapse (see "Model Karst Ordinance" 1993). The Committee prepared the ordinance largely in response to significant development pressures in northern New Jersey, coupled with an absence of appropriate planning measures being taken at the local level.

While the ordinance was still in draft form, the Committee began marketing this important planning tool. For example, it held a conference for professional planners, developers and engineers at which the draft ordinance was discussed and distributed. In 1993, after undergoing thorough geological, geotechnical and legal review, the ordinance was distributed throughout the region to local, county and state government representatives, as well as consulting engineers and planners.

Shortly after its distribution, the Committee contacted municipalities by phone and mail, offering free workshops and consultations to discuss karst geology, to talk about the ordinance, and to answer questions. The first few presentations focused on the importance of preventing groundwater pollution and structural collapse. The Committee learned, however, that municipalities were more responsive to the issues of legal liability and costs, should future problems occur. Therefore, the emphasis changed with future presentations. Furthermore, older communities that were fully developed tended to have different concerns from those that were still subject to significant development pressures. Again, this required shifts in focus on the part of the Committee. In general, presentations were useful because they helped communities overcome initial concerns about the perceived complexity and costs associated with ordinance requirements. They also provided the Committee with feedback on real issues and concerns at the local level.

To date, the Committee has met with 35 municipalities and counties collectively. Four communities have since adopted the model ordinance or variations thereof; six other municipalities are in the process of preparing ordinances. Requests for presentations are frequently triggered by press coverage of nearby sinkhole occurrences, ensuing litigation, or a controversial development project under review. The Committee is hopeful that with continued outreach, local interest in the model ordinance will be less reactive and more proactive.

C. Workshops, Training Programs, Consultations

Workshops, presentations and training programs have provided ideal forums for introducing planners, engineers, developers, legislators, farmers and other key players to the importance of appropriate planning, development as well as remediation in karst areas. In 1991, RC&D hosted a day-long seminar and field trip for planners and engineers. During the afternoon field trip, participants viewed actual sinkholes and other karst features that were discussed during the morning seminar.

The Committee spoke at events hosted by a professional engineering society and a regional watershed association. It also participated in a forum for mayors on sinkholes and other ground subsidence, which was sponsored by the State's Office of Legislative Services. The forum was organized in response to an incident in central New Jersey in which a young boy was killed when he fell into a hole in the ground created by decaying tree stumps buried underground. At this forum, Committee representatives stressed the important distinction between the causes of ground subsidence associated with geologic "sinkholes" and subsidence associated with buried construction debris.

The engineering and development community was targeted for a technical workshop entitled "SINKHOLE HAZARDS Engineering and Construction Techniques in Limestone Areas." This sold-out workshop included both classroom and field sessions on karst identification and management issues. Participants were able to observe various geophysical techniques, split barrel drilling and grouting techniques during this one day workshop.

The Committee developed an information packet which was distributed to state legislators representing districts within which carbonate rock formations occur. The packet included a cover letter, a brochure, a listing of the Limestone Committee members, and several articles. Subsequently they arranged meetings with several legislators to follow up on the correspondence. The impetus for contacting legislators was to comment on a proposed bill which would require fire inspectors to make annual "sinkhole" inspections of all apartment complexes. The bill was triggered by the death of the young boy mentioned above. By erroneously using the term "sinkhole" to describe voids created when buried construction debris decomposes, the bill was in effect directing a mandatory inspection process to identify geologic sinkholes rather than openings created by burying of debris.

Efforts to improve state regulatory programs have also been successful. The current draft of New Jersey Site Improvement Development Standards identifies communities underlain by limestone. Design engineers are encouraged to undertake appropriate studies and construction techniques when building in karst areas. The Committee is currently working with the New Jersey State Soil Conservation Committee on an appendix for their technical standards for Soil Erosion and Sediment Control Practices. This appendix discusses the relationship between soil erosion and sediment control, construction activities, sinkhole occurrence, and groundwater management issues. General guidelines on site investigation procedures, remediation techniques and technical references are included in the document.

Sinkholes on farmland can create water quality management problems as well as structural problems when they occur adjacent to farm buildings. To assist farmers and rural landowners with sinkhole problems, a sinkhole closure demonstration day was organized. Working with the USDA Natural Resources Conservation Service, a low technology sinkhole closure procedure was installed during a field day event. The intent of this field day was to show a lower cost solution (as opposed to higher cost grouting methods) to stabilizing sinkholes in rural areas. During this field day we also cleaned out and stabilized a "farmer" sinkhole in accordance with county and state regulations. Over fifty people representing local officials, farmers, state and local agencies attended this event.

Efforts directed at the agricultural communities farming the productive limestone river valleys have focused on managing agrichemicals. Our Council has been working cooperatively with the Rutgers Cooperative Extension and the Integrated Pest Management Program and the USDA Natural Resources Conservation Service to encourage farmers to adopt crop management practices which balance fertilizer and pesticide usage to the crop needs. Council's Agricultural Outreach Consultant has collaborated with these agencies over the last one and a half years to assist over 26 farms covering 5000 acres to adopt agrichemical management practices.

The New Jersey Geological Survey (NJGS), represented on the Limestone Committee, responds to inquiries by the public including property owners, developers, homeowners, businesses and public agencies. Phone calls are either responded to by the RC&D Coordinator and forwarded to NJGS when appropriate, or else they are taken directly by the NJGS. Typical inquiries come from concerned homeowners who have witnessed ground failure on or near their property. In some instances, the initial inquiry is made by a municipal engineer who has been contacted by the homeowner. Consulting planners, engineers and geologists contact NJGS when assessing the potential for karst features on properties proposed for development. In some cases, their concerns relate to specific surface depressions observed on undeveloped land. In others, sinkholes have opened up during the installation of infrastructure at a site. Generally, one of the state geologists visits the site and advises the property owner of the potential severity of subsidence features as well as steps the property owner can take immediately to address potential problems.

D. Funding

While Limestone Committee members provide many hours of service pro bono, publication of the brochure and model ordinance, as well as demonstration projects require substantial funding. State grants administered by the Department of Environmental Protection, Office of Environmental Services, supported publication and distribution of the brochure and model ordinance. An EPA Groundwater Pollution Grant totaling $25,000 helped fund the Farm Demonstration Project. The RC&D Council is also utilizing EPA Nonpoint Source Pollution Program funding along with EPA Pollution Prevention Program to staff the agricultural outreach position to educate farmers in karst areas about the need to manage the chemical inputs to protect their groundwater.

FUTURE EFFORTS

While much progress has been made, ongoing education is essential. The Limestone Committee hopes to reach out to many more communities, encouraging them to consider land use regulations specific to karst areas. Likewise, county planning boards and engineering departments need to incorporate appropriate measures into road and bridge projects as well as stormwater management regulations. Other target audiences for future training programs and seminars include local public works departments, realtors, lending institutions, insurance agents, builders' associations and attorneys. Additionally, the Committee is preparing an expanded fact sheet for homeowners, informing them of what to do in the event of a sinkhole occurrence or other suspected or actual karst-related problems.

SUMMARY

The marketing techniques used by the Limestone Committee, as well as many of the materials prepared, can be readily adapted for use elsewhere in the United States. To be successful, the organizing committee needs geotechnical experts, geologists, planners, and government officials, among others. They need to be accessible to the target audiences and must be able to make highly complex information understandable. Outreach can take a number of different forms but must be ongoing. Distribution of written materials should be followed up with meetings, presentations, and/or one-on-one discussions. The level of understanding and types of issues or misconceptions that various groups have should be identified early on, so that written materials and presentations can be structured to respond accordingly. Finally, outreach efforts must be all-inclusive. There are a great variety of groups, organizations and individuals who directly or indirectly affect land use and development in karst areas. All must be willing players in the development game in order to effectuate proactive planning and sensible land development.

REFERENCES

Fischer, J.A. and Lechner, H.L., 1989. A karst ordinance - Clinton Township, New Jersey: 3rd Multidisciplinary Conf. on Sinkholes, St. Petersburg Beach, Florida, pp 357-361.

The Limestone Resource Committee of the North Jersey Resource Conservation and Development Council, 1993. A karst model ordinance: Applied Karst Geology, Beck (ed.), Balkema, Rotterdam, pp. 273-276.

North Jersey Resource Conservation and Development Council is an independent, nonprofit organization represented by the Soil Conservation Districts and Freeholder Boards of six counties in northern New Jersey. The Council provides technical assistance, grant writing assistance, information and education to communities, organizations, businesses and individuals related to natural resource management.

Lithostratigraphic Models and the Geographic Distribution of Prehistoric Chert Quarries within the Cambro-Ordovician Lithologies of the Great Valley Sequence, Sussex County, New Jersey and Orange County, New York

Philip C. La Porta

ABSTRACT

Nodular chert occurs within all 13 members of the Cambro-Ordovician Kittatinny Supergroup of northern New Jersey, yet very little is known about their origin and history. Research studies in the Wallkill Valley of New Jersey indicate that the cherts form by pore-filling, dissolution, and replacement mechanisms. Because laterally persistent chert sequences can be utilized as marker horizons, detailed stratigraphy could be worked out on the basis of formation-to-formation variations in megascopic and mesoscopic texture and structure. The primary goal has been to use textures to develop models of the origin and diagenetic history of nodular cherts. A second goal has been to create geological models which accurately predict the locations of prehistoric chert quarries. A third goal has been to correlate the physical and chemical properties of prehistoric chert artifacts with specific chert horizons and even to one of the more than 300 chert quarries that have been located in northern New Jersey and southern New York.

Quarry investigations in the Wallkill River Valley suggest the presence of a "folk geology" operative during the entire Archaic Period. The practice includes following marker horizons across the landscape and the development of large and small-scale quarry operations through an acquired knowledge of the physical characteristics of the rock. This knowledge is reflected in the preferences visible in excavated stone tool assemblages. Also shared is a mining technology that includes quarry instruments fashioned from metaconglomerate, arkose, and quartzite.

INTRODUCTION

The central theme of this report is to describe the methods by which this researcher has been successful in locating the precise whereabouts of several hundred prehistoric chert quarries located within the northeast-southwest trending axis of the Wallkill River Valley of Sussex County, New Jersey, and neighboring Orange County, New York (La Porta, 1989). Many of these quarries were located over the past 15 years during a period of geological mapping within the Cambro-Ordovician lithologies of the Great Valley Sequence (La Porta, 1989). The geologic controls on the development of these prehistoric quarries include structural, stratigraphic, and sedimentologic elements. The interplay among these three elements has been resolved into a number of working models which can predict the precise locations of prehistoric chert quarries within this, as well as other, tectonic provinces.

Geological base maps and structure cross sections have been assembled for the Hamburg quadrangle, as well as for portions of the Branchville, Newton East, Franklin, Wawayanda, and Unionville quadrangles, Sussex County, New Jersey. In Orange County, New York, geological mapping is ongoing within the Pine Island and Goshen quadrangles. Accompanying the geological maps and structure cross sections are roughly 4000 ft of detailed stratigraphic sections. These include specific locations of unconformities, algal stromatolitic sequences, oolitic zones, supratidal micrites, storm deposits, paleokarst and lead-zinc bearing horizons, as well as the precise stratigraphic positions of chert-bearing lithologies.

Application of these models has been successful in locating chert quarries in the Siluro-Devonian lithologies of the second tectonic cycle, to the west and north of the study area (La

Porta, 1993). We are currently experimenting with models concerning Mississippian cherts, as well as with cherts occurring within the coal cycles of Pennsylvanian age. Strikingly different models have recently been developed which focus their capabilities towards discovering quarries in terrains which include deep water radiolarite cherts and associated volcanics in the New England provinces. These models have been field tested throughout the Appalachian-Ouachita orocline with formidable success.

We have summarized for the reader a layer cake stratigraphic sequence, accompanied by the textural properties of the cherts, or chert stratigraphy, and briefly summarize the structural and sedimentological aspects of the research (Table 1; La Porta, 1990). The following is a brief account of the construction of these models which has lead to the discovery of a great number of prehistoric quarries in a region which possesses no prior documentation of their existence.

Chert occurs as nodules in the Paleozoic carbonates of northwestern New Jersey. Cherts are more resistant to weathering than carbonates and stand out in bold relief in areas where the carbonates are poorly exposed. In many places, they are a convenient stratigraphic guide in the identification of the particular formation in which they occur. Cherts of individual horizons are easily distinguished from cherts of other horizons, a fact that is of considerable importance to the field geologist (Woodward, 1931; Markewicz et al., 1977). This distinguishability appears to be especially useful in the case of the Cambro-Ordovician carbonates of the Kittatinny Supergroup where the host carbonate members differ so slightly from each other that any assistance in their stratigraphic recognition is of special importance (Woodward, 1931).

The research has been at three levels of analysis: megascopic (base maps, major structure, and stratigraphy); macroscopic (outcrop to outcrop hand samples, color, texture, sedimentary, and structural features); and microscopic (thin sections and scanning electron microscope (SEM) analysis). An atlas of physical and chemical properties has served as a much needed mapping tool for the field geologist in this area. Furthermore, the research has provided information on the relationships between the physical and chemical characteristics of each chert type and the origin and subsequent diagenetic and structural history of the cherts and surrounding carbonate sequence.

Tectonics and Structure

The break apart of the Precambrian supercontinent occurred along a series of ridge axes and transform faults whose progressive extension allowed for the development of the Iapetic seaway during the beginning of the Cambrian period, roughly 543 million years ago. The orthogonal configuration of ridge axes and transform faults led to the development of a jigsaw-like pattern of attenuated Precambrian crustal blocks along what is now the eastern seaboard of North America (H. Rance, pers. comm., 1988). The ridge axes roughly conform or lead to the development of embayed regions referred to as reentrants, while the transform faults bound seaward projections of land known as promontories. Greater accumulations of carbonate sediment are found in reentrants, as opposed to promontories. Later, during the structural evolution of the eastern margin of North America, reentrants would evolve into salients, while promontories would become recesses (Thomas, 1977). This is largely due to the fact that compressive stress can be propagated greater distances through thicker packages of sedimentary strata.

Decollements or low-angle thrust faults are propagated nearly horizontally through the Precambrian crystalline rock and lowermost Cambrian strata of Hardyston and Leithsville age. The progressive diminution of compressive stress westward causes the thrust faults to step upward through Cambrian strata of the Limeport and Upper Allentown formations, and ramp or incline sharply upward through the lower Ordovician Beekmantown Group (i.e., the Rickenbach, Epler, and Ontelaunee formations), also referred to as the carbonate stiff layer (Geiser, 1988). Ramping is said to be due to the rheologic properties of the carbonate strata and more specifically, to the deforming characteristics of calcite. Eventually, within the thicker sequences of strata occurring within reentrants, the ramp faults will flatten within the foreland basin sediments of the middle Ordovician Jacksonburg Limestone and Martinsburg Slate. In essence, the Precambrian and lowermost Cambrian strata behave in a brittle fashion during deformation and transmit stress waves horizontally. The intersection of steeply inclined ramp thrusts within lower Ordovician lithologies creates ramp folds, thrust faults, and repetition of strata within the Beekmantown

Group. The overlying middle Ordovician Jacksonburg Limestone and Martinsburg Slate are much more ductile, and therefore stress waves flatten within this sequence. In vertical profile, the low-angle thrusts appear nearly Z-shaped; the horizontal and stratigraphically lowest sole thrusts step upward into a ramp, which flattens once again in younger lithologies, where it is referred to as a roof thrust. Therefore, sole thrusts penetrate Precambrian and Cambrian lithologies, ramp faults are inclined through the lower Ordovician strata, and roof thrusts flatten horizontally in the middle Ordovician lithologies.

Appalachian structural history is partially determined by stratigraphy; that is, tectonism takes advantage of weaker lithologies. Also, thicker as opposed to thinner stratigraphic packages behave differently under compressive stress. The thicker accumulations of carbonate strata within reentrants as opposed to promontories permits the development of a greater number of thrust surfaces and therefore strata can be propagated farther westward as the embayment evolves into a salient feature. The accumulation of chert-bearing sediments is greater in reentrants than in promontories. Within promontories, sedimentary accumulations are thinner, allowing the development of fewer thrust faults hindering rock from westward transport, and thus allowing promontories to evolve into recesses. The thicknesses and internal properties largely determine the subsequent architecture of resulting folds, as well as the stratigraphic positions of low-angle thrust faults that transport the rock landward. Many of these thrust faults occur within chert-bearing lithologies in the study area; some of these lithologies may have originally been evaporitic sequences. The resulting spatial distribution of repeated thrust slices of chert-bearing sequences is largely determined by the behavior of chert beds during periods of tectonism. Greater sedimentary accumulations occur within reentrants as opposed to promontories, and therefore the likelihood of the occurrence of repeated thrust slices of chert-bearing strata are greater within the resulting salients as opposed to recesses. The S-shaped configuration of the Appalachian-Ouachita orocline is largely the result of the structural evolution that takes place within this tectonic setting.

Geologic setting and depositional environments for the origin of chert

Cambro-Ordovician post-rift thermal subsidence permitted the accumulation of a shallow marine shelf sequence along the east-facing ramp of a laterally extensive miogeocline along the eastern margin of North America (Bond et al., 1984). The study area within the Wallkill River Valley of Sussex County, New Jersey is composed mostly of carbonates which represent a shallow depositional environment (predominantly proximal facies), that was periodically emergent (Braun and Friedman, 1969; Mazzullo and Friedman, 1975; Bova and Read, 1987). Subsequently, the carbonates were folded and thrust into their present position representing an Alpine-like duplex thrust upon the Martinsburg Shales of Middle Ordovician age. Cherts occur in nearly every member of each formation (Markewicz and Dalton, 1973; Markewicz et al., 1977; La Porta, 1989).

The chert also preserves very delicate sedimentary features whose fragile structures would otherwise be eradicated by diagenesis (particularly dolomitization) and tectonism. These preserved features make it possible to infer depositional settings, sedimentary facies, and other features of the host carbonates (La Porta, 1990). Where macro-invertebrate fossils are present, they too are commonly preserved in chert. This preservation of uncommon fossils may be critical in determining more precise age relations of the various formation members in the future. Also, the chert has preserved a full spectrum of algal stromatolite forms throughout the Cambrian and lower Ordovician section (Aitken, 1967).

The following chert stratigraphy has aided in unravelling the rather complicated structural style of deformation within the Hamburg and contiguous quadrangles. The varieties of chert unique to each formation member allowed the mapping of successive thrust slices which are barely discernable without the aid of the chert, and this mapping has lead to the proposal that the terrain was deformed as an Alpine-type duplex system (La Porta, n.d.).

Nodular cherts should not be confused with bedded cherts that form by the lithification of oozes composed of siliceous organisms such as diatoms (diatomites) and radiolaria (radiolarian cherts). Nodular cherts occur as lenticular- to irregularly-shaped masses or as layers within a host sediment such as phosphatic shales, limestones, or dolomites. There are currently many models to explain the origin of nodular chert (Durney, 1972; Knauth, 1979; Clayton 1986; Maliva and Siever

1988; Maliva 1989a, 1989b), but no single model appears to explain all nodular cherts. There are three general problems with nodular chert formation: the source of the silica; the chemical environments that cause the silica to dissolve, migrate, and finally precipitate; and the mode of growth of the silica nodules. The textural study that is the focus of this research is designed to address all three questions.

The textures of the cherts of the 13 members of the Kittatinny Supergroup are extremely variable and suggest that each chert horizon formed under unique conditions. Nevertheless, there appear to be three general mechanisms of chertification; void-filling, dissolution, and replacement. Void-fill cherts form, or at least start to form, within pre-existing spaces such as along fractures, between bedding planes, between breccia fragments, and between shell fragments in coquinas. They tend to form where the host sediment has a pronounced porosity such as along paleokarst horizons, within reef or mound structures, paleo-aquifers, unconformities, or within oolitic sequences. Dissolution cherts form during the solution and removal of the host sediment and are associated with distinct dissolution features such as stylolites, solution cleavage, and solution seams (Durney, 1972; deBoer, 1977). Replacement cherts appear to require a molecule-by-molecule replacement of carbonate with silica because the process leaves intact such delicate primary features as oolites, casts of evaporites, and fossils (such as stromatolites).

Most of the features described above are the result of investigations of outcrops, hand samples, polished slabs, and microscopic thin sections. The further study of these diverse chert textures on an SEM scale has resulted in an increased understanding of chert formation. The application of the EDX (energy dispersive X-ray) has provided a semiquantitative chemical fingerprint of the cherts, which has been useful in elucidating the diagenesis of the chert as well as providing a chemical framework for provenancing stone tools. Textural information derived from the SEM has proved to be critical in understanding the origin of many of the cherts.

We are currently working with approximately 18 models for the development of nodular cherts. Some of the variables of each model appear to be applicable to the myriad of chert types present within the Wallkill Valley. However, four or five models can account for some of the greatest accumulations of silica present within the research area. Interestingly, some chertification mechanisms, which are considered rare, are ubiquitous to the Cambro-Ordovician lithologies. These include the precipitation of chert from the dissolution of marine transgressive quartz sands and chertification through the development of silcretes. Also, the results of our study clearly suggest that pressure solution cherts and early diagenetic cherts are more prevalent than the literature indicates. The following is a brief description of the most common models for chertification applicable to the lithologies which are the focus of this study.

Field relations for the origin of chert in the Wallkill River Valley

All of the chertification models require a silica source, a transportation mechanism, and a site of deposition. Certainly, the most likely sites for the reprecipitation of silica as chert include those environments or sedimentary facies that are transitional between marine and meteoric conditions. That is, the tidal flat environments, including the lower supratidal, upper intertidal, and shallow subtidal facies of a sabkha-like setting serve as the most likely sites for chert precipitation within Cambro-Ordovician lithologies (La Porta, n.d.). These are also the regions where regression and transgression are strictly recorded and chertification in mixing zones is common.

The starved margins of regressive sequences are also recorded as surfaces of unconformities. The eroded, sometimes uneven, hummocky surfaces of unconformities later serve as the porous zones or voids where dissolved silica can be reprecipitated as chert. This is especially true of the upper surface of the Upper Allentown Formation, where chert marks a succession of unconformities. Fluctuating eH and pH conditions in brackish water environments permit the formation of the necessary redox conditions which will allow chertification to proceed. The results of all the tested models clearly point to the shoreline facies as the principal target for the thickest accumulations of chert and cratonic clay as the primary source of silica. It must be kept in mind that shoreline facies are rarely, if ever, evenly contoured in terms of sediment type, and therefore, along any one particular shoreline, chert-bearing horizons may wax and wane. Shaly, mudbearing lagoonal facies may carry silica to the shallow and deeper subtidal sections of the depositional environment, therefore one might expect cherts in these environments to be bedded, but discontinuous along stratigraphic strike. The thickest accumulations and most persistent chert-bearing horizons occurring along stratigraphic strike would occur within the nearshoreline facies of the Beekmantown Group; including the Rickenbach, Epler, and Ontelaunee formations.

Cherts occurring on surfaces of unconformities are found within the Big Springs Member of the Epler Formation, the Hamburg Member of the Leithsville Formation, the Harmonyvale Member of the Ontelaunee Formation, and especially within the Upper Allentown Formation. The Big Springs Member of the Epler Formation also includes pervasive chertification within the vadose zone cave features of a paleokarst horizon incised during the development of the Sauk unconformity. The zone of paleokarstification is evident within the Hamburg, Branchville, and Newton East quadrangles where roughly 300 quarries occur scattered along stratigraphic strike. The distribution of chert-bearing horizons within the Beaver Run Member of the Ontelaunee Formation may represent the spatial distribution of bryozoan mounds or sponge reefs facing the middle Ordovician foreland basin. Lastly, the discontinuous nature of the Harmonyvale Member may result from extreme erosion of this lithology during the incisement of the Sauk unconformity. This same erosional event forms the cave filling cherts within the Big Springs Member of the Epler Formation (Figure 1; La Porta, n.d.).

Chert Stratigraphy

Hardyston Formation

The first sediments to accumulate along the rifted margin include a predominance of clastics derived from the weathering of the Precambrian craton. In the study area, the basal Cambrian Hardyston Formation occurs as a residuum within sags and structural lows incised within Precambrian rock. In many locations, the boundary between the Precambrian and the Hardyston Formation is non-discernable as the Precambrian is so thoroughly weathered that the Hardyston Formation occurs as a saprolite overlying igneous and metamorphic rocks. In Sussex County, the Hardyston may be 10 - 100 ft thick and consists of alternating layers of arkosic sandstone, argillic claystone, and conglomeritic sandstone (Aaron, 1969). Although jasper or ferruginous cherts are known to be associated with the Hardyston Formation elsewhere (Hatch, 1994) chert has not yet been documented within the Hardyston Formation within the immediate study area. It should be noted, that to the south in Warren County, near Califon, New Jersey, a residuum of chert is known to overlie the Hardyston Formation, and much of that chert is brown and yellow. Elsewhere to the north, in Litchfield County, Connecticut, near the town of Washington, ferruginous chert is associated with the Denton Formation, which is roughly coeval with the Hardyston of New Jersey, and the chert-bearing Hardyston Formation of southeastern Pennsylvania. The Hardyston Formation is not included in Table 1 because it is largely clastic as opposed to carbonate and non-chert-bearing within the immediate research area. However, the Hardyston Formation is included within the stratigraphic units of the Cambro-Ordovician in northwestern New Jersey (Berg et al., 1983).

Leithsville Formation

The Leithsville Formation may be as much as 700 ft thick in this study area and has been divided into three members, the Lower Califon, Hamburg, and Upper Wallkill members. All three are chertbearing and represent the accumulation of transgressive carbonates on the rapidly subsiding continental margin.

Califon Member: The Califon Member is largely a basin axis filling shale and dolomite. Chert occurs as large and small pods up to a meter in length and their form may be the result of a type of structural deformation known as boudinage. Other varieties show concentric banding which may be diagenetic and suggest an organic origin. Califon chert is largely opaque, translucent along thin edges, contains much pyrite and emits a rank, fetid hydrogen sulfide odor when struck. Colors range from dark gray to light gray within the study area and light gray to blue gray varieties have been found within the Easton, Pennsylvania quadrangle (La Porta, 1986). Near Califon, New Jersey, alternating gray and yelloworange varieties occur, and this variety has also been found at

Macungie, Pennsylvania. When found in situ, the base of Califon pods often bear an open coxcomb structure, unsealed fractures intersect the outer portions of the pods, and a dusky, yellow iron oxide coating occurs on weathered outcrop surfaces as well as on artifacts. Stress tests performed upon Califon pods suggest that the outer shells of Califon pods are brittle, glassy, and break rather easily, while the internal portions of the pods are fibrous, waxy to dull, and exhibit extreme resistance to breakage when struck.

Hamburg Member: The Hamburg Member dolomite is a light gray, cyclic, pink to gray, thinly bedded dolarenite with shale partings, occasional algal stromatolites, and sulfide horizons. The chert within the Hamburg Member occurs in two stratigraphic positions. The lower chert occurs as thin beds up to 3 in thick, 20 - 30 ft in length, and pinches out into stringers and nodules. The chert is dark, charcoal gray. and weathered surfaces bear a blue cast. Freshly broken surfaces are saccharoidal, pyrite is visible while fractures are widely spaced and usually sealed, and euhedral microcrystals of quartz and pisoids may be present. Vugs, a few millimeters in diameter, are either filled with concentric chalcedonic quartz or with microcrystallites of euhedral quartz. The range of colors and textures of the lower Hamburg chert are very limited, as are the number of chert-bearing outcrops occurring along stratigraphic strike. Prehistoric quarries occurring in Amity, New York, and to the south 10 miles in Hamburg, New Jersey, yield similar textural fingerprints. The upper chert occurs along the crest of the Hamburg Member, as thick and thin beds which are ash gray to charcoal gray to brown. The ash gray zones are dull and matted, while the charcoal areas are extremely glassy. Close inspection of the ash gray portions indicate the presence of small angular fragments of what may be fossil debris, possibly graptolite fragments, or some type of shardy material. Blocks with widely spaced fractures are common.

Wallkill Member: The Wallkill Member occurs as a thickly bedded, coarsely crystallized, light gray dolarenite. Outcrops of the Wallkill Member are difficult to find, as they usually occur as structural terraces or benches above streams. Chert occurs as nodules and pods from less than an inch to greater than 20 in.; the larger variety being common at only one location in the Unionville quadrangle. The internal portions of the nodules reveal concentric banding which is associated with extreme variations in the texture of the chert. Some layers will be fibrous and waxy, while others are extremely glassy and highly translucent. The color and textural banding conforms to the outline of the pods, and the colors range from light gray to deep blue gray. Unsealed fractures intersect the pods, and their centers sometimes contain a claystone or ankeritic concretion. Iron pyrite is commonly finely dispersed through the nodules.

Limeport Formation

The Limeport Formation, which is 400 - 700 ft thick in northern New Jersey (Markewicz et al., 1977) is a thickly bedded dolomite of peritidal origin, which consists of oolitic beds, biostromal reefs, and shale-bearing lagoonal sequences (Zadnick and Carozzi, 1963). Algal stromatolites proliferate during this period of sea level rise, and several varieties of chert occur. At the bases of many of the algal stromatolitic sequences is often times a charcoal gray to black, highly translucent, oolitic chert which occurs as thin to thick beds and stringers. Closely spaced joint surfaces within the chert are resealed with microcrystalline quartz. Oolitic cherts are the most common variety within this formation, and petrographic thin sections indicate that the oolites are oftentimes deformed. At Wildcat Road in Franklin, New Jersey, in the Franklin quadrangle, a second variety of chert occurs as a burrow filling which contains the remains of fossil fragments, pisoids, and fecal pellets. The third type of chert is an organic replacement chert which is found as silica replaced algal stromatolites. This variety often contains alternating layers of chert and dolomite. Most of the chert-bearing facies are associated with strata which have been interpreted as lagoonal sequences.

Upper Allentown Formation

The Upper Allentown Formation is a very thickly bedded dolomite of subtidal origin which attains a thickness of just greater than 1000 ft in the Hamburg quadrangle. The deposition of this dolomite marks the maximum of marine transgression upon the land surface, and the formation is capped by a pronounced unconformity which punctuates sea level rise and terminates the deposition of Cambrian strata. Chert occurs sporadically within this formation as thin beds and nodules. At the top of the sequence there is a series of wispy beds which outline a succession of chert lined disconformities. The chert is black, highly lustrous and translucent along the edges. Associated with these cherts are silicified algal stromatolites, which are of a domal nature, and whose dimensions do not exceed a meter in width. Chert in this form is black, opaque, and bears alternating lighter colored layers, which mark the trace of the stromatolites. Thin and thick beds of quartzite mark the termination of the Upper Allentown.

Rickenbach Formation

The Rickenbach Formation is roughly 500 ft thick, subdivided into three members and is chert-bearing throughout. The members are, in ascending order; the lower unnamed member, the middle Hope Member, and the upper Crooked Swamp Facies. Due to the interplay of tectonics and sedimentation during this geological interval, the facies mosaic of these three members can occur in almost any order, and the most normal occurrence is described here (Table 2; La Porta, n.d.).

Lower unnamed member: The lower unnamed member contains numerous quartz sand lenses throughout its base, as well as chert replaced algal stromatolites. Chert, where it is common, occurs as thin pods and beds which are slightly convex upwards. Beds are rarely greater than an inch or two in thickness, and close inspection reveals an abundance of floating quartz sand grains occurring within the chert. The chert is black to blue gray and translucent along the edges .

Hope Member: The Hope Member contains chert which may be in the form of an algal replacement. The chert occurs as thin, convex upward beds which are rarely more than a few inches thick, and as much as 3 - 4m in length. The black to dark blue-black, mildly translucent chert layers are common throughout this member. Chert replaced oolitic sequences are also common here. At one stratigraphic position within the Hope Member, several chert layers occur closely spaced, creating a distinctive marker horizon which can be traced from Orange County, New York, through Sussex and Warren Counties, New Jersey, into the Easton quadrangle in Pennsylvania. This distinctive chert-bearing horizon has been employed as a mapping tool and stratigraphic aid due to its lateral persistence (Markewicz et al., 1977).

Crooked Swamp Facies: The coarse grained, thickly bedded, saccharoidal dolomite of the Crooked Swamp Facies may be fairly thin and discontinuous within the upper Rickenbach. The member bears chert as nodules, elongate pods, and algal replacements. The chert is deep blue gray to blue-black, highly translucent and delicately varved with finely dispersed organic filaments. Fractures within Crooked Swamp chert are usually bounded by smooth surfaces, are usually unsealed, and are visible in artifact form. The uppermost strata of the Crooked Swamp Member bear a very distinctive chert which has been interpreted (La Porta, 1989) as a dilation breccia (Roehl, 1981; Roberts, 1966). The brecciated chert sequence is thick, distinctive, and occurs at the interface between the Crooked Swamp and the lower Branchville Member of the Epler Formation, wherever the two members are visible. The chert can be up to one meter in thickness and pinch and swell up to distances of several hundred meters along stratigraphic strike. Close inspection reveals angular fragments of dark, translucent Crooked Swamp chert embedded within a matrix of a second generation lighter colored chert which is usually ash gray to pale blue-gray. At some locations, such a s Rock Island in the Hamburg quadrangle, the chert clasts and matrix are thoroughly welded together, so that the contact between clast and matrix is only discernable in microscopic thin section. The dilation breccia is common throughout Orange County, New York, in the Goshen and Pine Island quadrangles, where it outlines a series of imbricate thrust surfaces, as well as farther south within the Hamburg and Branchville quadrangles in Sussex County, New Jersey.

Epler Formation

The Epler Formation is 600 ft thick and divided into three members; the lower Branchville, middle Big Springs, and upper Lafayette, all of which are chert-bearing (Table 1; La Porta, n.d.).

Branchville Member: The Branchville Member shares the dilation breccia (Roehl, 1981) with the upper portion of the Crooked Swamp Facies of the Rickenbach Formation, therefore, the base of the Epler Formation is cherty (Markewicz and Dalton, 1974). But several other varieties of chert occur in minor amounts throughout the member. Stratigraphically lowest is a series of finely dispersed, thin lenses, and beds of oolitic chert. The oolites are much larger than those present either within the Rickenbach or Limeport formations. The chert is distinctively charcoal gray to black and translucent only along the thinnest edges. The second variety of chert occurs as a highly lustrous, thinly bedded, black chert with a purple cast. The chert is highly translucent, bounded by sharp unsealed fractures, and forms thin convex upward beds around large algal stromatolites. The third variety of chert is closely associated with oolitic sequences and coarse sand-bearing horizons. It occurs as a purple to lavender to orchid color, thinly bedded, highly lustrous to waxy chert, which contains finely interspersed sand grains. Occasionally this chert is seen to replace or underlie algal stromatolite features within this member.

Big Springs Member: The Big Springs Member is a thickly bedded series of unconformity bounded sequences containing a myriad of chert types (La Porta, 1987). The base of the member contains a thin to thick bed of ash gray, porcellainous chert (Markewicz et al., 1977). The chert is punky to matted, dull to waxy, and contains the remains of rhombic vacuoles where dolomite euhedra have been pitted by solution. Above this marker horizon is a zone of chertification, which includes intraformational conglomerates composed of chert clasts and paleokarst features, which are filled with collapsed chert breccias (Mustard and Donaldson, 1990). The paleokarst features include fallen and eroded blocks of purple chert recemented in a matrix of a second generation of chert which occurs as gray to white to milk white highly translucent infillings within the paleokarst features. Average hand samples of this material yield welded masses of angular pieces of purple chert cemented into a matrix of white chert. Rhombic vacuoles are common in the white phase. At one location within the Branchville quadrangle, the white chert is translucent enough to appear chalcedonic. At the same location near Harmonyvale in the Branchville quadrangle, silicified cave infillings within the Big Springs occur as maroon to bright red chert sequences associated with gray to jade green chert sequences, all occurring within the same horizon. Rhombic vacuoles are prevalent within all the cave filling cherts, an index of their replacive nature. Low to intermediate level SEM analysis has revealed a triple point novaculitic structure present within some samples of the white chert.

Lafayette Member: The Lafayette Member is similar in appearance to the Branchville Member, but contains more shale and less sulfides. Chert occurs as black, opaque, thinly developed beds which pinch and swell, and are continuous for only a few meters along stratigraphic strike. More characteristically, Lafayette chert occurs as steel blue nodules and thin beds, which are translucent only along the thinnest edges. Fracture sets occurring within Lafayette chert pods are usually lighter colored than the surrounding chert and contain a carbonate cement. Chert replaced oolitic sequences are also present.

Ontelaunee Formation

The Ontelaunee Formation is approximately 400 feet thick and represents the uppermost formation of the lower Ordovician. It is divided into two members: the lower Beaver Run and the upper Harmonyvale Member (Markewicz and Dalton, 1976; La Porta, n.d.; Tables 1 and 2).

Beaver Run Member: The lower Beaver Run Member begins at an unconformity at the top of the Lafayette Member of the Epler Formation. Tt occurs as a thin to thickly bedded, dark sulfide rich dolomite and chert appears approximately 40 ft up into the section. The thickest chert accumulations occur approximately 60 70 ft up in the section, where the chert occur as beds which reach a thickness of 8 - 10 ft and pinch and swell along stratigraphic strike. The anastomosing cherts may be laterally extensive ranging from 100 - 200m and in cross section appear as large boudins. The chert accumulations may represent silicified bryozoans and sponge mounds. The chert may be black to charcoal gray, opaque to highly translucent, and often times contains floating sand grains. Brecciated and algal stromatolitic forms are common and weathered surfaces patinate nearly white. Low level SEM images reveal the presence of sponge spicules within this chert. Stratigraphically upsection, the dolomite becomes lighter, as does the associated chert, and strata which are transitional between Beaver Run and Harmonyvale contain varieties of chert which are black to navy blue to blue gray. Several unconformities are present within the upper portion of the Beaver Run Member.

Harmonyvale Member: The Harmonyvale Member is a very thickly bedded, massive, micritic dolomite which contains abundant solution cleavage and weathered surfaces are white. The chert within the Harmonyvale Member occurs as beds up to a foot thick and greater than 100 ft in length and are usually bounded on their upper surfaces by a centimeter or so of illitic clay. The chert occurs as robin's egg blue, laminated to massive beds which grade to gray and almost white in the upper portion of the member. In general outline, the beds appear to be somewhat convex upwards and may represent large scale boudins. Internal cracking or brecciation is common within Harmonyvale chert, as are sealed and unsealed fractures. Acid etched slabs reveal intraformational conglomerates within the Harmonyvale beds suggesting the presence of hidden unconformities. Where the transition between the Beaver Run and Harmonyvale Members is abrupt, as at the Lower Road Quarry, near Unionville, New York, Orange County, the chert may grade from black to robin's egg blue within a single hand sample. Elsewhere, the chert can be highly lustrous and glassy, as at the Phillip's Quarry, within the Hamburg quadrangle, Sussex County.

Interstate correlations

Field work in the tri-state New York-New Jersey-Pennsylvania region has disclosed a considerable number of general correlations between chert-bearing strata within Cambrian and Ordovician rocks (Table 2). Employing the stratigraphic sections from northwestern New Jersey, we found the following relationships. In ascending order, within the lower Cambrian Leithsville Formation, the unconformity bounded chert within the Hamburg Member could be easily traced into Orange County, New York. In Duchess County, New York, the distinctive cherts of the Hamburg Member have been described at Stissing Mountain (Knopf, 1962). Califon and Wallkill members and their associated cherts were not present to the north of the study area. To the south, in the Easton quadrangle, cherts representative of the Califon Member were present. It is worth noting that in Virginia Woodward (1931) described several varieties of bedded and nodular cherts within the Shady and Elbrook formations, which are strikingly similar to those occurring with the Hamburg and Wallkill members of the Leithsville Formation (La Porta, n.d.) .

The oolitic cherts of the Limeport Formation are present throughout Orange County, New York, as well as within the Lehigh Valley sequence of Pennsylvania. The coeval Clarendon Springs Formation of the Champlain Valley has many of the same characteristics as the Limeport Formation in northwestern New Jersey (Twenhofel, 1954). The Little Falls dolomite of central New York and the Mines Formation of central Pennsylvania are roughly equivalent in age to the Upper Allentown, yet all three associated cherts are very different in their appearance.

The Rickenbach Formation of upper most Cambrian, lower Ordovician age is the oldest formation within the Beekmantown Group. The lower member cannot be traced to the north or south of the study area without great difficulty. Conversely, the Hope member is visible in Orange County, New York, Sussex and Warren Counties, New Jersey, and is present and chert-bearing within the Lehigh and Lebanon Valley sequences of east-central Pennsylvania. The distinctive marker horizon within the Hope Member can be traced from Orange County, New York to just south of the Easton quadrangle in eastern Pennsylvania. The Crooked Swamp Facies is visible in Orange County, but the Rickenbach Formation in general is thinly developed in this area. When chert occurs, its textural characteristics are identical to those of the Crooked Swamp Facies in Sussex and Warren Counties, New Jersey. The lower member of the Rickenbach is not present in Orange County, and the Briarcliff Formation is then roughly equivalent to the Hope member of the Rickenbach (Offield, 1967). In New York State, the Crooked Swamp Facies is placed stratigraphically within the base of the Halcyon Lake Formation, which is actually a group.

The Halcyon Lake Group includes the Crooked Swamp Facies of the Rickenbach Formation, all three members of the Epler Formation, as well as the entire Ontelaunee formation. The grouping of all three formations into one has masked the resolution of five chert-bearing members. The Epler Formation, which is included in the middle of Halcyon Lake is also cherty in Orange County, New York, but the paleokarst horizons are absent. Instead, at the base of the Big Springs Member, there is an ash gray, porcelain-like chert which can be traced to Fishkill, New York, greater than 100 miles north of the immediate study area. What is more striking, is that stratigraphically upsection from this gray chert horizon occurs a series of lavender to purple, poorly developed chert beds, which are identical to those occurring in the Big Springs Member of the Epler Formation at the type section in Sussex County, New Jersey. The white and lavender brecciated cherts of the paleokarst horizons present in Sussex County, as well as their associated green and red cave in-filling cherts occur as a restricted zone within Sussex County. The massive black chert beds of the lower Beaver Run Member of the Ontelaunee Formation are also present in southeastern New York State, within the Halcyon Lake Formation. The black chert beds pinch out north of Maybrook, New York, where they are replaced by a series of algal stromatolites. To the south, near Unionville, New York, blue gray chert beds of the Harmonyvale Member of the Ontelaunee overlie black cherts of the Beaver Run Member at the top of the Halcyon Lake Formation. To the south in the Lehigh Valley Sequence a nd in Lebanon Valley, both the Epler and Ontelaunee formations are chert-bearing (Hobson, 1963; La Porta, n.d.; Table 2). Farther west in central Pennsylvania, the Epler equivalents in the Nittany and Axeman Dolomites are also chert-bearing. The Ontelaunee equivalent in central Pennsylvania, the Bellefonte Formation, contains chert as nodules which bear only a minor resemblance to the cherts of the Ontelaunee Formation in New Jersey.

Farther to the south in the Tennessee salient, the Mascot and Kingsport formations possess strikingly similar characteristics to the Epler and Ontelaunee formations in New Jersey, including the presence of the characteristic varieties of chert and paleokarst features (Markewicz et al., 1977). In Virginia, the Jonesboro, Nittany, and lower Stones River formations, which are Beekmantown equivalents, are also chert-bearing.

The spatial distribution of quarries within the study area

The present study has shed some light on the controls that stratigraphy have over the development of structure, and this is especially true of the Cambro-Ordovician carbonates. On a refined scale, the sedimentology of the carbonates, the shallow inclination of the miogeoclinal ramp, and the periodic emergence of that ramp lead to the development of a great number of closely spaced chert-bearing horizons. The greatest number of chert rich facies and the broadest variety of chert types occur within the lower Ordovician Beekmantown Group; whose sedimentary facies mosaics are highly complex. This is largely due to the interplay between eustasy and tectonics, which determine the character and duration of transgression and regression on the carbonate ramp. On a slightly broader scale, the chert-bearing carbonates of the Beekmantown Group behave differently under compressive stress than do the underlying Cambrian and overlying middle Ordovician lithologies. The variations in rheologic properties of the three sedimentary packages permit the development of sole thrusts, ramps, and roof thrusts. The upper and lower lithostratigraphic units transmit stress horizontally, while the intermediate unit refracts stress waves upwards, generating a series of complicated folds and thrusts within the lower Ordovician units. This process permits the development of repeated exposures of chert-bearing strata across stratigraphic strike. On a more regional scale, greater accumulations of chert-bearing carbonates form within reentrants. The carbonate sequences forming within reentrants contain greater concentrations of chert due to factors of sedimentology, stratigraphy, and paleoslope of the miogeocline. As the reentrants evolve into salients the chert-bearing strata are folded and thrusted repeatedly. The structural evolution occurring in the salients promotes the development of pressure solution cherts within these embayments. Thinner sedimentary accumulations, within promontories, hinder the westward migration of stresses propagated as thrust faults. Variations in sedimentology and stratigraphy, as well as differences in structural evolution limit the development of chert-bearing strata within the resulting recess. Field evidence indicates that the Cambrian cherts are fairly continuous between salients and recesses, but cherts occurring within the lower Ordovician lithologies are best developed in salients and poorly developed along recesses. These observations indicate that the Cambrian paleogeography was fairly uniform within both reentrants and promontories. This is largely due to the fact that the Cambrian sequence was deposited during a period of rifting and uniform thermal subsidence of the continental margin (La Porta, n.d.). Heterogeneities within the paleolandscape were created during several episodes of Ordovician tectonism. Despite the disruption caused by tectonics, the lower Ordovician carbonate sedimentary facies are remarkably persistent along stratigraphic strike. This suggests that the lower Ordovician lithologies were probably formed in direct response to regional tectonics, are similar to each other within salients, and exhibit marked facies changes within recesses. The striking similarity between the Mascot and Kingsport formations occurring within the Tennessee salient and the Epler and Ontelaunee formations of the Pennsylvania salient are confirmation of this hypothesis (La Porta, n.d.).

The spatial distribution of prehistoric quarries within the immediate study area is largely the result of the interplay between stratigraphy and structure on these three levels. The heterogeneities present within the carbonates lead to archaeological considerations on three levels. Firstly, the lower Ordovician Rickenbach, Epler, and Ontelaunee formations are folded and thrusted into a relatively narrow band trending northeast-southwest along the axis of the Wallkill River Valley. The steeply dipping chert beds and repeated thrust slices occurring along chert-bearing sequences are exposed in a narrow zone of the valley. Prehistoric quarries occurring within all eight members of the three formations are often in close proximity to each other. Extensive quarry operations have been discovered within both menabers of the Ontelaunee Formation. Quarries have been developed in the lower Beaver Run Member and where erosion has not removed the upper Harmonyvale Member, both are mined together. Quarries of this type frequently range from 100 - 200m in length. The steeply dipping beds offer excellent access to chert-bearing horizons. Chert quarries within this formation occur along the western side of the Wallkill River Valley, adjacent to the Jacksonburg Limestone and the Martinsburg Slate. The linear distribution of Beaver Run quarries found along strike may represent the ecological zonation of lower Ordovician sponge reefs or bryozoan mounds. The distribution of Harmonyvale quarries is largely dependent upon the degree of middle Ordovician erosion. The extensive prehistoric quarries developed within the Ontelaunee Formation are always associated with a highly organized quartzite mining technology. Beaver Run quarries occur in a trend from Orange County, New York through Sussex, Warren and Hunterdon counties, New Jersey, as well as in eastern Pennsylvania.

Prehistoric quarries developed within the Epler Formation are generally smaller than those occurring within the Ontelaunee. Quarries discovered within the Big Springs Member of the Epler Formation occur in a narrow, linear band outcropping within three quadrangles. The quarries are small, less than 75m in length, and sporadically developed due to the brecciated nature of the karstfilling chert. The outlines of the quarries are generally determined by the dimensions of the paleokarst features and also by the number of associated chertbearing horizons. Quarries developed within the Big Springs Member will also include the chert-bearing upper Lafayette Member, as well as the porcelain chert which occurs at the base of the Big Springs Member. Occasionally, cherts within the Branchville Member are exploited in the same operations. Although the brecciated cherts occur in a restricted zone, the porcelain gray chert within the base of the member has been traced for 100 miles to the northeast where prehistoric quarries are found in Fishkill, New York.

An extensive zone of brecciated chert occurs at the interface between the Branchville Member of the Epler Formation and the Crooked Swamp Member of the Rickenbach Formation. The chert has been classified as a dilation breccia (La Porta, n.d.) and occurs as a single thick chert bed which follows along strike. Prehistoric quarries in the form of trenches and conical pits occur along the length of the chert-bearing outcrops. In Orange County, New York, the dilation breccia marks the surfaces of several repeated thrust slices occurring within the Halcyon Lake Group. The elucidation of the complicated style of structural deformation within the area of the Pine Island and Goshen quadrangles (La Porta, n.d.) has led to the discovery of more than 20 prehistoric quarries within this chert-bearing horizon (J. Webster, pers. comm., 1991-1994).

Chert quarries developed within the Rickenbach Formation represent the smallest class of prehistoric quarries within the Beekmantown Group. Although chert occurs within all three members, it is generally scattered as thin beds and nodules and rarely occurs as an extensive concentration. Stone tool inventories suggest that all three members were mined, but to date, quarries discovered within this formation are numerous, but small, usually less than 25m in length. The Rickenbach Formation is the stratigraphically lowest formation within the Beekmantown Group, and this important fact may have determined the limitations of its use as a prehistoric lithic resource. Due to its low stratigraphic position, ramp faults developed within the Beekmantown Group often place the Rickenbach Formation in a footwall relationship with limited surface exposure. The beds may occur along steep-sided east-facing walls, which renders them difficult to mine, regardless of their angle of inclination.

The Hardyston, Leithsville, Limeport, and Upper Allentown formations occur within the zone of the sole thrust in the study area. They are often bounded to the east by allochthanous masses of Precambrian crystalline rock and in general comprise the lower elevations of the valley along the eastern side of the Wallkill River. Their low relief and mild topographic expression is further masked by a thick veneer of glacial drift which covers the valley floor. Outcrops of steeply dipping Cambrian strata are most common when they are in close association with Precambrian rocks. Prehistoric quarries occurring within these formations are generally widely scattered and poorly developed. Rarely are beds inclined steeply enough to afford easy access. Most quarries are developed as small conical pits and outcrop quarries. Oftentimes, Califon, Hamburg, and Wallkill member cherts are gathered from pits excavated into the residuum which forms above the outcrop. In southeastern Pennsylvania, Califon chert occurs intimately associated with ferruginous chert or yellow jasper of the Hardyston Formation.

Prehistoric quarries developed within the Limeport and Upper Allentown formations are more numerous than those occurring within the Leithsville Formation. This is due to the proximity of these formations to the ramp thrusts of the Beekmantown Group. The sole thrust occurring within the floor of the valley, steps upward through the Limeport and Upper Allentown formations, creating a series of footwall relationships scattered across the valley floor. The washboard effect formed by the sole thrust during its westward migratory transition into a ramp creates a variety of steeply inclined exposed surfaces, which when chert-bearing are suitable for mining. To the south in the Paulins Kill Valley, structural complications result in excellent exposures of the Limeport Formation, and as a result it was extensively mined in prehistoric times. Lastly, our research has suggested that prehistoric quarries occurring within the Cambro-Ordovician carbonates are most common within salient features which evolve from the structural deformation of reentrants. Quarries are less common along promontories which accumulate thin packages of sedimentary strata and evolve into recesses.

Stratigraphy of the Dutchess Quarry Area

The lithologies cropping out within the vicinity of the Dutchess Quarry area are those of the Halcyon Lake Formation. The Halcyon Lake Formation was first described by Knopf (1946) at the Halcyon Lake type section in Dutchess County, New York. The formation was described as Canadian in age, which is Lower Ordovician (505-475 Ma) and roughly equivalent to the Beekmantown Group rocks occurring to the north and south of the study area. A Middle Ordovician unconformity caps the Halcyon Lake Formation, and is subsequently overlain by the Rochdale and Balmville limestones and Mt. Marino shale. Compressed within the Halcyon Lake Formation is much of the Beekmantown Group (Figure 2), which is represented to the south in New Jersey by three formations, divisible into eight distinct, chert-bearing members. The formation occurring stratigraphically lowest in New Jersey, and equivalent to the base of the Halcyon Lake, is the Rickenbach Formation (Figure 2). The uppermost member of the Rickenbach Formation, the Crooked Swamp, contains a highly translucent, black to blue-gray chert occurring as nodules and replacements of algal stromatolites that may appear as finely laminated, chert pods which ocasionally retain their original rounded form. The procurement locus named New Quarry #2 occurs approximately one mile to the east of Lookout Mountain, and is developed within the Crooked Swamp facies. Above this is the Epler Formation, which contains the Branchville, Big Springs and Lafayette members, all of which are chert-bearing. The Epler Formation is roughly equivalent to the middle portion of the Halcyon Lake Formation. Infrequently is the Epler Formation exposed in this region; owing to structural complexities, it usually occurs deep in the subsurface. Potential quarries within the Epler Formation crop out along a thrust fault at a reservoir several miles to the north of Lookout Mountain.

The Ontelaunee Formation comprises the upper portion of the Halcyon Lake Formation in New Jersey. It was recognized in New Jersey by Markewiecz and Dalton (1974, 1976). The Ontelaunee Formation contains two members: the lower Beaver Run member, which is 150-200 feet thick, and the upper Harmonyvale Member, which is in excess of 220 feet thick. At many locations, the Harmonyvale has been completely eroded away, and the Jacksonburg Limestone (Balmville equivalent) is deposited directly on the Beaver Run. An exception to this is the Lower Road quarry, where abrupt facies changes bring the Beaver Run and Harmonyvale members in close contact. The Beaver Run member contains three distinct units, the lowest of which is a coarsely-crystalline, fetid or sulfurous dolomite approximately 40 feet in thickness. This unit would occur below the base of Lookout Mountain at Dutchess Quarry, and would be only infrequently visible as outcrop. New Quarry #1 is located at the top of this facies. Above this is a 50-100 feet thick massive dolomite, which contains individual chert beds up to 10 feet thick. The top of this unit occurs at the 520-foot contour interval, and is exposed along the western base of Lookout Mountain. Extensive chert beds within this unit house the prehistoric quarries at Houston Road, Lower Road, and elsewhere in the region. The upper portion of this member, which can be 50 feet thick, is medium-grained, black to gray dolomite with intermittent chert beds and pods of lighter gray color. It is the upper unit which comprises the walls of Lookout Mountain, the caves, and the chert quarries occurring at the top of the mountain.

The Halcyon Lake Formation is a condensed section, and possibly an entire formation group, as it comprises most of the Beekmantown Group lithologies. The Crooked Swamp Member of the Rickenbach Formation, the Branchville, Big Springs, and Lafayette members of the Epler Formation, and the Beaver Run and Harmonyvale members of the Ontelaunee Formation are all roughly equivalent to the Halcyon Lake Formation.

Criteria for Quarry Development

The traditional view of prehistoric quarries and chert exploitation relies heavily upon the assumption that quarries are found where chert is highly concentrated. More recent studies (e.g., La Porta, 1989, 1994) have presented strong arguments to suggest that the structural history of the rock determines the spatial distribution of quarry areas and associated reduction sequences more often than does the simple presence of chert. Unlike other areas of the world, chert occurring in the Paleozoic rocks of the Appalachians oftentimes occurs as thin beds, deformed boudins (sausage-shaped structures), and stratabound layers of nodules embedded in a great volume of surrounding country rock. The development of a quarry (or motion; La Porta, n.d.) depends largely upon the following criteria:

1. the angle of inclination of the beds, or the dip angle with respect to horizontal
2. the presence of joint surfaces
3. the presence of well-defined bedding planes
4. the development of fracture cleavage
5. the concentration of chert-bearing units

Dolomite beds which range from being steeply to gently inclined lend themselves to chert extraction by levers or wedges. Where chert occurs in horizontal beds, the extraction process involves the removal of great quantities of overburden rock or surrounding country rock (gangue) in order to reach the chert-rich horizons. The process often involves the development of a vertical shaft or conical pit, such as those discovered at Dutchess Quarry site Locus 2 (Costello et al., 1992). This type of extraction process, which has been referred to as a prospect, usually fails owing to the difficulty in removing the chert (ore). Horizontal beds are most easily mined along cliff faces, or where the horizontal beds are interrupted by an erosional break in slope in the local topography, such as at Dutchess Quarry Locus 3 (in scree; Figure 3).

Joints are open fracture spaces in rock that form as a result of warping or folding of strata. They often occur in intersecting pairs, and the accentuation of jointing by groundwater activity leads to the development of karst ("sinkhole") topography. The Ontelaunee Formation exhibits all of these traits. Because the Ontelaunee was multiply deformed during the Alleghenian mountain-building event, the jointing has been refolded. Despite this fact, excellent examples of well-integrated master joint systems are present within this Ordovician formation. The joint surfaces permit the use of mining tools such as levers and wedges to further accentuate the openings in the rock, increasing the ease of ore extraction.

Where bedding planes exhibit a contrast in grain size, the weaknesses therein developed may be exploited to break rock in a direction perpendicular to the joint surface. At many locations, where chert comprises a distinct unit between beds of dolomite, a force applied directly at the interface between the chert and dolomite will serve to dislodge the chert from the country rock.

During the development of regional folds, cleavage develops as a fabric within the rock, especially fine-grained rock. Cleavage is a preferred orientation of grains which appears as closely-spaced flat planes in microscope thin section and hand sample. Although cleavage appears to be best developed in shales and slates, the fabric is ubiquitous in all deformed rocks. Because of the differences in rheology (style of deformation) between chert and dolomite, closely-spaced cleavage planes refract and widen as they penetrate chert nodules and beds. The spaces between fracture cleavage surfaces in chert vary from less than a millimeter to several centimeters in width, and the cleavage surface itself appears as a smooth, flat plane, much like that developed in a slate. Between fracture cleavages, the homogeneous chert is referred to as the microlithon, and represents the template upon which the stone tool technologist begins lithic reduction.

The association of several closely-spaced, chert-rich beds presents an attractive target for mining activity. These beds are often left undisturbed, however, if they are not inclined or do not face an abutment.

Quarry Types

During the past several years of quarry research, a number of different quarry types have been documented (e.g., La Porta, 1990). These include conical pits developed in soil or regolith, inclined shafts cut through rock, terraced mines, screes, dip-slope mines, and declivities in horizontal strata. In the immediate study area, the prehistoric quarries are of the dip-slope variety. In this quarry type, the exposed limbs of gently-dipping folds are cut by more steeply dipping erosional faces, so that a succession of chert-bearing beds are exposed along a single slope. Joint blocks containing ore may then be easily removed without the development of a vertical shaft (Figure 4).

Quarry Instruments

The zones of extraction, or declivities, require the largest mining instruments. These are generally fashioned from metaconglomerates, and less commonly from arkosic sandstones, gneisses, and quartzites. They usually display at least one wedge-shaped surface bearing large flake scars from battering. They range in size up to 100 pounds or more, and are typically found in close association with the zones of extraction.

A second class of instruments includes milling and concentrating tools that weigh about half as much as the extraction tools. They are usually composed of arkosic sandstone and, to a lesser degree, quartzites. They are rectangular in shape, and often display signs of crushing or battering along one or more edges. These tools are employed to free chert from its dolomite country rock, separate high and low tenor ore, and free chert along the microlithon surface.

The third class of instruments includes smaller hammerstones, which are roughly circular in outline and may possess a flattened upper surface. This class of tools is usually associated with non-portable anvils and reduction sequence debitage related to the production of bifaces and cores found on flat terraces above the quarry surface. They are almost always made of quartzite.

Model for the Development of a Typical Quarry: The Houston Road Quarry

Steeply to moderately dipping strata are best suited to the extraction process. Gently dipping or horizontal strata are usually bypassed because they require the excavation of vertical, conical pits through the country rock in order to penetrate the chert-bearing strata. Conical pits in bedrock must be widened in all directions, and the floor of the pit must be constantly maintained. Beneficiation, or upgrading the tenor of the chert, is therefore difficult because the quantity of country rock so greatly exceeds the volume of chert extracted by this type of process. Horizontal beds are usually mined where they are exposed along a steep cliff face, where joint surfaces can be accentuated by lever methods.

The extent or dimensions of a potential quarry face, or declivity, are determined by the development of joint surfaces and the spacing between joints in the chert-bearing strata. The Cambro-Ordovician lithologies under investigation have undergone several episodes of tectonism and structural deformation that have led to the generation of multiple sets of joints, fractures, and cleavages that intersect at differing angles. This creates irregularities within the chert, rendering the mining practice more difficult.

The development of a quarry face or declivity, such as the ones created at Houston Road, begins with the accentuation of joint surfaces by the use of levers. The joint surfaces themselves may project through several beds of chert-bearing rock, or may terminate randomly at any one bed surface. Accentuation of the joint surface proceeds by hammering wooden wedges into the open spaces. At several locations within the Wallkill River Valley, expended quartzite hammerstones and anvils are found wedged between joint blocks. This wedging procedure would generally take place in the autumn, allowing winter snow and ice to freeze in joint surfaces. The expansion and contraction of joints due to freeze-thaw then ruptured the rock along the joint surface. Quarrying activity is accelerated during the spring months when weakened joint-faced blocks are loosened by the use of levers, and the blocks of ore are transported to a position below the quarry face. This procedure of accentuating joint surfaces will continue until the joint surfaces connect from different directions, thereby creating a vertical notch projecting into the quarry wall, which is then bounded on its lower surface by a flat bedding plane. The bedding plane serves as a stable platform for quarry operations.

Extensive exploitation of the joint surfaces over a prolonged period of time results in the development of a stepped surface within the v-shaped notch, which is now referred to as a declivity. The controlling joint surfaces from which chert is extracted are referred to as the master joint system. Generally, declivities are abandoned when the volume of country rock on the stepped floor of the quarry so greatly exceeds the volume of ore to be extracted that further extraction of the ore is not economically viable. Usually, the declivity is abandoned for an adjacent area of easier extraction. Thus, as declivities are developed along vertical faces in inclined strata, the profile of the quarry takes on a saw-toothed form, bearing a series of both active and depleted and abandoned declivities. Historically this process is called stoping, and the extraction process leaves behind pedestals or pillars of ore. In fully developed quarry surfaces, widely-spaced declivities are bounded by projections of undisturbed pedestal rock. The convergence of two declivities results in the formation of a v-shaped projection which, being ore-rich, is vulnerable to mining from both sides of adjacent declivities. Where the lateral distribution of chert occurs as boudins or disconnected pods, the pedestals are usually chert-free and left standing between declivities, as was the case in the Wallkill River Valley within the Cambro-Ordovician lithologies.

At the Houston Road quarry, close inspection of the declivity surface reveals the presence of cuspate surfaces and v-shaped notches. The cuspate surfaces are essentially carved into the exposed chert, although the upper edges have been pounded into a white, saccharoidal external rind. The dimensions of the cuspate surfaces precisely match the outline of the outer edge of the metaconglomerate extraction tools. Where the castellated surfaces are not present, a small v-shaped notch penetrates the chert along the wall. The v-shaped notches represent an area in which crushing was successful in removing chert along intersecting fracture cleavage surfaces. Thus the presence of the cuspate surfaces suggests a failed attempt to extract chert.

The block removed from the wall will be bounded on two sides by intersecting fracture cleavage surfaces, and the upper face of the chert will bear battering marks and the remnants of a partially developed cusp surface.

Ore Processing Stations

It has been noticed that even within historic mines, ore is never hoisted above the mine surface. It is instead dropped below to a stable area where it is concentrated before removal from the mine. The same is true in prehistoric quarries. The extracted fracture-faced blocks are dropped down below the quarry face to a stable platform which serves as an ore processing station. Several activities take place in the ore processing station, of which the most important is referred to simply as ore dressing.

Ore Dressing

The ore dressing process involves the separation of the dolomite or limestone from the chert. The limestone and dolomite blocks become a tailings pile of little or no value. The dressed ore, bounded by numerous close-spaced fracture surfaces, is now free of gangue. Observations at Houston Road indicate that the ore is transported manually to either side of the tailings pile, but generally not any further below it.

Ore Grading, or Further Beneficiation

At some position to either side of the tailings, ore of all qualities or tenor is placed in piles for inspection. Here blocks of chert bounded by fractures are placed on large anvils and further reduced to rectangular and wedge-shaped blocks by crushing the upper surfaces with quartzite wedges and splitters. The anvils are generally large blocks of extracted, low tenor ore or country rock, which serve as temporary stable areas along a steep slope. At these locations, ragged edges are removed from the joint blocks and the chert is cleaned of highly fractured material. Low tenor ore in the form of large blocks and shatter, are discarded along slopes at these positions. High tenor ore, or chert bounded by even fracture surfaces and bearing highly translucent phases of silica, are further separated from the ore and transported to a surface above the quarry. An intermediate type of ore, one which bears both high and low tenor chert, is found abundantly at these locations. Large blocks of low tenor chert may contain small patches of high tenor ore that are suitable for stone tool manufacture. These blocks will be further split and broken along fracture cleavage surfaces to release the desirable chert. During this process, the fracture cleavage and joint surfaces of the block are removed. The result is a quarry core which serves as a source of small quantities of high tenor chert, but the core itself never leaves the quarry surface.

The Reduction Sequences

The finer reduction of the chert, i.e., the production of stage one bifaces and cores, is conducted above the quarry face. My research in the Wallkill River Valley clearly indicates that the finest scale of reduction that takes place in the quarry occurs above the zones of extraction. High tenor ore is transported from the processing stations to a stable area above the declivity. Non-portable anvils that serve as stable workstations for skilled technicians are usually found here, and are generally fashioned from quartzite glacial erratics. The glacial erratics are typically surrounded by an apron of fine flaking debris produced as the fracture-bounded blocks of ore are flaked into bifaces and cores. Organized clusters or piles of small pieces of chert are common at these locations, as are discarded pieces of chert which do not pass final inspection.

Summary

Chert is present in all 13 formation members within the Cambro-Ordovician lithologies of the Great Valley Sequence in Sussex and Warren counties, New Jersey. The cherts appear to be restricted to tidal flat or supratidal facies, and associated intertidal sequences. Cherts are present as early diagenetic, late replacive, dissolution, paleokarst, and pressure solution cherts. Cherts are nearly absent in the deeper subtidal Upper Allentown Formation. The textures of the cherts and their associated dolomite are laterally persistent for tens to hundreds of kilometers to the north and south of the study area (Table 2). Similar cherts are found at even greater distances, within coeval strata, within the Champlain embayment and the Tennessee salient. The replacive nature of the chert as well as its stratigraphic position marking unconformities of regional extent allows for easy correlation on a statewide basis. The cherts appear to be time stratigraphic along stratigraphic strike, and only mildly time transgressive between various carbonate basins. The evenness of the CambroOrdovician miogeoclinal ramp is most likely responsible for the lateral persistence of the sedimentary carbonate facies. If most of the cherts are carbonate replacements, then it can only be concluded that the chert marker horizons could be employed as mapping aids on a statewide basis.

Chert occurring on local unconformities, within paleokarst horizons and as organic replacements will be geographically restricted, as will early diagenetic cherts. Cherts occurring within the paleokarst horizons of the Big Springs Member of the Epler Formation are the most localized. Cherts lining unconformities within the Hamburg Member of the Leithsville Formation and at the crest of the Upper Allentown Formation may be of regional significance, but are difficult to trace northward into Orange County. Although sponge spicules are present under SEM within the Beaver Run and Harmonyvale members of the Ontelaunee Formation, they cannot account for the vast volume of chert present within the study area. Several other sources including cratonic silica, the dissolution of transgressive marine quartz sands, and the development of pressure solution cherts provide the necessary mechanisms and models to account for the great quantity of chert within these lithologies.

The structural, stratigraphic, and sedimentological models lead to the following archaeological considerations. Quarries occurring within the Leithsville, Limeport, and Upper Allentown formations are usually associated with sole thrusts and occur as small, spatially widespread, lithic resources. In the Hamburg and contiguous quadrangles, the Cambrian lithologies underlie topographically low lying regions. Many of the small scattered quarries occur in steeply inclined strata juxtaposed to allochthanous Precambrian sequences. The Precambrian and Cambrian lithologies are located geographically within the eastern portion of the Hamburg quadrangle.

Quarries occurring within the Rickenbach, Epler, and Ontelaunee formations occur within the carbonate stiff layer, and their fault-bounded folded nature compresses these formations into a narrow band, trending northeast-southwest through the study area. Most outcrops occur along the western side of the Wallkill River Valley in the Hamburg and Branchville quadrangles. Thrust faulting, in some areas, causes a repetition of chert-bearing outcrops, the thinly developed shoreline facies present narrow outcrop patterns, which implies that a great number of chert-bearing horizons representing different formation members could be exposed over a geographically narrow distance. The greatest concentration of prehistoric chert quarries occurs within the lower Ordovician Beekmantown Group, whose three formations, and eight chert-bearing members of shallow, intertidal origin, comprise a narrow belt of dolomite which trends northeast-southwest along the western limb of the axis of the Wallkill River Valley. Complications of folding and thrusting within the carbonate stiff layer reveals a great number of repetitive thrust slices whose outcrop patterns are the traces of chert beds. The greatest concentration of prehistoric chert quarries occurs within the Beekmantown Group, in a restricted area, coinciding with the trace of the thrust faults, in these narrowly restricted zones of folded and thrusted strata a great variety of cherts can be easily acquired. The roof thrust within the Jacksonburg Limestone and Martinsburg Slate occurs along the w estern portion of the valley and is not chert-bearing, but contains minable quantities of metamorphosed slates and argillites .

Recent discoveries have been made of several extensive prehistoric quarries developed within both the Beaver Run and Harmonyvale members of the Ontelaunee Formation in the vicinity of the Dutchess Quarry site. The most extensive of the quarries, Houston Road, is a series of declivities located within the middle chert-bearing unit of the Beaver Run Member. Rapid facies changes between the upper unit of the Beaver Run and the Harmonyvale Member permit the development of a second large quarry, the Lower Road Quarry in Unionville, New York. Quarries developed within the lower unit of the Beaver Run Member represent unsuccessful attempts at quarrying (New Quarry #1). Where the Crooked Swamp Member of the Rickenbach Formation is exposed at a thrust surface one mile to the east of Lookout Mountain, a successful quarry operation was established.

Lookout Mountain, above the Dutchess Quarry caves, contains a series of vertical prospect pits (Locus 2), three failed declivities in gently inclined strata (Locus 5), and the successful quarry operation developed within a scree (Locus 3) (Figure 3). Traditionally, the chert-bearing sequences are associated with chert-bearing horizons in the Ontelaunee Formation. Exposed along the southwest face of Lookout Mountain, within the same stratigraphic horizon as the caves, is a series of algal stromatolite zones bearing chert. The uppermost of these zones is made visible by these biogenic structures in the base of the prospect pits of Locus 2 (Figure 3). A second, lower marker horizon is exposed at Locus 3 and Locus 5. Stromatolites are also abundant at the Houston Road Quarry, where they serve as a useful stratigraphic guide in locating both the Beaver Run Member and chert-bearing units. The spatial distribution of the various quarry activities at Lookout Mountain suggests that the algal marker horizon and associated chert-bearing units were mined out systematically where they were exposed. This could have been accomplished by traversing perpendicular to stratigraphic strike until the chert and associated stromatolites are encountered, and then following the outcrop pattern along stratigraphic strike.

The integrated quarry activities atop Lookout Mountain are minor, largely due to the fact that the upper unit of the Beaver Run Member of the Ontelaunee Formation is largely chert-deficient. A natural beneficiation of the ore takes place where the gently inclined beds are intersected by an equilibrium slope, creating the scree at Locus 3. Here chert could be easily removed where the beds jutted out along a moderate slope. The presence of cuspate surfaces on chert blocks also suggests that the chert was worked from beds that were in place along the quarry wall by a procedure very similar to that employed at Houston Road. Large metaconglomerate extraction instruments were located at the base of the scree, and quartzite impact spalls were discovered mixed in with the tailings along the face of the scree. The spatial distribution of the various quartzite instruments discovered in and around Locus 3 strongly resembles the distribution reflecting task subdivision at Houston Road.

The remains of quarry activities at Lookout Mountain suggest failed attempts at "folk mining" activity. Only the scree at Locus 3 represents a development of a declivity that was successful for some period of time. Certainly, the quarry activities at Houston and Lower Roads were more successful because they were located stratigraphically within the chert-bearing portions of the Ontelaunee Formation. It is important to note that the technology at all of these locations was apparently shared. Both the quarry extraction process and "tool kit" are similar at each location.

The examination of archived stone tool collections suggests that the chert-bearing outcrops have been quarried from the Paleo period (12,000 B.P.) up to the historic period (1600 A.D.). The most intensive use of the quarries occurs between 7,000-3,000 B.P. Furthermore, examination of diagnostic Orient Fishtail projectile points (Transitional age; 3000 B.P.) and associated bifaces recovered from Locus 1 along the eastern side of the mountain yield the following information. The SEM characterization of the chert employed to fashion the Orient Fishtails matches the Crooked Swamp chert located at New Quarry #1, located one mile to the east. The large, pale gray-blue bifaces and biface thinning and reduction flakes suggest provenance in the upper unit within the Harmonyvale Member at the Lower Road Quarry, seven miles to the west. The association of both Lamoka and Orient Fishtail projectile points, fashioned from Crooked Swamp chert and found with large bifaces of Harmonyvale chert, is common in the upper watersheds of the Wallkill River Valley. Tests on both varieties of chert suggest that the clay-deficient Crooked Swamp chert is extremely brittle, and does not thin or resharpen well, rendering it useful for projectile points as impact instruments. On the other hand, the Harmonyvale chert has a high illite clay content that is amenable to resharpening in biface form. The association of these two cherts in artifact form originating from two specific quarries suggests shared knowledge of the characteristics of the chert and the whereabouts of suitable outcrops. Excavated assemblages throughout the region clearly illustrate understanding of the mechanical characteristics of the local cherts. Moreover, the unique cherts in artifact form relay both symbolic and practical information concerning the topography of the region, and even the mining experience.

REFERENCES CITED

Aaron, J.M., 1969, Petrology and origin of the Hardyston Quartzite (Lower Cambrian) in eastern Pennsylvania and western New Jersey, *in* Subitzky, S., ed., Geology of Selected Areas in New Jersey and Eastern Pennsylvania and Guidebook of Excursions: New Brunswick, New Jersey, Rutgers University Press, p. 21-34.

Aitken, J.D., Classification and environmentl significance of crypt-algal limestones and dolomites, with illustrations from the Cambrian and Ordovician of Alberta: Journal of Sedimentary Petrology, v. 37, p. 1163-1178.

Berg,T.M., McInerney, M.K., Way, J.H., and MacLachlan, D.B., 1983, Stratigraphic correlation chart of Pennsylvania: Pennsylvania Geological Survey, General Geology Report 75.

Bond, G.C., Nickeson, P., and Kominz, M.A., 1984, Breakup of a supercontinent between 625 Ma and 555 Ma: New evidence and implications for continental histories: Earth and Planetary Science Letters, v. 70, p. 325-345.

Braun, M., and Friedman, G.M., 1969, Carbonate lithofacies and environments of the Tribes Hill Formation (Lower Ordovician) of the Mohawk Valley, New York: Journal of Sedimentary Petrology, v. 39, p. 113-135.

Bova, J., and Read, J.F., 1987, Incipiently drowned facies within a cyclic peritidal ramp sequence, Early Ordovician: Geological Society of America Bulletin, v. 98, p. 714-727.

Clayton, C.J., 1986, The chemical environment of flint formationin Upper Cretaceous chalks, in Sieveking, G. de G., and Hart, M.B., eds., The Scientific Study of Flint and Chert: New York, Cambridge University Press, p. 43-54.

Costello, M.A., LaFleur, R.C., Hartgen, K.S., Bouchard, J.W., Krievs, A., and La Porta, P.C., 1992, *Dutchess Quarry & Supply Company, Inc. Cultural Resources Survey Stages 1 and 2, Goshen Quarry Future Mining Area, Town of Goshen, Orange County, New York:* Report prepared by Dunn Corporation and Hartgen Archaeological Associates.

deBoer, R.B., 1977, On the thermodynamics of pressure solution - interaction between chemical and mechanical forces: Geochimica et Cosmochimica Acta, v. 41, p. 249-256.

Durney, D.W., 1972, Solution-transfer, an important geological deformation mechanism: Nature, v. 235, p. 315-317.

Geiser, P., 1988, Mechanisms of thrust propagation: Some examples and implications for the analysis of overthrust terrains: Journal of Structural Geology, v. 10, p. 829-845.

Hatch, J.W., 1994, The structure and antiquity of prehistoric jasper quarries in the Reading Prong, Pennsylvania, *in* Bergman, C.A. and Doershuk, J.F., eds., Recent Research into the Prehistory of the Delaware Valley, Journal of Middle Atlantic Archaeology , v. 10, p. 23-46.

Hobson, J.P., 1963, Stratigraphy of the Beekmantown Group in Southeastern Pennsylvania: Pennsylvania Geological Survey (4th Series), General Geological Report 37.

Knauth, L.P., 1979, A model for the origin of chert in limestone: Geology, v. 7, p. 274-277.

Knopf, E.B., 1946, Stratigraphy of the Lower Paleozoic rocks surrounding Stissing Mountain, Dutchess County, New York [ABS]: Geological Society of America Bulletin, v. 57, p. 1211.

Knopf, E.B., 1962, Stratigraphy and structure of the Stissing Mountain Area, Dutchess County, New York: Geological Sciences, v. 7, no. 1, 55 p.

La Porta, P.C., n.d., The Cambrian and Ordovician Carbonates of the Wallkill River Valley: The Nature of the Diagenesis of Chert and Its Archaeological Behavior [Ph.D. thesis]: New York, Queens College of the City University of New York.

La Porta, P.C., 1994, Lithostratigraphic models and the geographic distribution of prehistoric chert quarries within the Cambro-Ordovician lithologies of the Great Valley Sequence, Sussex County, New Jersey, *in* Bergman, C.A. and Doershuk, J.F., eds., Recent Research into the Prehistory of the Delaware Valley, Journal of Middle Atlantic Archaeology , v. 10, p. 47-66.

La Porta, P.C., 1993, *Predictive Model for Quarry Locations, Delaware Water Gap National Recreation Area, Phase I Report:* Report submitted to 3D/Environmental Services, Inc., Cincinnati, Ohio for National Park Service, Washington, D.C.

La Porta, P.C., 1990, The Stratigraphic Relevance and Archaeological Potential of the Cambro-Ordovician Kittatinny Supergroup of the Wallkill River Valley of Northern New Jersey [M.A. thesis]: Queens College of the City University of New York, 50 p.

La Porta, P.C., 1989, The stratigraphic relevance and archaeological potential of the chert-bearing carbonates within the Kittatinny Supergroup: New York State Geological Association Field Trip Guidebook, 61st Annual Meeting, Middletown, New York.

La Porta, P.C., 1987, Prehistoric resource analysis: field observations and petrographic characteristics of Cambrian-Ordovician chert: Geological Society of America, Abstracts with Programs, v. 19(1), p. 24-25.

La Porta, P.C., 1986, The archaeological potential of the Leithsville Formation: A Lower Cambrian chert-bearing carbonate in New Jersey: Geological Society of America, Abstracts with Programs, v. 18(1), p. 28-29.

Maliva, R., 1989a, Chertification histories of some Late Mesozoic and Middle Paleozoic platform carbonates: Sedimentology, v. 36, p. 907-926.

Maliva, R., 1989b, Nodular chert formation in carbonate rocks: Journal of Geology, v. 97, p. 421-433.

Maliva, R., and Siever, R., 1988, Pre-Cenozoic nodular cherts: Evidence for opal-CT precursors and direct quartz replacement: American Journal of Science, v. 288, p. 798-809.

Markewicz, F.J., and Dalton, R., 1973, Stratigraphy and structure of Branchville, Franklin, Newton East and Newton West, Pine Island, Stanhope, Tranquility, Unionville and Wawayanda quadrangles: New Jersey Department of Environmental Protection, Bureau of Geological Topography, Geology Overlay Sheet no. 22.

Markewiecz, F.J., and Dalton, R., 1974, Subdivision of the Lower Ordovician Epler Formation in New Jersey: Geological Society of America, Abstracts with Programs, v. 6(1), p. 52.

Markewiecz, F.J., and Dalton, R., 1976, The Lower Ordovician Ontelaunee Formation in New Jersey: Geological Society of America, Abstracts with Programs, v. 8(2), p. 225-226.

Markewicz, F.J., Dalton, R., Spink, W., Metsger, R., and Lucey, C., 1977, The stratigraphy and applied geology of the Lower Paleozoic carbonates in northwestern New Jersey: Guidebook, 42nd Annual Field Conference of Pennsylvania Geologists, Harrisburg, Pennsylvania.

Mazzullo, S.J., and Friedman, G.M., 1975, Conceptual model of tidally influenced deposition in margins of epeiric seas: Lower Ordovician of eastern New York and western Vermont: American Association of Petroleum Geologists Bulletin, v. 59, p. 2123-2141.

Mustard, P.S., and Donaldson, J.A., 1990, Paleokarst breccias, calcretes, silcretes and fault talus breccias at the base of upper Proterozoic "Windermere" strata, northern Canadian Cordillera: Journal of Sedimentary Petrology, v. 60, p. 525-539.

Offield, T.W., 1967, Bedrock Geology of the Goshen-Greenwood Lake Area, N.Y.: New York State Museum and Science Service, Map and Chart Series no. 9.

Roberts, A.E., 1966, Stratigraphy of Madison Group near Livingston, Montana, and discussion of karst and solution-breccia features: U.S. Geological Survey Professional Paper 526-B.

Roehl, P.O., 1981, Dilation brecciation - a proposed mechanism of fracturing, petroleum expulsion and dolomitization in the Monterey Formation, California, *in* Garrison, R.E., Douglas, R.G., Prosciotto, K.E., Isaacs, C.M., and Ingle, J.C., eds., The Monterey Formation and Related Siliceous Rocks of California: Society of Economic Paleontologists Mineralogists, Pacific Section, p. 285-316.

Thomas, W., 1977, The evolution of salients and recesses from promontories and reentrants within the Appalachian-Ouachita chain: American Journal of Science, v. 277, p. 1233-1278.

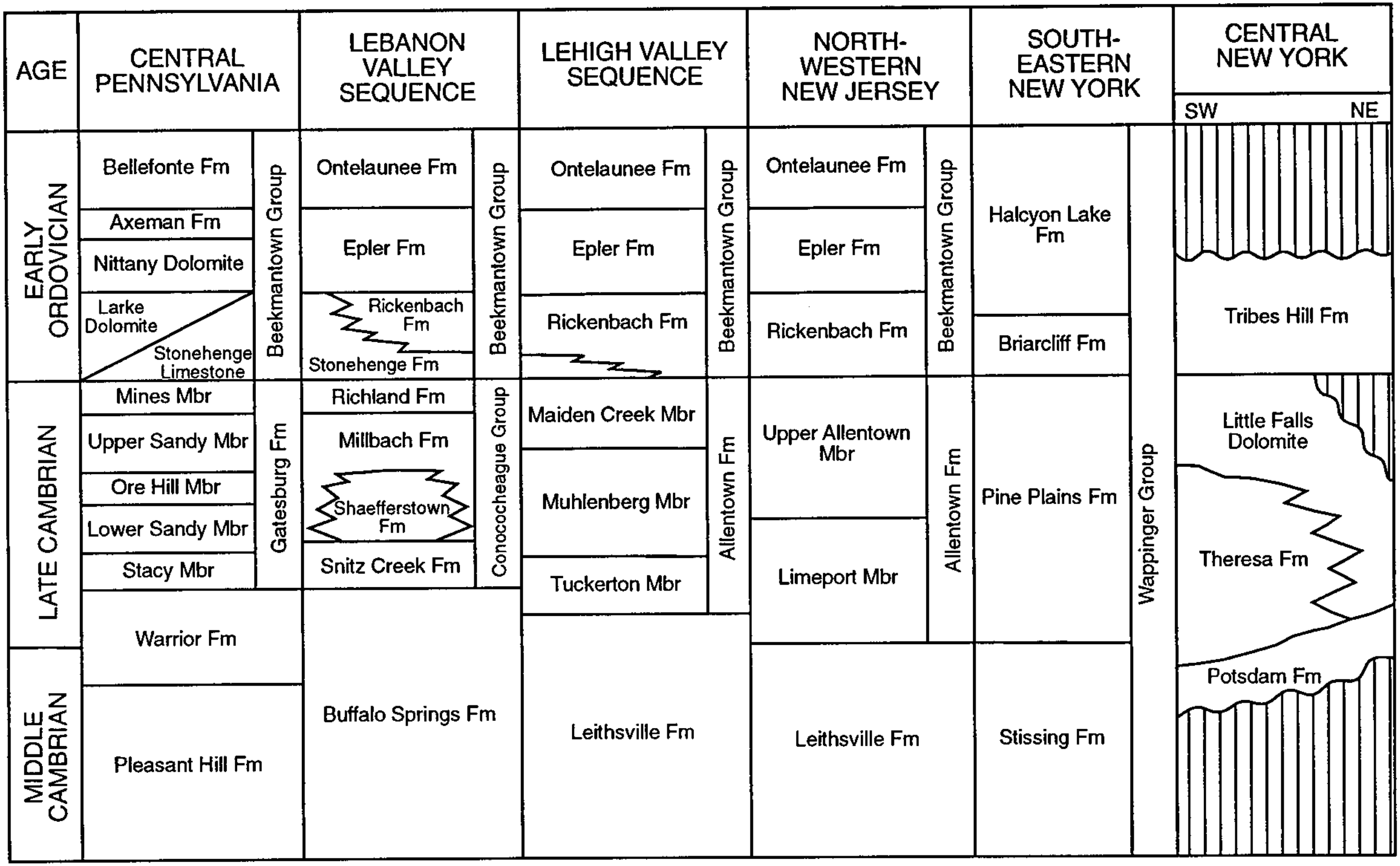
Twenhofel, W.H., 1954, Correlations of the Ordovician formations of North America: Geological Society of America Bulletin, v. 65, p. 247-298.

Woodward, H.P., 1931, Paleozoic cherts of west-central Virginia: Journal of Geology, v. 39, p. 277-287.

Zadnick, V.E., and Carozzi, A.V., 1963, Sedimentation cyclique dans les dolomies du Cambrian Superieur de Warren County, New Jersey, USA: Bulletin Institute National Genevois, v. 62, p. 3-55.

	Formations recognized by E.B. Knopf (SE NYS)	Formations recognized by H.B. Kummel and others	Formations recognized by A.A. Drake & F.J. Markewicz	Current Stratigraphy as used by F.J. Markewicz & R.F. Dalton			Chert Stratigraphy	Lithostratigraphy
LOWER ORDOVICIAN	HALCYON LAKE GROUP	BEEKMANTOWN GROUP	Epler Fm	Ontelaunee Fm (Oo)	Harmonyvale Mbr (Oo$_2$)		light blue, blue/gray, thin & thick, laminated beds	light blue micritic, extremely massive, finely laminated dolomite
					Beaver Run Mbr (Oo$_1$)		thick black massive beds, stromatolitic, brecciated, boudinage	black, sulfide-rich, coarsely crystalline, laminated dolomite
				Epler Fm (Oe)	Lafayette Mbr (Oe$_3$)		steel blue/gray pods & beds, laminated, oolitic sequences	black, sparkly, thick-bedded dolomite
					Big Springs Mbr (Oe$_2$)		lavender, orchid or white laminated beds (also red & green in karst)	massive, iron-stained, highly siliceous dolomite
					Branchville Mbr (Oe$_1$)		opaque, brecciated, thin & thick bedded, porcelain gray & black beds	sulfide zone, black, coarsely crystalline, thinly-bedded dolomite
			Rickenbach Fm	Rickenbach Fm (Or)	Hope Mbr (Or$_2$)	Crooked Swamp dolomite facies (Or$_3$)	Or$_3$ - highly translucent, light blue/gray, algal sequences, dilation breccias	extremely coarse-grained, sulfide-rich, light blue-gray dolomite
							Or$_2$ - convex pods, dark blue/gray to blue, cont. beds, replacing evaporites	massive, fine-grained, dark blue, thinly-bedded dolomite
	Briarcliff Fm				Lower Mbr (Or$_1$)		Or$_1$ - brecciated, massive blue/gray matrix with black clasts	discontinuous, sandy dolomite
CAMBRIAN	Pine Plains Fm	Allentown Fm	Allentown Fm	Allentown Fm (Ca)	Upper Mbr (Ca$_2$)		algal, oolitic, black, homogeneous, thin-bedded, silcrete	massive, thick-bedded, coarse-grained to micritic dolomite
					Limeport Mbr (Ca$_1$)		oolitic, cryptalgal, stylolitic, black	shallowing-upward cycles, microbial laminate, oolitic dolomite
	Stissing Fm	Tomstown Fm	Leithsville Fm	Leithsville Fm (Cl)	Wallkill Mbr (Cl$_3$)		translucent blue/gray pods	coarse-grained, sparkly, stromatolite-rich dolomite
					Hamburg Mbr (Cl$_2$)		black, sparkly, vuggy, thin-bedded	cyclic, sulfides, mud cracks, ripple marks, pink, green & gray dolomite
					Califon Mbr (Cl$_1$)		black to dark gray pods & colliform masses	black shale, mud cracks, ripple marks, tidal flat dolomite, *Skolithos*

TABLE 1



AGE	CENTRAL PENNSYLVANIA		LEBANON VALLEY SEQUENCE		LEHIGH VALLEY SEQUENCE		NORTH-WESTERN NEW JERSEY		SOUTH-EASTERN NEW YORK		CENTRAL NEW YORK SW NE
EARLY ORDOVICIAN	Bellefonte Fm Axeman Fm Nittany Dolomite Larke Dolomite Stonehenge Limestone	Beekmantown Group	Ontelaunee Fm Epler Fm Rickenbach Fm Stonehenge Fm	Beekmantown Group	Ontelaunee Fm Epler Fm Rickenbach Fm	Beekmantown Group	Ontelaunee Fm Epler Fm Rickenbach Fm	Beekmantown Group	Halcyon Lake Fm Briarcliff Fm	Wappinger Group	Tribes Hill Fm
LATE CAMBRIAN	Mines Mbr Upper Sandy Mbr Ore Hill Mbr Lower Sandy Mbr Stacy Mbr	Gatesburg Fm	Richland Fm Millbach Fm Shaefferstown Fm Snitz Creek Fm	Conococheague Group	Maiden Creek Mbr Muhlenberg Mbr Tuckerton Mbr	Allentown Fm	Upper Allentown Mbr Limeport Mbr	Allentown Fm	Pine Plains Fm		Little Falls Dolomite Theresa Fm
	Warrior Fm		Buffalo Springs Fm		Leithsville Fm						
MIDDLE CAMBRIAN	Pleasant Hill Fm						Leithsville Fm		Stissing Fm		Potsdam Fm

TABLE 2

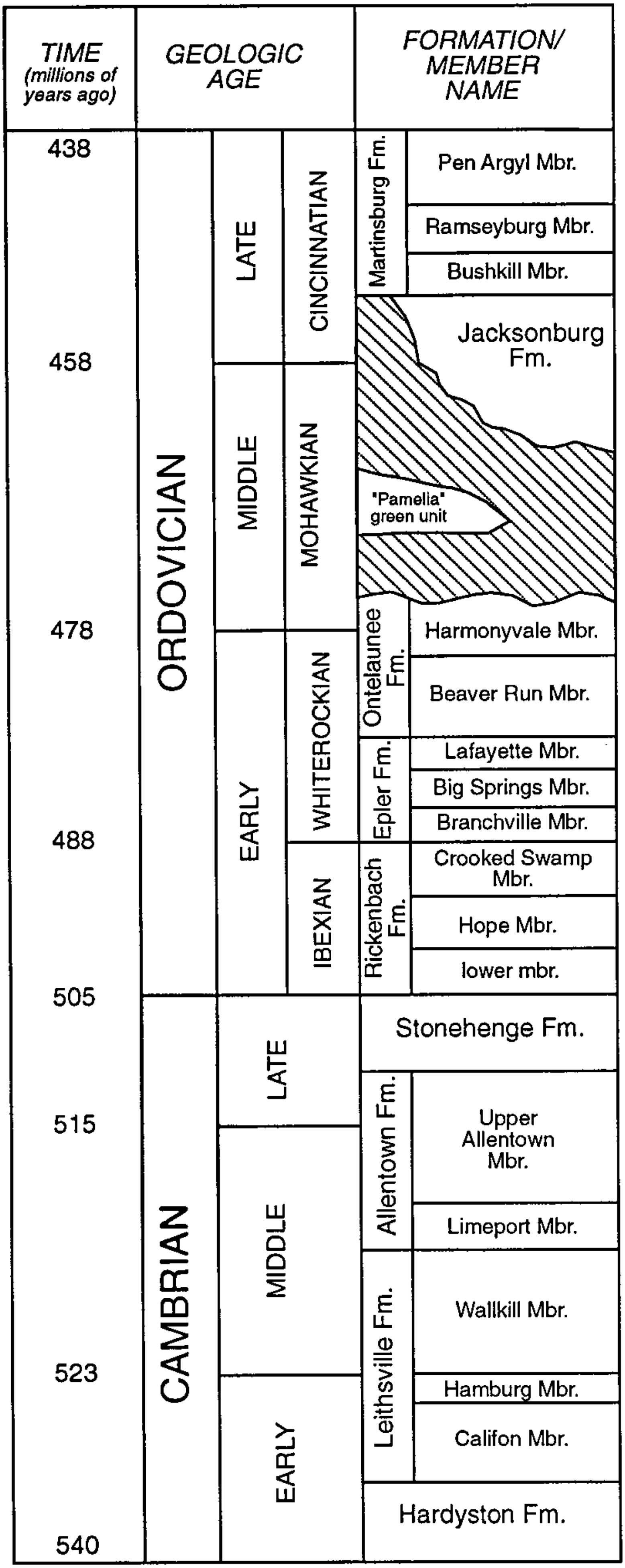

TIME (millions of years ago)
GEOLOGIC AGE
FORMATION/ MEMBER NAME
438
458
478
488
505
515
523
540
ORDOVICIAN
CAMBRIAN
LATE
MIDDLE
EARLY
LATE
MIDDLE
EARLY
CINCINNATIAN
MOHAWKIAN
WHITEROCKIAN
IBEXIAN
Martinsburg Fm.
Pen Argyl Mbr.
Ramseyburg Mbr.
Bushkill Mbr.
Jacksonburg Fm.
"Pamelia" green unit
Ontelaunee Fm.
Harmonyvale Mbr.
Beaver Run Mbr.
Epler Fm.
Lafayette Mbr.
Big Springs Mbr.
Branchville Mbr.
Rickenbach Fm.
Crooked Swamp Mbr.
Hope Mbr.
lower mbr.
Stonehenge Fm.
Allentown Fm.
Upper Allentown Mbr.
Limeport Mbr.
Leithsville Fm.
Wallkill Mbr.
Hamburg Mbr.
Califon Mbr.
Hardyston Fm.

FIGURE 1

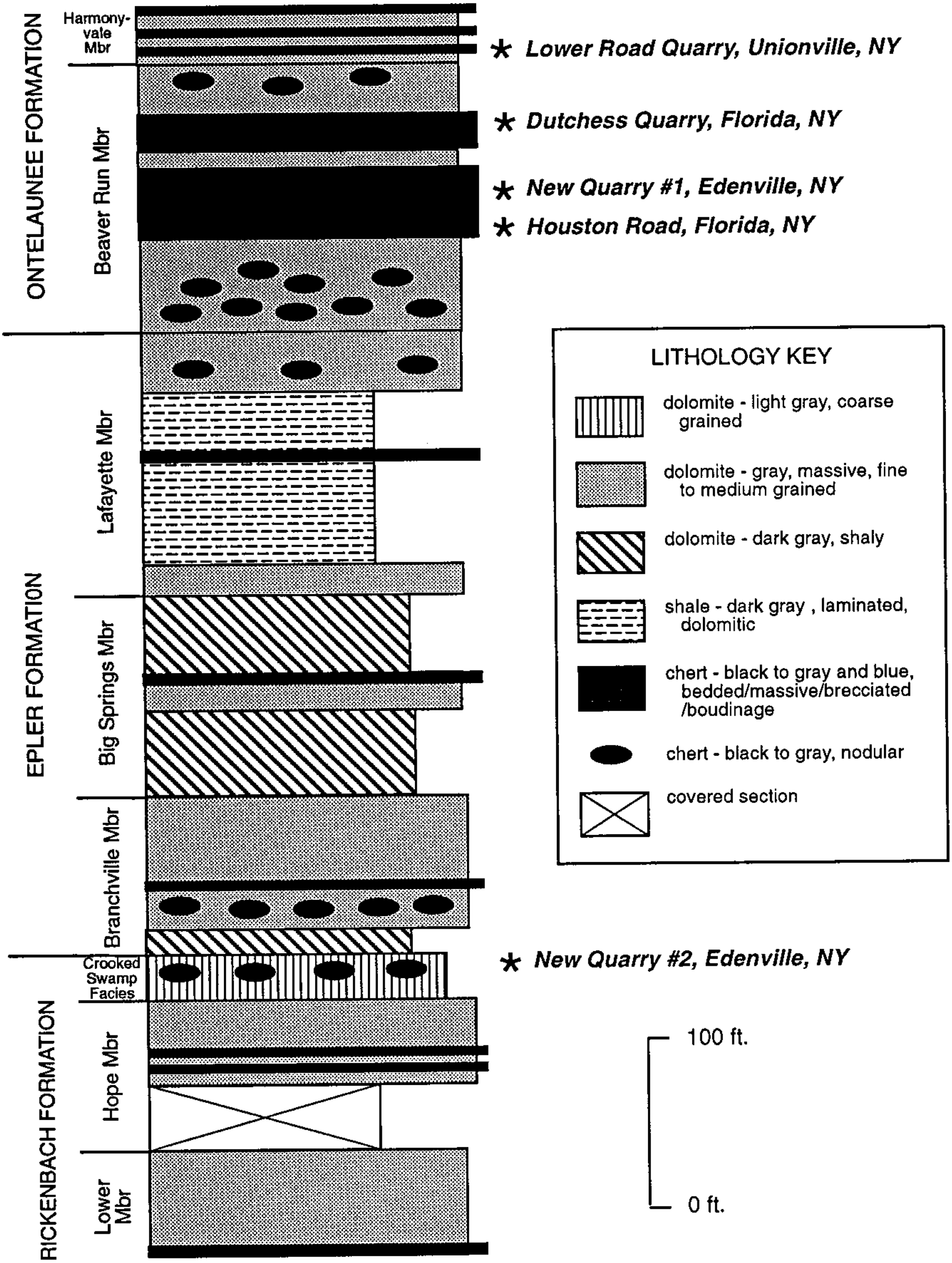

ONTELAUNEE FORMATION
Harmony-vale Mbr
Beaver Run Mbr
EPLER FORMATION
Lafayette Mbr
Big Springs Mbr
Branchville Mbr
Crooked Swamp Facies
RICKENBACH FORMATION
Hope Mbr
Lower Mbr
★ Lower Road Quarry, Unionville, NY
★ Dutchess Quarry, Florida, NY
★ New Quarry #1, Edenville, NY
★ Houston Road, Florida, NY
★ New Quarry #2, Edenville, NY
LITHOLOGY KEY
dolomite - light gray, coarse grained
dolomite - gray, massive, fine to medium grained
dolomite - dark gray, shaly
shale - dark gray , laminated, dolomitic
chert - black to gray and blue, bedded/massive/brecciated /boudinage
chert - black to gray, nodular
covered section
100 ft.
0 ft.

FIGURE 2

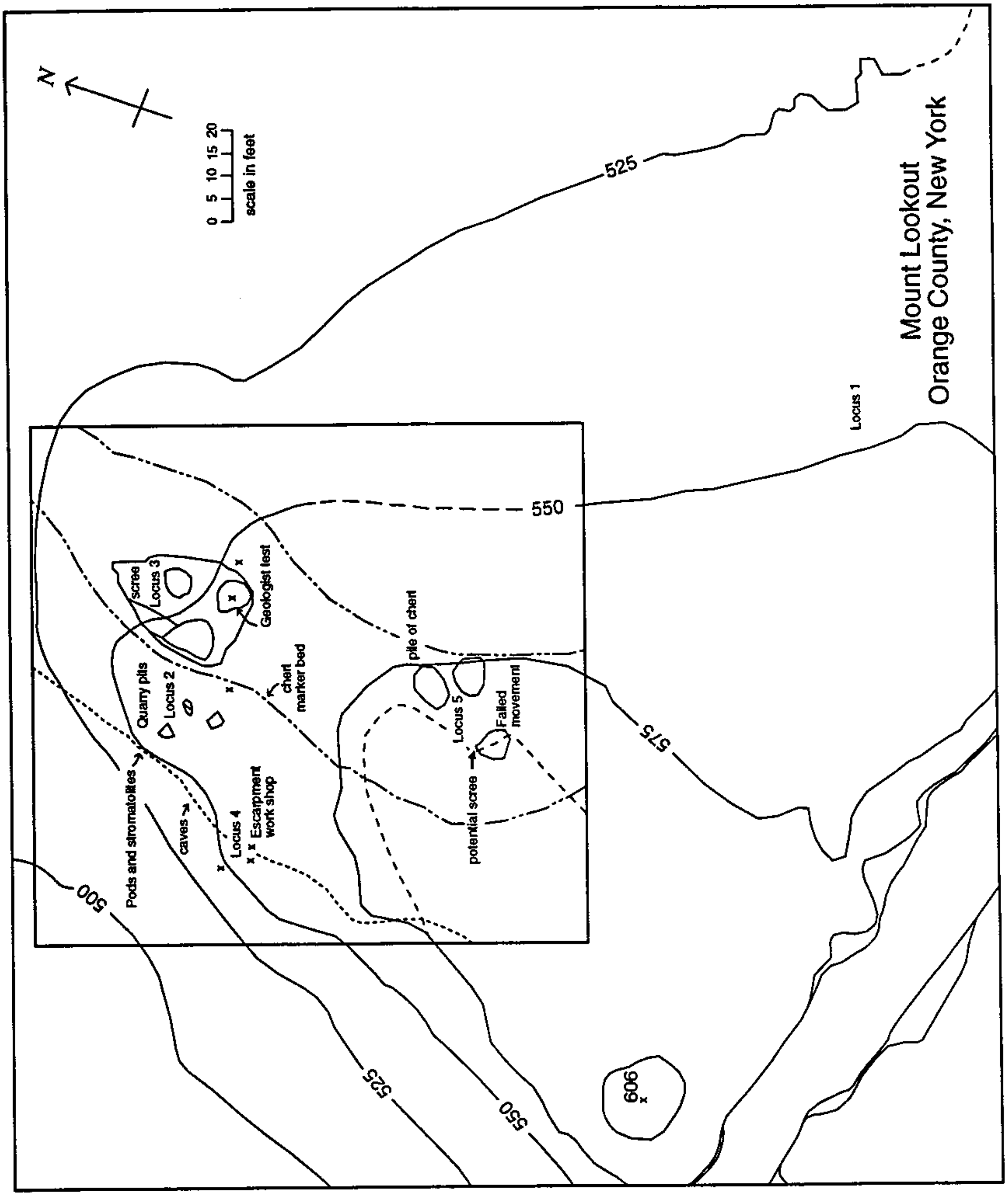
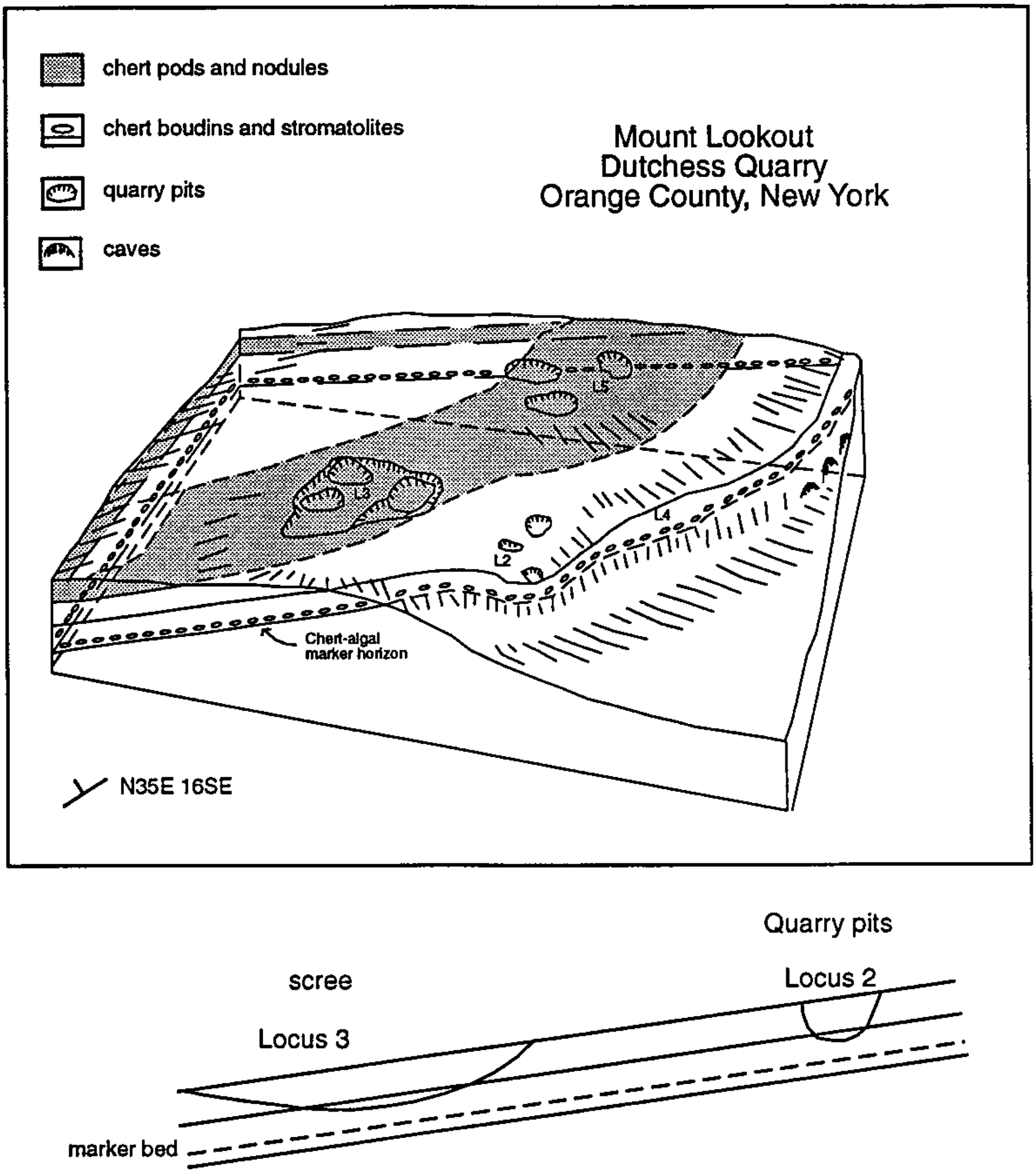

N
0 5 10 15 20
scale in feet
Mount Lookout
Orange County, New York
525
550
575
500
525
550
606
Locus 1
Locus 2
Locus 3
Locus 4
Locus 5
scree
Geologist test
pile of chert
chert marker bed
Quarry pits
Pods and stromatolites
caves
Escarpment work shop
Failed movement
potential scree

FIGURE 3



chert pods and nodules
chert boudins and stromatolites
quarry pits
caves
Mount Lookout
Dutchess Quarry
Orange County, New York
L5
L3
L4
L2
Chert-algal marker horizon
N35E 16SE
Quarry pits
scree
Locus 2
Locus 3
marker bed

FIGURE 4

Karst Hydrogeology of the Shuster Pond Area, Hardwick Township, Warren County, New Jersey

Robert Canace *
Donald Monteverde *
Michael Serfes *
*** New Jersey Geological Survey**

INTRODUCTION

Karst landscapes result from the action of water on soluble rocks. The term is principally reserved for carbonate rocks. The hydrology of karst regions presents unique problems to hydrologists. The subject is receiving increasing attention, because karst terrane covers about 40% of the land surface east of the Mississippi (White and others, 1995). Increasing land development in many previously undeveloped karst areas is calling attention to challenging environmental issues associated with karst, including water-related issues. The area around Shuster Pond in Hardwick Township, Warren County (field trip log, fig. 1, stop 4), provides a classic model of karst hydrology in New Jersey. It illustrates some of the complexities associated with understanding the dynamics of an integrated karst surface- and ground-water flow system.

Karst hydrologic systems are characterized by streams that sink into the ground, underground streams, springs both large and small, and complex ground-water flow paths that can change depending on antecedent ground- and surface-water levels. Nutter (1973) suggests that abundant springs are one of the most important features of carbonate rock terranes and that these discharge signficant quantities of water from the karst ground-water system.

Shuster pond is host to a high-discharge spring in the Allentown Dolomite. Several other signficant springs occur in the area, including Bonnie Brook spring, which appears to be hydraulically connected to Shuster Pond. Other characteristic karst features in the area include disappearing streams, "dry valleys," gulfs, sinkholes, caves, pinnacle-and--trough topography, solution-enlarged joints, and other features characteristic of karst. These features constitute elements of the karst drainage system.

ACKNOWLEDGEMENTS

The authors would like to thank William Eagen, owner of Mountainwood Springwater Company and Bonnie Brook spring for graciously allowing access to his land for research. Special thanks go to Greg Herman and Richard Dalton of the New Jersey Geological Survey. Greg for his participation in the geological investigation of the study area, particularly for his insights on geologic structures in the carbonate rocks, Richard for his information on caves and his insights on karst in general. We greatly appreciate the efforts of Richard Fenton of NJDEP Bureau of Water Monitoring for collecting water-quality field parameters and samples. Thanks go also to Frank Getchell of Leggette, Brashears & Graham, Inc., Ramsey New Jersey, and to

William Gold, Esquire, of Hardwick Township for graciously sharing information collected on Shuster Pond spring.

GEOLOGIC SETTING

The Shuster Pond area lies in the eastern part of the Valley and Ridge Province. Cambrian and Ordovician carbonates, shales and sandstones cover the region in long linear, northeast-trending belts. The area experienced a varied history of deformation. This includes folding during the Taconic Orogeny, extensive thrust faulting and contemporaneous folding in the Alleghenian Orogeny and finally, possible fault reactivation under the extensional conditions of Mesozoic rifting. These periods of deformation imparted a wide assemblage of secondary structures on the rocks in this area. The immediate area of Shuster Pond lies in the Paulins Kill thrust belt (Herman and Monteverde, 1989). Folds and faults cause duplication of stratigraphic units in the area.

The Lower Paleozoic carbonates in the Shuster Pond area were deposited in a passive margin setting. They are part of a thick assemblage of sedimentary rocks termed the Kittatinny Supergroup (Drake and Lyttle, 1980). The Kittatinny consists of a sequence of dolomite with interbedded dolomitic shale and sandstone (see Markewicz and Dalton, 1976). Stratigraphic units in the study area consist of the Allentown Dolomite and the Beekmantown Group. The latter consists, in ascending age, of the Rickenbach, Epler and Ontelaunee Formation. Dolomite dominates in these units although lenses and beds of limestone occur within the Epler and Ontelaunee.

The Jacksonburg Limestone, which varies from a limestone to an argillaceous limestone, lies unconformably on top of the Kittatinny. Capping the region is the Martinsburg Formation, which developed in a foreland basin. The Martinsburg is made up of claystone slate (Bushkill Member) overlain by an interbedded slate and sandstone (Ramseyburg Member).

Shuster Pond lies in the Allentown Dolomite (figure 1). The Allentown strikes northeast and dips to the northwest. Beekmantown through Martinsburg rocks overlie the Allentown to the west. East of the Paulins Kill, a sequence of thrust faults carrying small silvers of carbonate rock exist. Martinsburg shales and sandstones were thrust up against the entire package and reside further east.

The structural deformation that assembled the units in their current arrangement also imparted smaller scale features. A well developed slaty cleavage occurs within the Martinsburg. Folds and faults within the carbonates caused a spaced cleavage to develop. The spacing on this cleavage is variable, depending on the host lithology. A well developed joint pattern is found throughout the carbonates

An analysis of the secondary features within the carbonate rocks was performed to understand their orientations and relate them to ground water flow. Data collected during a 1:24,000 scale geologic mapping program (Monteverde and Herman, unpublished data) along with subsequent site mapping was used in the analysis. Data is from the northwest dipping units

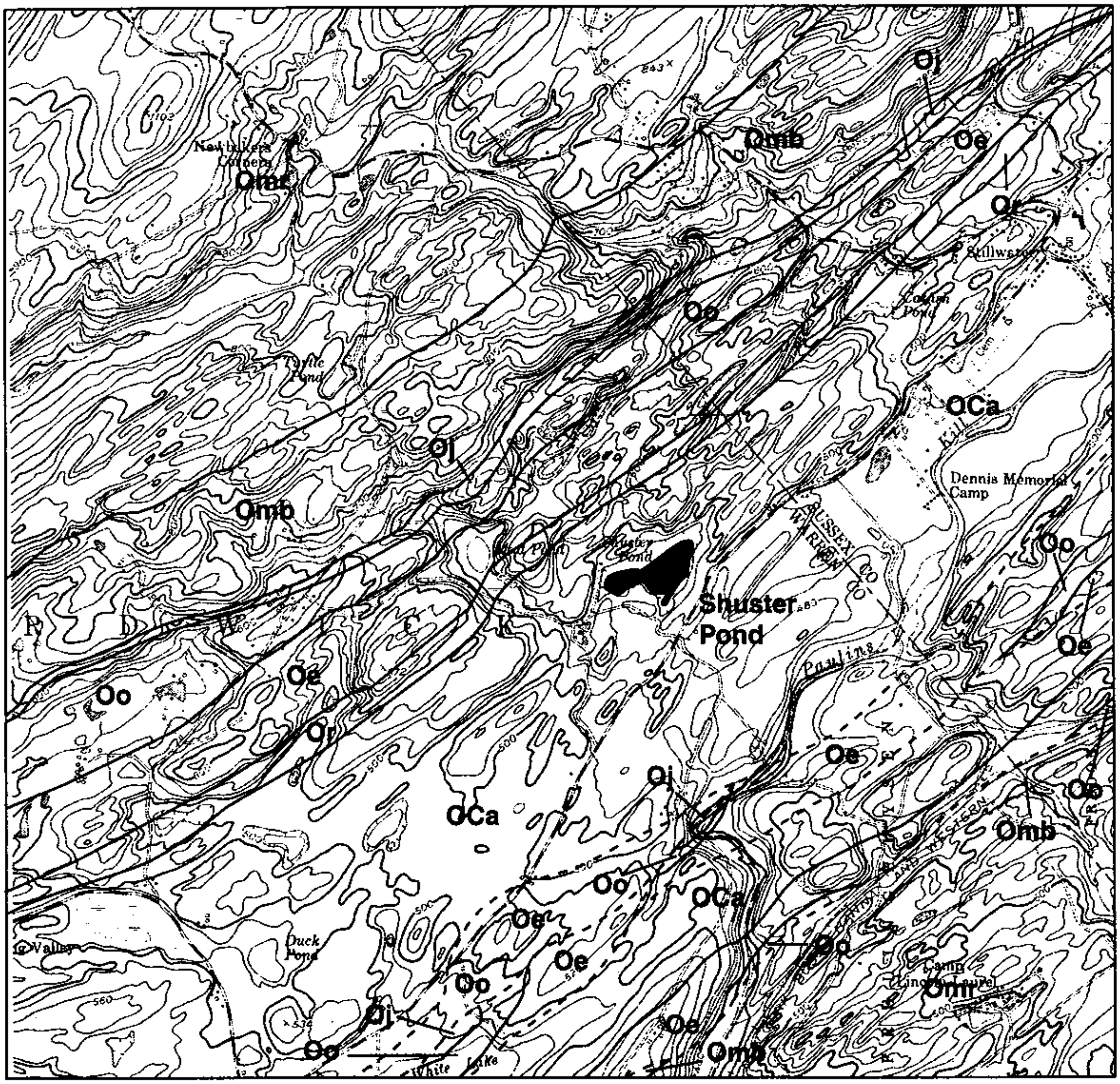


Figure 1. Site geologic map of Shuster Pond region from unpublished data of D. Monteverde and G. Herman. Solid lines are unit contacts, dashed lines are faults. OCa = Allentown Dolomite, Or = Rickenbach Dolomite, Oe = Epler Formation, Oo = Ontelaunee Formation, Oj = Jacksonburg Limestone, Omb = Bushkill Member of the Martinsburg Formation, Omr = Ramseyburg Member of the Martinsburg Formation.

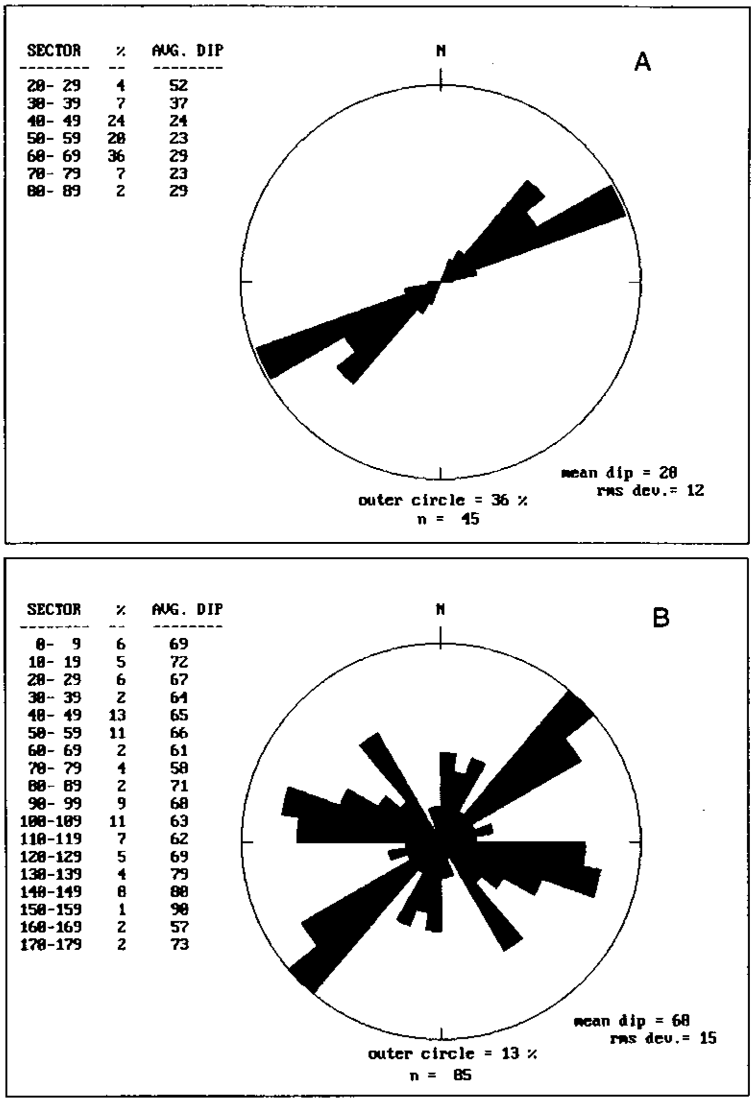


Figure 2. - Rose diagrams of structural orientation data from the Shuster Pond area collected at the outcrop scale during geologic mapping. A- Bedding trends from the surrounding carbonate rocks. B- Compilation of joint, spaced cleavage and vein trends from the carbonate rocks.

east of the Martinsburg Formation and west of the thrust fault. Rose diagrams were constructed based on an analysis of the frequency of structural trends in the data compilation (figure 2).

KARST HYDROGEOLOGY

Karst hydrogeology is characterized by diffuse recharge through weathered joints and strata, by concentrated recharge by way of sinkholes, disappearing streams, box canyons, underground streams, and springs. All of these features are found or are suspected in the study area (figure 3).

Primary porosity in dolomitic bedrock is extremely low. For example, primary porosity of the carbonate Black River Formation, Trenton Limestone and Beekmantown Group from Wood County, West Virginia, as measured in laboratory tests range from 0.4 percent to 0.9 percent (Manger, 1963). Ground-water flow in indurated carbonates such as those found in the Appalachians is transmitted by secondary pores, consisting of bedding-plane partings, joints, cleavage, and shear fractures. Many of these structures are enlarged through the solutioning of the rock.

White (1970) points out that in carbonate rocks ground water in solution-enlarged conduits may represent a significant percentage of the total volume of ground water in the aquifer. Specific ground-water flow paths are controlled by the orientation and interconnection of fractures and the distribution of water levels in the aquifer. According to White, the dominance of strike-oriented caves in the folded Appalachians following a single bed or set of beds for long distances points to the importance of lithologic controls on secondary porosity. No definite relationship was found to occur between the spacing of bedding plane partings and the degree of cavern development in the Paleozoic carbonates of western Pennsylvania. Both thin and thick-bedded units occur that are both highly cavernous and non-cavernous.

Palmer (1987) points out that folded and faulted rocks with prominent bedding, such as those found in the Appalachian Valley and Ridge of New Jersey, exhibit the strongest coincidence between the orientation of vadose(unsaturated)-zone conduits and primary geologic structures. White (1970) suggests that in steeply dipping strata of the carbonate Bush and Penns Valleys in Pennsylvania the greater surface exposure of the beds due to the steep dip has resulted in increased cavern development.

According to White (1963), solution-modified conduits usually follow the dominant joint systems. Davies (1958) in his study of caves in West Virginia concluded that joints determine the patterns of caves. He found bedding planes and faults of secondary importance in controlling cave directions. Joints connecting with faults showed more cave development in his study.

Lithology plays a role in the development of solution cavities in the carbonate bedrock. According to White (1970), the most important lithologic factor controlling solution development in carbonate rocks is the presence of clay minerals and dolomite content. He suggests that those carbonate rocks with the lowest clay and dolomite content exhibit the greatest solution-channel development. Ferrari and Sessa (1937) claim that the rate of solutioning of the

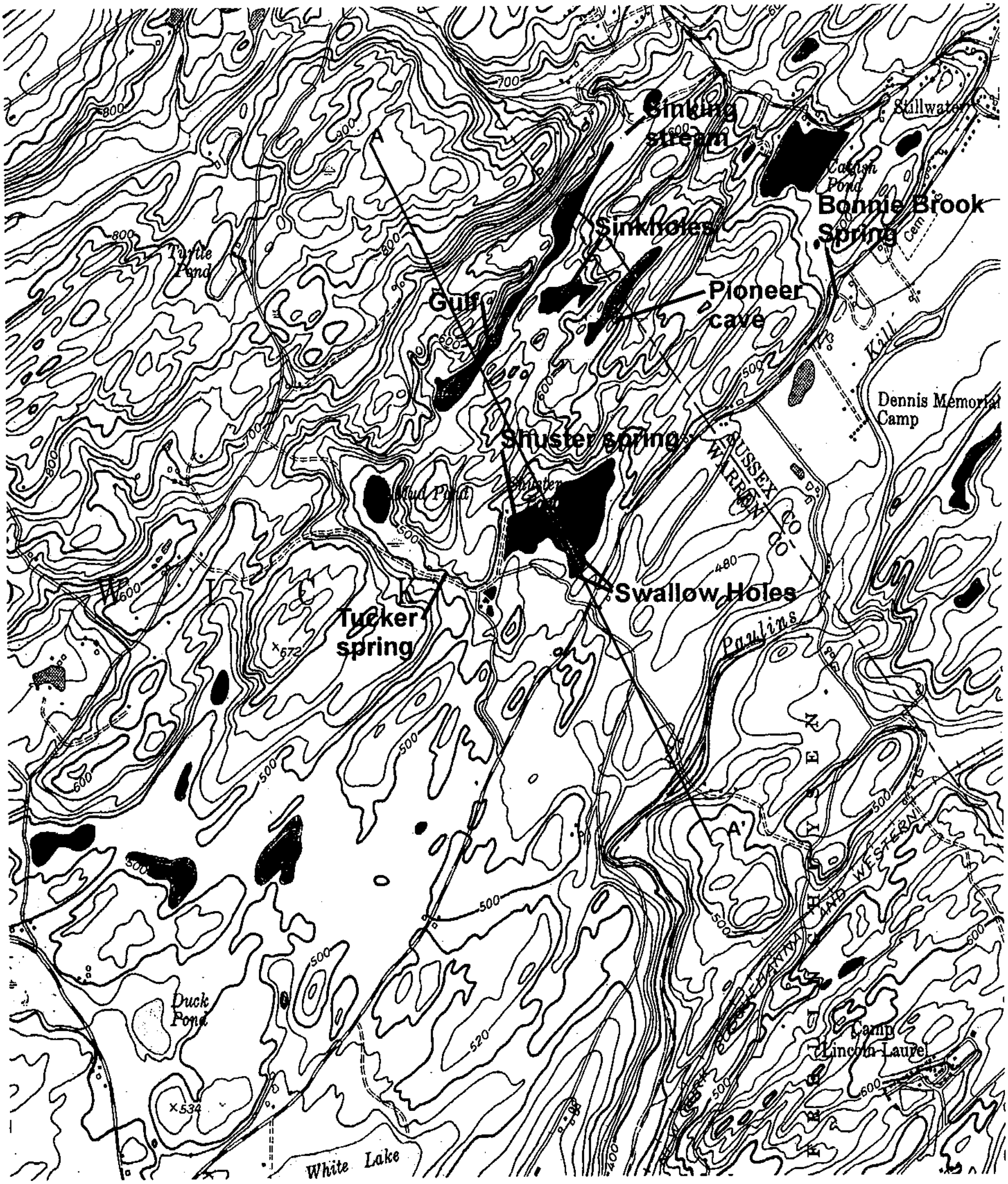


Figure 3. Shuster Pond area, Hardwick Township, Warren County and Stillwater Township, Sussex County. Locations of significant karst features are shown. Base map is U.S. Geological Survey 1:24,000 Flatbrookville topographic quadrangle.

mineral calcite is about 150 times that of dolomite. Markewicz and Dalton (1976) suggest that dolomitic rocks with the largest grain size are most susceptible to chemical weathering. Miller and Skelton (1979) point out that the coarse-grained dolomitic beds of the lower Gasconde Dolomite of Missouri weather to produce higher well yields than fine-grained units.

According to Palmer (1987), within the weathered, shallow part of karst systems (the epikarst), intersecting structures cause infiltrating ground water to converge as tributaries to large conduits. The larger conduits exhibit relatively low hydraulic heads relative to surrounding saturated fractures and act as drains. Ground-water tracer studies of limestone aquifers show that ground water in karst follows convergent paths. Palmer concluded that the overall pattern of ground-water flow in karst systems resembles that of surface streams in non-karst areas. Seventy-five percent of mapped caves exhibit dendritic patterns reminiscent of surface-water geometry.

Diffuse vs. Conduit Flow Systems

Karst ground-water systems have been characterized as lying along a contiuum between "diffuse flow " and "conduit" or "free-flow" systems (White, 1963; Smart and Hobbs, 1987). Diffuse-flow systems are found in most bedrock aquifers, wherein ground-water storage and movement occurs in a variably connected network of open fractures of relatively narrow aperture size. Conduit flow occurs primarily in carbonate bedrock. The conduits consist of solution-enlarged fractures. Ground-water flow rates can be significant in these conduits, approaching those of surface water.

Springs fed by diffuse flow systems have a long residence time, small variability in discharge, small variability in chemistry, low turbidity and are often near saturation with respect to calcite and dolomite. Low turbidity is an indication that ground-water flows through diffuse systems principally in fractures as low-velocity laminar flow (Palmer, 1987). Palmer (1987) suggests that diffuse flow paths in carbonate aquifers often exhibit strong anisotropy.

Conduit systems typically drain through a small number of high discharge springs (Rauch and White, 1970). The springs act as a sink to drain ground water from saturated fractures in the surrounding bedrock and from conduits at higher elevations. The main water-bearing conduits apparently flow at or somewhat below regional base level (White, 1963). The conduit system is generally characterized by a low hydraulic gradient, sustained by the high permeability of conduits and discharge from the open spring outlet. Springs fed by conduit systems have a short residence time, are sometimes turbid, and experience large variations in chemistry and discharge. Flow in conduits is often turbulent,

Ground-water levels in conduit systems exhibit marked variations, in response to sudden, high-volume inputs to the ground-water system through sinking streams and sinkholes. Water levels in wells in the carbonate Nittany Valley of Pennsylvania may raise 30 feet or more to accommodate a single period of snow melt or rain as surface water is recharged through sinkholes (Parizek and others, 1971).

Ground-Water Recharge in Karst

Ground-water recharge in karst aquifers occurs through several mechanisms. Recharge realms can be divided into two basic categories - "allogenic" and "autogenic" recharge (White and others, 1995) (figure 4).

Allogenic recharge originates in areas other than those underlain by the karst aquifer. The most common and recognizable example of allogenic recharge to a karst aquifer is a stream that drains adjacent, non-karst uplands and seeps into the ground as it encounters karst terrain. Such disappearing streams are extremely common in the Appalachians. Allogenic streams can often be traced from their source through significant cavern systems in the carbonate aquifer to large-capacity springs (White, 1963). They are often the prime source of large springs that emerge in the karst. Parizek and others (1971) report that the main source of ground water for the Ordovician Bellfonte Dolomite in western Pennsylvania is surface runoff from mountain streams that recharge into the carbonate aquifer through sinkholes. They point out that sinkholes have opened to accommodate the entire flow of individual mountain watersheds. White (1970) observed that in the carbonate Nittany, Bush, and Sugar Valleys in Pennsylvania small mountain streams draining upland areas underlain by shale sink near the limestone/shale contact to become points of localized recharge to the carbonate aquifer. He suggests that this mechanism is the main source of recharge to the carbonate system. In these areas stream recharge flows principally through conduits in the limestone to a relatively small number of big springs that discharge this water to perennial streams in the carbonate valley.

The length of underground flow routes from stream disappearance to spring emergence varies greatly in eastern North America, typically ranging from one to a few tens of kilometers (White, 1970). Subsurface flow rates in carbonate aquifers can be substantial. Miller and Skelton (1979) estimated underground flow rates from dye-tracing in an Ordovician dolomite in Missouri. They calculated straight-line velocities range from 0.6 to 0.8 kilometers per day from points of submergence to emergence, and point out that the likely presence of tortuous ground-water flow paths probably means that velocities are significantly higher than those calculated. Nutter (1973) suggests flow rates of up to 2000 feet per day in the Nittany Valley.

The chemistry of allogenic-stream recharge often makes it aggressive to carbonate rocks. Upland runoff from non-carbonate terrain is often under-saturated with respect to calcium carbonate and of a lower pH. An aggressive allogenic stream can consume calcium carbonate in the aquifer, causing chemical weathering of the carbonate rock. According to White and others (1995), when acidic water contacts carbonate rock the majority of the dissolution potential of the water is expended within a few hours, but may last days before it is used up. Thus, solutioning of the carbonate bedrock may be most intense near sinking streams. The energy of the stream is available to move dissolved and disaggregated limestone as it invades the subsurface, reinforcing the weathering process.

Autogenic recharge is that which occurs within the carbonate terrain. Autogenic recharge takes place through unconsolidated overburden on top of the carbonate rock, through

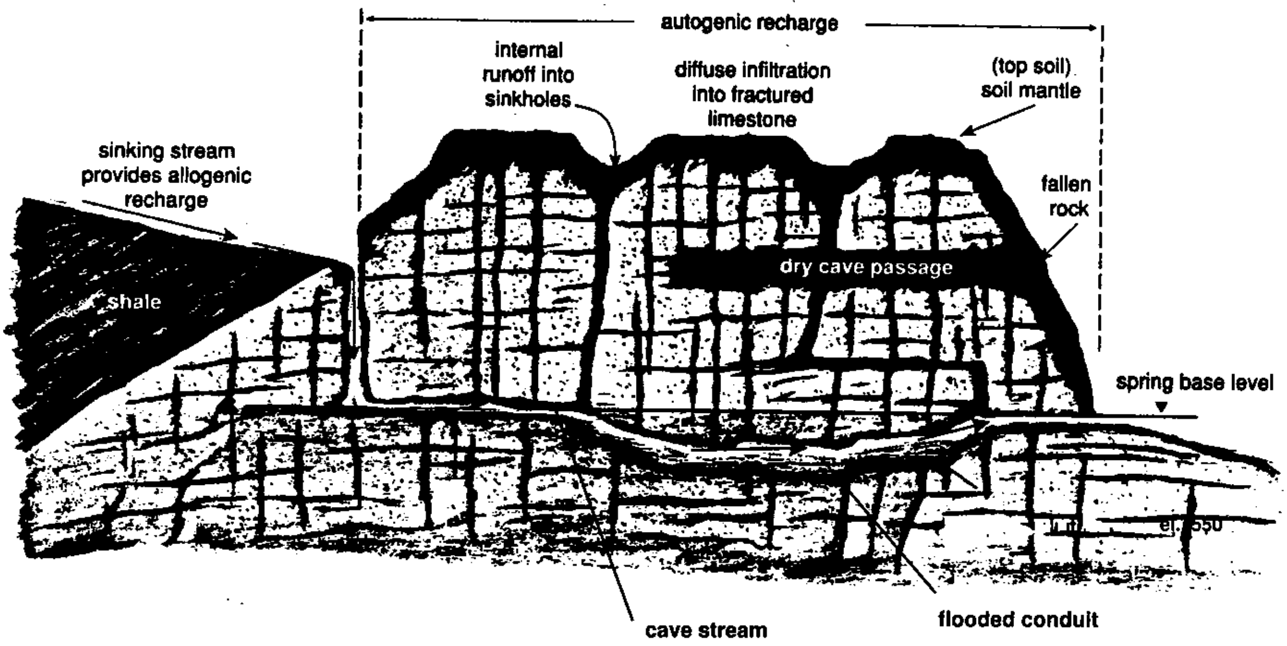


Figure 4. Recharge zones in karst hydrologic system (modified after White, 1995, fig. 4; reprinted with permission of "American Scientist," v. 83)

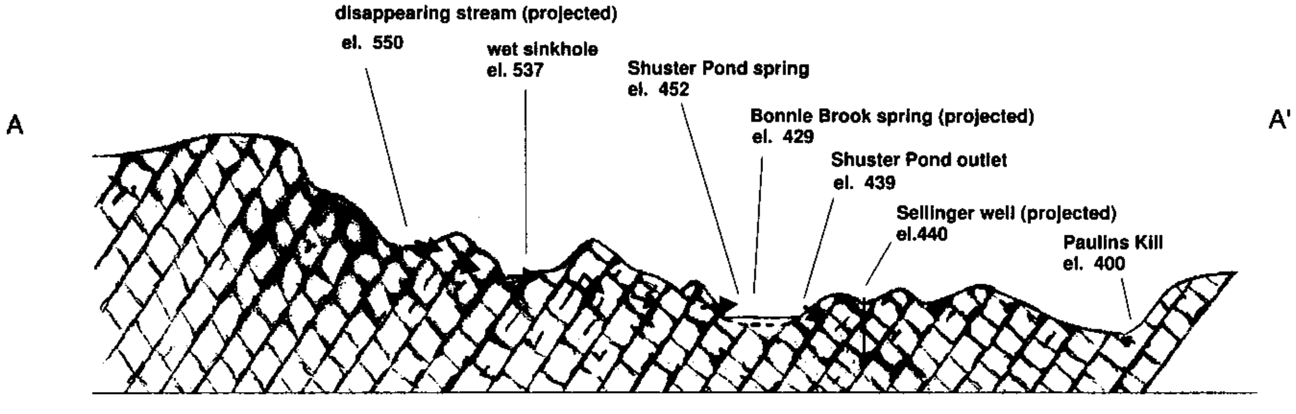


Figure 6. Elevations of water levels at various points in the karst drainage system in the area of Shuster Pond. Elevations measured using a digital altimeter. (Section A - A', figure 3)

exposed, open fractures, such as joints and bedding-pland partings, and by way of sinkholes developed on top of the carbonate rock.

Solutioning of carbonate rocks by carbonic acid and humic acid contained in infiltrating water in the autogenic zone cause about karstification of the bedrock. Carbonic acid forms through the interaction of precipitation and carbon dioxide in soil. Biological processes in the soil can elevate carbon dioxide levels in soil gas to as high as 10 percent. Carbonic acid in percolating ground water attacks carbonate rock, causing etching of exposed fractures. Percolating waters continue to exploit these solution-enlarged fractures, enhancing the permeability of the zone below the soil. Carbonic acid is consumed in this process, diminishing the aggressiveness to the carbonate bedrock with depth. Nutter (1973) points out that the zone of greatest circulation and solution is just below the water table.

Diffuse infiltration in the epikarst zone is often near chemical saturation (Rauch and White, 1970). Solutioning is this zone is often gradual in comparison to the potential for large-scale conduit development often associated with allogenic recharge.

KARST HYDROLOGY OF THE SHUSTER POND AREA

The Shuster Pond area exhibits disappearing streams, springs, and ground-water flow characteristics typical of a karst conduit-influenced flow system. Shuster Pond appears to represent a large sinkhole pond formed through the coalescing of karst subsidence features, including sinkholes and possible cavern collapse. The dynamics of this process are evident today, wherein land at the edges of the pond is being undermined and the pond expanding by subsidence of the glacial till mantle. Active sinkholes form at the pond's edge, capturing pond runoff. These sinks enlarge at a relatively rapid rate once the pond begins to drain into them. For example, one the principal discharge areas for the pond is a swallow hole at its southeastern edge. Three years ago this swallow hole consisted of a mound of winnowed glacial cobbles. At the date of this publication, the cobble mound has exhibited significant collapse and is an active area of subsidence (figure 5B). Several new sinkholes have opened along the pond's southern periphery over this period as well.

Allogenic recharge may contribute considerable water to Shuster spring and other springs in the area, including "Tucker spring" and Bonnie Brook spring. A stream drains the upland underlain by clastic rocks of the Martinsburg Formation and disappears into its stream bed as it flows across the contact with the Jacksonburg Limestone up-section of Shuster Pond (figure 3). A series of large, elongate sinkholes follows the strike of bedding and the dominant joint strike from the site of this stream disappearance. The morphology of these sinkholes suggest that they represent a karst "gulf," or exposed, collapsed cavern (Dalton, NJGS, verbal communication). These sinks appear to variably discharge and accept drainage, as springs emerge at the edge of the sinkholes only to sink into the ground nearby. It appears that ground water that may follow the linear band of sinkholes discharges in part to Mud Pond.

Autogenic recharge contributes to the flow at Shuster Pond. The presence of sinkholes in the dolomite outcrop area around Shuster Pond indicates that bedrock cavities may be present. The part of the study area underlain by carbonate bedrock has no visible surface streams. A "dry

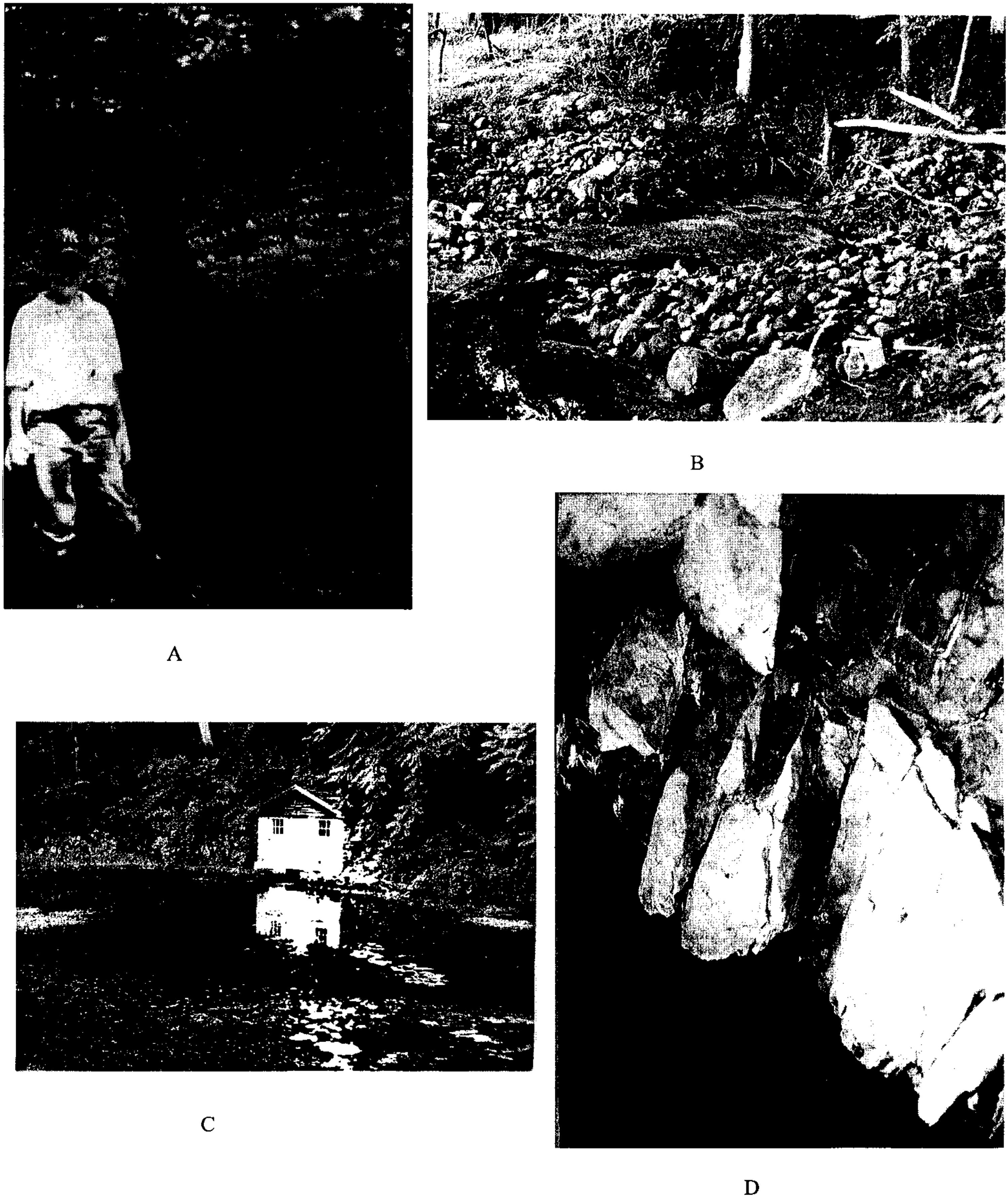


Figure 5. (A) North-south solution-enlarged joint and bedding-plane cavity in Allentown Dolomite near Shuster Pond (William O'Connell III provides scale); (B) Swallow hole where Shuster Pond drainage sinks; (C) Bonnie Brook spring, Stillwater Township; (D) Spring outlet at Bonnie Brook spring. View is southwest, showing solutioning along spaced cleavage (vertical) and bedding plane fracture (inclined left-to-right).

valley" can be seen at the northern end of Shuster Pond. Such dry valleys are typical of karst landscapes. This valley has numerous sinkholes that intercept surface runoff. These most likely recharge conduit systems directly, which in turn recharge the spring or the pond. Overburden on the carbonate outcrops at Shuster Pond consists of a thin layer of late-Wisconsinan glacial till. Thus, it is not likely that the overburden stores a substantial amount of ground water or contributes signficant recharge to the bedrock aquifer.

Recharge to the carbonate bedrock also occurs in the study area through exposed, solution-enlarged joints in the dolomite bedrock. These may be primarily near-surface joints that conduct infiltrating water to the water table. High-angle, solution-enlarged joints in the dolomite bedrock in the study area most likely function as the vadose pores of Palmer (1987). Several interconnected joint sets are visible in outcrop, all of which dip at a high angle and are thus exposed to recharge. These solution joints appear to be well connected to bedding-parallel cavities. The interconnection between solution-enlarged joints and bedding planes can readily be seen on the dip-slope above Shuster Spring. The most prominent orientation of these joints is north-south and their dip is near vertical (figure 5A).

The orientation of geologic structures in the study area provides an insight into the possible ground-water flow path taken by the disappearing stream and the path taken by water that drains from Shuster Pond and sinks into the ground. It is likely that once it sinks into the ground the sinking stream draining the shale upland follows solution-enlarged beds and/or strike-subparallel, high-angle solution-enlarged joints with a northeast trend orientation. This mechanism would direct ground-water flow to Mud Pond. At the southern edge of this pool water visibly drains into exposed, high-angle, bedding sub-parallel joints in the dolomite bedrock. This spring appears to reemerge approximately 200 feet downhill to the south at a spring pool, which discharges to a channel that feeds Shuster Pond. This flow path indicates that bedding-parallel joints that allow Tucker spring discharge to sink into the ground at the spring pool permit cross-strike ground-water flow or that they are connected to other fractures that permit flow across the strike of bedding.

For the allogenic stream to reach Shuster spring, ground-water to flow across the strike of bedding and dominant joints would need to occur. As discussed above, north/south and northwest oriented sets of open, solution-enlarged joints or spaced cleavage are evident in outcrops at the site. These structures, in addition to cross-strike joints with an east/west trend shown as co-dominant in figure 2b, would provide for cross-strike flow of ground water. It is suspected that periodic flooding of the ground-water system through inundation of sinkholes may induce additional ground-water flow in a north-south direction, across the dominant regional joint trend. This may help explain large variations in discharge at Shuster spring, as well as the consistent temperature of the spring, discussed below.

Shuster Pond drains into a box canyon formed by a resistant ridge of dolomite at its southern end. There, the drainage sinks into the dolomite via several swallow holes through the overlying glacial till. The morphology of of Pioneer Cave, located in the study area (fig. 3) provides some insight into the possible path of ground-water flow once it sinks at Schuster Pond. The cave (figure 7) appears to be formed by solution of bedding-subparallel, high-angle, eastward-dipping joints. It is elongate sub-parallel to the strike of bedding, and appears to align with the dominant northeast joint set shown in figure 2a. Solution-enlarged joints are seen in outcrop at the Bonnie Brook spring discharge (figure 5D). These joints are parallel to a line between the outlet for Shuster Pond and Bonnie Brook spring.

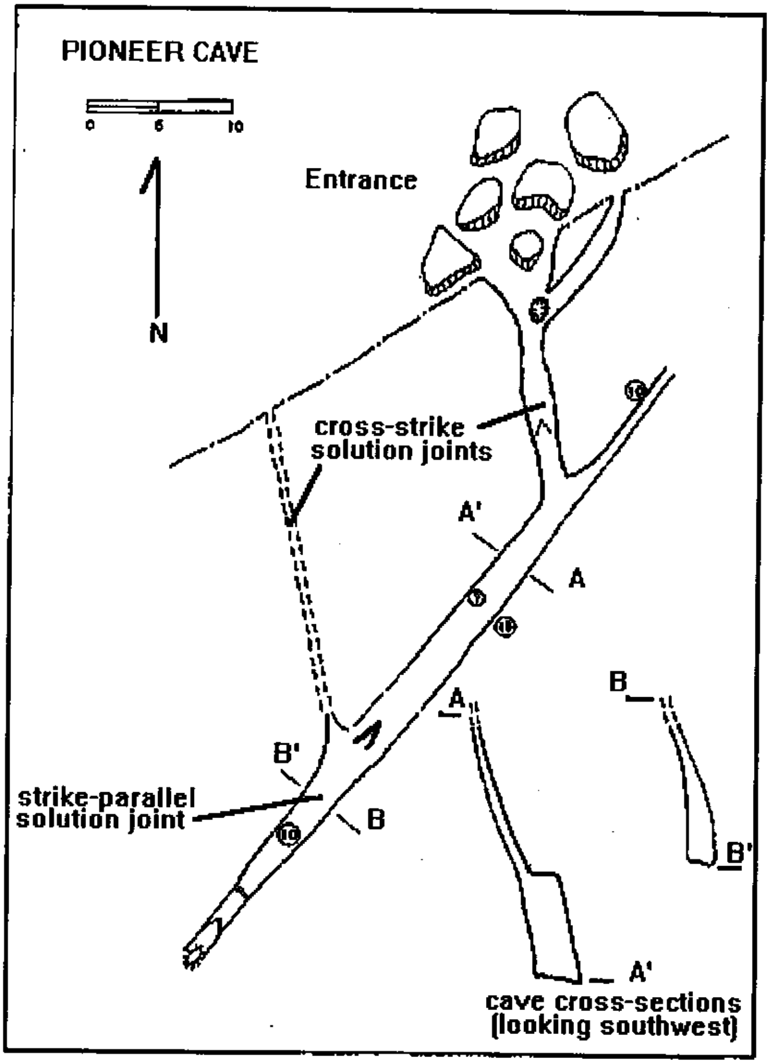


Figure 7. Plan view and cross-sections of Pioneer Cave (modified from Dalton, 1976, figure 33)

Spring discharge and ground-water levels

The discharge from the spring at Schuster Pond varies significantly over time. Getchell (1992) measured discharge at the spring between September 1991 and October 1992 (figure 8). Discharge was measured using a continuous recording device, stilling well and staff gage. A small volume of spring flow could not be accounted for because of the construction of the spring house. Discharge measurements for the spring ranged from less than 0.22 cubic feet per second (cfs) (100 gallons per minute (gpm) or 0.144 million gallons per day (mgd)) to slightly more than 8.9 cfs (4000 gpm or 5.76 mgd). Getchell points out that the period studied had below average rainfall, so that these measurements should be viewed as conservative.

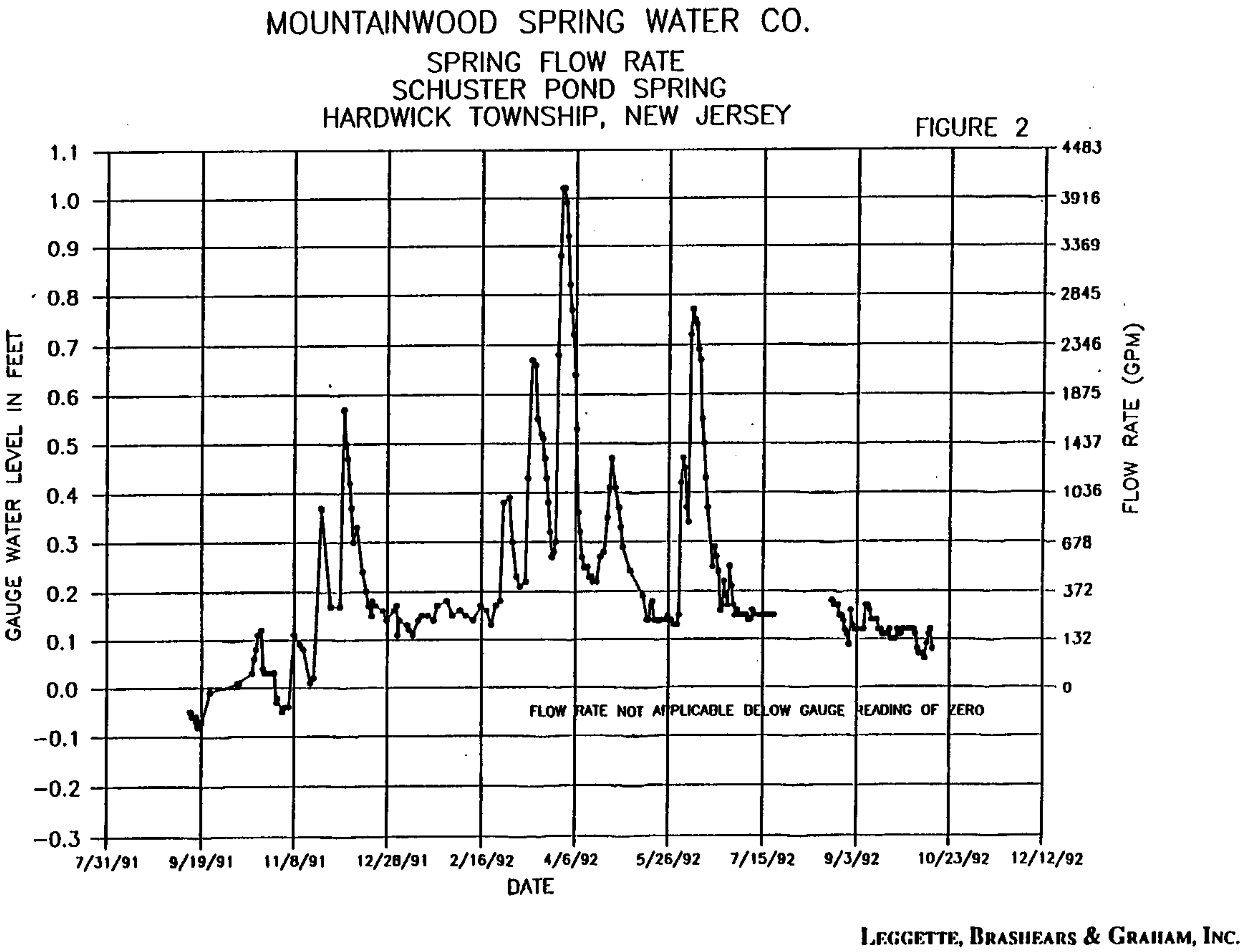


Figure 8. Discharge of Shuster Pond spring, from July 1991 to October 1992 (reproduced with permission of Getchell of Leggette, Brashears & Graham, 1992, figure 2)

The discharge of Shuster spring was measured on August 6, 1996 by NJGS. Spring flow was measured using a stream-flow meter (Teledyne Gurley model 645) to measure discharge through the rectangular, concrete outlet channel for the spring. An instantaneous discharge of 3.7 cfs (1,630 gpm) was measured using the flow meter. This corresponds to a daily discharge of 2.345 million gallons.

The record of spring discharge as measured by Getchell shows significant variation over the course of a year, including changes exceeding an order of magnitude within time spans of one month. The record resembles a stream hydrograph, which would experience rapid and signficant changes in discarge correlative to precipitation events. Such extreme variations in discharge from a major spring is an indication that the spring at Schuster Pond is fed by a conduit system. The regular changes in spring discharge further support the idea that the system is being fed by a surface-water source. It is not clear at this time whether the surface source consists of the allogenic stream, flooded large sinkholes, or both. These sources lie above the spring elevation and can contribute to its discharge.

The discharge at Bonnie Brook spring was measured in a previous study and as part of the current study. A report on file with the NJGS claims that the maximum known flow at Bonnie Brook spring was 11.1 cubic feet per second (4,981 gpm), measured on May 22, 1967 (NJGS permanent notes). The report cites a measurement of 10.1 cfs (6.5 mgd) on October 25, 1970, and claims that a flow of 3.09 cfs (2 mgd) was measured on October 19, 1970 after a 3-inch rainfall event. Thus, Bonnie Brook spring appears to respond acutely to precipitation events and exhibits behavious characteristic of conduit-fed springs.

The discharge at Bonnie Brook spring was measured on August 6, 1996 as part of the current study. Discharge was estimated by measuring the flow through the rectangular, concrete discharge outlet and an associated outlet that conducts water from a spring outside the spring house using a flow meter. The instantaneous discharge of the spring was estimated to be 10.3 cfs (4,613 gpm or 6.64 mgd) based on this measurement.

Ground-water level and discharge fluctuations at Shuster spring and in nearby sinkholes supports the characterization of the hydrologic system as a conduit-controllled system. Water levels in large sinkholes above Shuster Pond and in the pond itself exhibit large variation. Water-level changes in excess of 15 feet were observed in large, wet sinkholes northeast of Mud Pond between 1995 and 1996. On August 6, 1996, a measurement was taken of the difference between a high water mark at Shuster Pond made during the spring meltoff and the summer pond level. The difference in water levels was measured at 10.3 feet.

INTERPRETATION OF KARST HYDROLOGY USING PHYSICAL AND CHEMICAL PARAMETERS

The interaction between carbonate bedrock and acidic water produces the dissolution features characteristic of Karst landscapes. Gaseous carbon dioxide (CO_2) from the atmosphere (.03 percent CO_2 by volume), soil air (up to 50 to 100 times higher that the atmosphere) and other sources dissolves in and reacts with water producing carbonic acid (H_2CO_3). Carbonic acid increases the acidity of water and reacts with and dissolves calcite and dolomite. The dissolution of dolomite is represented by equation (1) below:

$$(Ca,Mg)CO_3 + H_2CO_3 \text{ -----> } (Ca,Mg)^{2+} + 2HCO_3^- \qquad (1)$$

From equation (1) it can be inferred that the greater the concentration of carbonic acid available for reaction, the greater the concentration of dolomite that can be dissolved. In an "open system" the water is in contact with a constant supply of CO_2 gas from a source such as the atmosphere. This condition can occur in a stream or pond where the water is in direct contact the atmosphere. In this case carbonic acid can continuously be formed, pushing the reaction above to the right, until an equilibrium is established. In a "closed system" the water is isolated from CO_2 sources and the concentration of carbonic acid available for reaction is limited. This condition can occur in ground-water systems isolated from CO_2 sources. Under closed system conditions carbonate minerals are less soluble and have higher equilibrium pH values. Most ground water from carbonate terranes have a pH between 7.0 and 8.0 indicating that open system conditions are common (Freeze and Cherry, 1979). Water flowing through karst terranes are intermittently exposed to variable CO_2 environments. The potential for this situation is evident in the Shuster Pond area where streams in contact with the atmosphere sink into the ground-water system, and spring water issuing from the ground-water system contacts the atmosphere.

Evaluation of Relative Spring Water Residence Time in the Flow System

Precipitation can be characterized as a dilute, acidic, oxidizing solution. When precipitation contacts carbonate rock directly, or after passing through the unsaturated zone, progressive increases in the pH, total dissolved solids (TDS), alkalinity and other parameters will occur as calcite and dolomite dissolve. The water temperature will approach that of the aquifer it is flowing through. These parameters will stabilize when a chemical and thermal equilibrium are established. An estimate of the relative water/rock interaction time can be made by comparing certain physical and chemical parameters. These comparisons may be useful for assessing potential flow paths, evaluating regional versus local flow systems and determining the types of openings in which ground water is flowing.

Ground water from wells in the Kittatinny Supergroup (which is mainly comprised of dolomitic rocks) will generally have a longer residence time and therefore be more chemically mature than water discharging from springs in the Shuster Pond area. To illustrate this assumption, a statistical summary of the chemical and physical parameters for precipitation, the Shuster Pond spring, the Bonniebrook spring and the Kittatinny Supergroup was compiled (Table 1). Box and pin diagrams (figure 9) provide visual comparisons of the same data. The quality of some of the older data from the Shuster Pond and Bonniebrook springs cannot be determined, however, the precipitation data from Lord and others (1990) and the Kittatinny Supergroup data from Serfes (in prep.) was collected and analyzed following United States Geological Survey protocols. It is also significant to note that the low number of sample analyses available in some cases may not be statistically representative of the population. The following comparisons of the data sets recognize the limitations in data collection and inherent uncertainties in data analysis.

Specific conductance is related to the concentration of dissolved solid material in water. Conductivity values shown in figure 9 increase from precipitation to spring water to ground water. The Shuster Pond spring has a generally lower conductivity than ground water, however, Bonniebrook spring's water is similar to it.

This data suggests that the spring water from Bonniebrook spring is more chemically evolved than water from the Shuster Pond spring. This evaluation is consistent with a tracer study that indicated that water from the Shuster Pond spring flows in the subsurface to Bonniebrook spring. Water recharging Bonniebrook spring from other sources must also be chemically mature.

Spring Flow System Type (conduit versus diffuse flow)

Temperature has been used to differentiate between conduit versus diffuse flow types at springs (Shuster and White, 1971). Water from springs that are mainly recharged by conduit flow systems show seasonal temperature variations while those with diffuse systems show steady temperatures similar to local ground water. Since the temperature measurements in this study were taken during the summer you would expect conduit fed spring water to be warmer than local ground water. Table 2 shows that the ground-water temperatures from dolomites in northern New Jersey range from 10 to 12.5 C. The spring water at site (D) had a temperature of 14.5 C. indicating that it is recharged by conduit flow. At site (F) the temperature was 10.1 C in June and 10 C in August. These temperatures are similar to the coolest ground water and therefore indicate that this spring is fed by a diffuse recharge system. Site (H) had a temperature of 13.9 C in June and 15.3 C in August. This is warmer than local ground water indicating that recharge from a conduit flow system is involved.

Potential Hydraulic Flow Path Assessment

Recent field measurements of temperature, specific conductance, pH and alkalinity shown in Table 2 were collected at streams, springs, sinkholes and swallow holes to determine the validity of a proposed conduit flow path in this complex karst drainage system. Samples sites (A) through (H) outline the proposed horseshoe shaped flow path shown on figure 10. A brief description of the flow path is followed by a discussion of the field data collected along it's path.

It is assumed that at least some of the water from the allogenic stream that sinks into the subsurface at sampling site (A) follows bedding and fracture controlled conduits to the southeast, along a line of large, elongated sinkholes (site B) to Mud Pond at site (C). Water in Mud pond discharges to the subsurface and flows south emerging as a spring at site (D) (Tucker spring). After the water from the spring flows about 200 feet it sinks back into the subsurface emerging again a short distance away. It eventually flows into Shuster pond from the west as a stream at site (E).

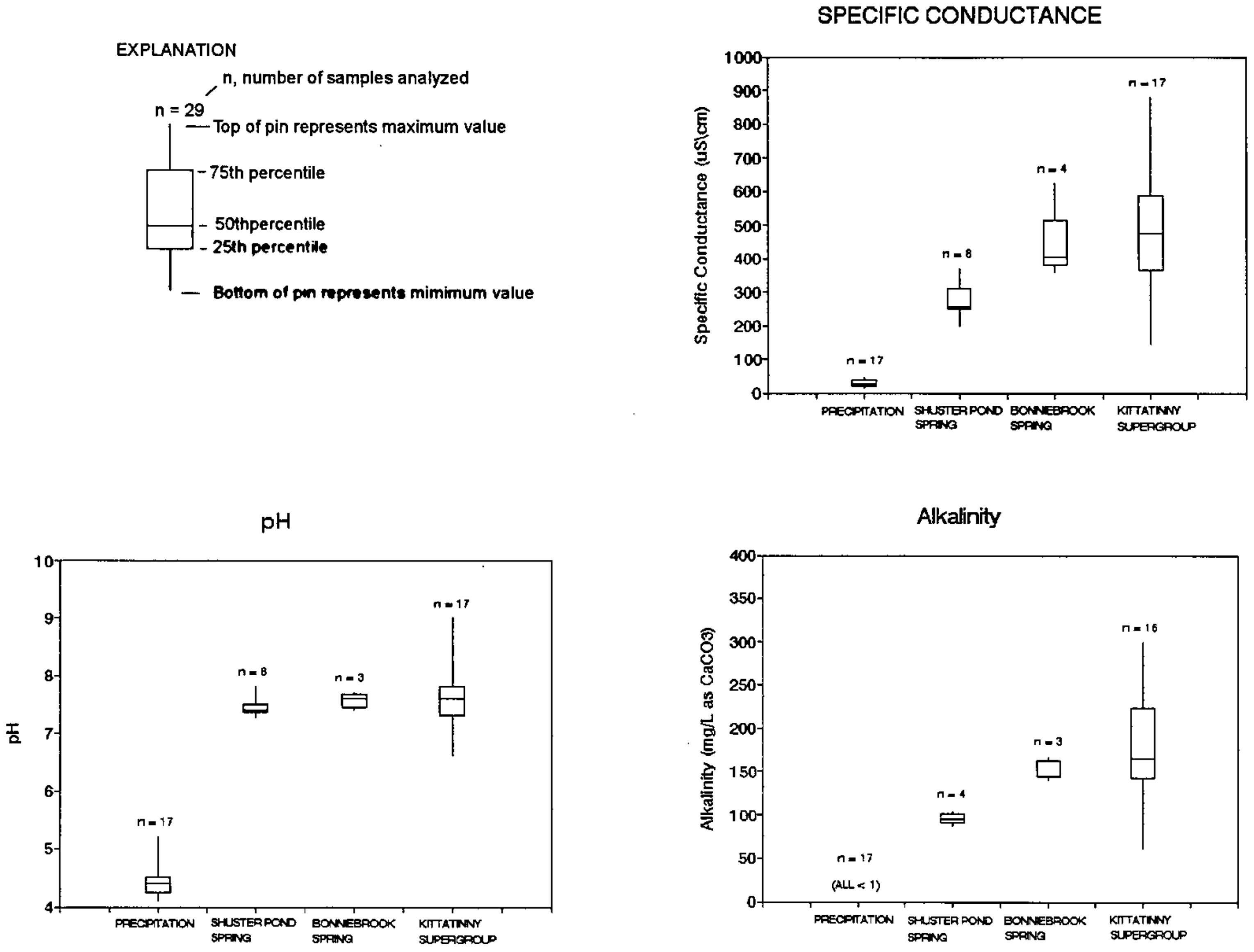
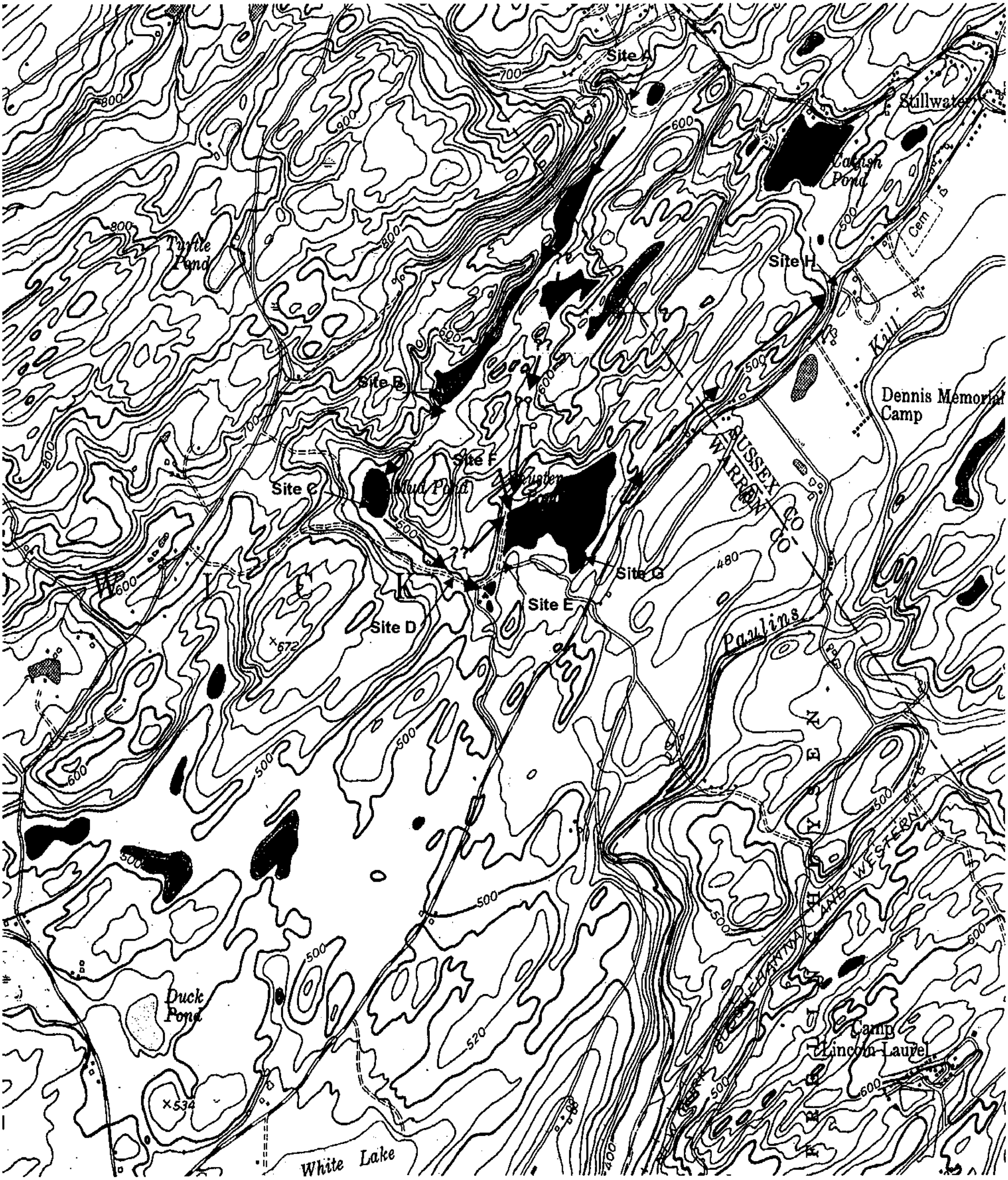


Figure 9. Box and pin diagrams show the concentration distributions of specific conductances, pH, and alkalinity for precipitation,. Shuster Pond spring water, Bonniebrook spring water, and ground water from the Kittatinny Suprgroup (mostly dolomite).



→ Suspected path of ground-water flow (? where path is intermittent)

Figure 10. Location of ground- and surface-water sampling sites, summer 1996.

Shuster Pond spring (site F) contributes most of the recharge to the pond. The pond water discharges into swallow holes on the eastern side of the pond, represented by site (G). Conduit flow from site (G) to Bonniebrook spring at site (H) has been verified by the tracer experiment, as discussed above.

Changes in specific conductance, alkalinity and temperature were useful in determining flow paths by relating water at one location to another. The water from the allogenic stream at site (A) was relatively dilute (114 uS/cm) and had a low alkalinity (24 mg/L). The sinkhole at site (B) had some standing water which was slightly more mineralized, however, it was difficult to determine it's connectivity to the subsurface. At Mud Pond the water was much more mineralized than (A) with a specific conductance of 310 uS/cm and had a higher alkalinity 132 mg/L. This is consistent with water that has dissolved carbonate minerals as it flowed, probably via conduit, from site (A) to Mud Pond.

The spring water at site (D) is more mineralized (381 uS/cm) than the water in Mud Pond and has a higher alkalinity (178 mg/L). Therefore, more dissolution of the carbonate bedrock occurred between the pond and spring. The temperature is cooler than Mud Pond yet still indicates conduit flow. The stream at site (E) had exactly the same conductivity as site (D) and nearly the same alkalinity. This strongly indicates the two are related. This water discharges into Shuster Pond.

The other obvious source of water recharging Shuster Pond is the Shuster Pond spring at site (F). As discussed above, the low temperature of the spring water indicates that it is recharged from a diffuse flow system. The specific conductances determined in June and August 1996 ranged from 250 to 271 uS/cm. The alkalinity was 99 mg/L. This is distinctly different than the spring water at site (D) which has a much higher conductivity and alkalinity.

At the swallow hole in Shuster Pond at site (G) the specific conductance (292 uS/cm) and alkalinity (114 mg/L) values fall between the stream and spring recharging the pond. If it is assumed that no other significant sources of recharge water are entering the pond, and no major chemical changes are occurring in the pond water, then mixing of the two recharge waters may account for the values at site (G). A past tracer test indicated that this water flows from Shuster Pond to Bonniebrook spring, site (H). The water there is more mineralized (403 uS/cm) and alkaline (166 mg/L) than at site (G). The warmer than ground water temperatures measured there indicate conduit flow. Multiple sources of water recharging this spring are suspected .

CHARACTERISTIC OR CONSTITUENT	Number of Samples	Minimum	25th per-centile	Median	75th per-centile	Maximum
CHARACTACTERISTICS						
PRECIPITATION						
Specific Conductance (uS/cm)	17	12	18	26	36 46	
pH (standard units)	17	4.1	4.2	4.4	4.5	5.2
Field Alkalinity (mg/L as $CaCO_3$)	17	<1	<1	<1	<1	<1
SHUSTER POND SPRING						
Temperature (C)	3	10	10	10	10.1	10.2
Specific Conductance (uS/cm)	8	200	250	255	313	368
pH (standard units)	8	7.3	74	7.4	7.5	7.8
Field Alkalinity (mg/L as $CaCO_3$)	8	88	91	96	101	103
Solids1, dissolved (mg/L)	8	139	140	147	174	206
BONNIEBROOK SPRING						
Temperature (C)	2	13.9	--	14.8	--	15.3
Specific Conductance (uS/cm)	4	360	381	403	514	626
pH (standard units) 3	7.4	7.4	7.6	7.7	7.7	
Field Alkalinity (mg/L as $CaCO_3$)	3	140	145	162	163	166
Solids1, dissolved (mg/L)	4	200	212	225	287	350
KITTATINNY SUPERGROUP						
Temperature (C)	17	10	11	11	11.5	12.5
Specific Conductance (uS/cm)	17	144	364.7	474	586	878
pH (standard units)	17	6.6	7.3	7.6	7.8	9
Field Alkalinity (mg/L as $CaCO_3$)	16	61	142.5	165	223	299
Solids1, dissolved (mg/L)	17	81	197	254	322	448

Table 1. Statistical summary of analyses of precipitation, Shuster Pond spring, Bonniebrook Spring and well water from the Kittatinny Supergroup. Precipitation data is from Lord and others, 1990, and was collected in Burlington County, New Jersey. The Kittatiny Supergroup data is from Serfes, in prep.

In some cases, estimates of total dissolved solids were made using the specific conductivity and vice versa. Note that the lower the number of samples in a sample population the lower is the chance that the percentile measures represent the population.

[uS/cm, microsiemens per centimeter, mg/L; milligrams per liter; --, no data available]

SITE WHERE SAMPLE TAKEN	DATE MEASUR-MENT TAKEN	TEMPER-ATURE WATER (DEG C)	SPECIFIC CONDUCT-ANCE (US/CM)	OXYGEN DIS-SOLVED (MG/L)	pH STD. UNITS FIELD	ALKA-LINITY FIELD (MG/L AS CACO3)
A	8-13-96	17.1	114	--	7.8	24
B	8-13-96	20.1	130	--	7.5	60
C	8-15-96	25.2	310	--	7.85	132
D	8-15-96	14.5	381	--	7.29	178
E	8-15-96	--	381	--	8	171
F	6-01-96	10.2	250			
	8-13-96	10	259	9.2	7.36	99
	8-15-96	10	271	10.8	7.28	--
G	8-15-96	21.6	292	6.9	8.02	114
H	6-01-96	13.9	360			
	8-14-96	15.3	403	4.4	7.41	166

Table 2. Analytical results from recent field sampling in and around Shuster Pond. Sites A - H are shown on figure 10; --, no measurement taken. A - disappearing stream; B - elongate sink hole; C - Mud Pond; D - spring down-slope from Mud Pond (Tucker spring); E - stream entering Shuster Pond; F - spring at Shuster Pond; G - water entering swallow hole at Shuster Pond; H - Bonniebrook spring.

SUMMARY

The Shuster Pond area provides a classic example of karst hydrology in northern New Jersey. Disappearing streams, springs, sinkholes, caves, swallow holes, dry valleys, and other karst features are significant and abundant in the area. Shuster Pond is host to a high-capacity spring that feeds a pond which subsequently drains into the ground in box canyon. This drainage appears to reemerge at a high-capacity spring nearly a mile to the north, Bonnie Brook spring.

Shuster Pond spring is part of a complex karst drainage system that is fed, in part, by a sinking stream that drains an adjacent upland underlain by clastic rocks of the Martinsburg Formation. Geologic structures and geochemical data permit an assessment of the possible subterranean flow routes of the disappearing stream. Solution-enlarge joints and, possibly, bedding-plane cavities in the Cambrian and Ordovician carbonate rocks of the area control ground-water movement. These structures have been mapped previously and were evaluated as part of the present study. The dominant orientiation of these structures in the study area is northeast-southwest, but a significant north-south component exists as well. Pioneer Cave, located in the study area, confirms the development of large-scale solution features with a northeast-southwest orientation. Spring flow has been observed to emanate from and disappear into bedrock joints with a northeast-southwest orientation.

Ground-water discharge characteristics at Shuster Pond spring indicate that it is fed in part by a conduit system. Discharge varies significantly over time. A hydrograph of spring flow recorded over nearly a year resembles a stream hydrograph. It is likely that discharge at the spring is influenced by changing flow rates in a sinking stream upgradient and/or by discharge to the ground-water system via large sinkholes during wet periods.

Water chemistry reveals elements of the ground-water flow system in the karst aquifer. Temperature proved effective in demonstrating that Tucker spring and Bonnie Brook spring are influenced by nearby surface-water. Temperature readings at Shuster Pond spring indicate that it is fed primarily by ground water. Additional data is needed to correlate spring-flow variations with temperature variations.

REFERENCES

Dalton, Richard F., 1976, Caves of New Jersey, Bulletin 70, Bureau of Geology and Topography, NJ Dept. of Environmental Protection, Trenton, NJ, 51 p, 7 plates.

Davies, William E., 1965, Caverns of West Virginia, State of W.Va. Geological and Economic Survey, V. XIXA, Morgantown, W.Va., 330 p., w. supplement.

Drake, Avery A. and Lyttle, Peter T., 1980, Alleghanian thrust faults in the Kittatinny valley, New Jersey, in, Field studies of New Jersey geology and guide to field trips: 52nd annual meeting of the New York State Geological Association, Rutgers University-NCAS, Newark, NJ, p. 92-115.

Herman, Gregory C. and Monteverde, Donald H., 1989, Tectonic framework of Paleozoic rocks of northwestern New Jersey; Bedrock structure and balanced cross sections of the Valley and Ridge province and southwest Highlands area, in Paleozoic geology of the Kittatinny Valley and southwest Highlands area, N.J., Guidebook, Sixth annual meeting of the Geological Assocation of New Jersey, October 20-21, 1989, Lafayette College, Easton, Pa., I.G. Grossman, ed., p. 1-94.

Freeze, R.A. and Cherry, J.A., 1979, Groundwater. Prentice-Hall, Englewood Cliffs, NJ.

Getchell, Frank J., 1992. Summary of hydrogeologic assessment of the Shuster Pond spring, Mountainwood Spring Water Company, Inc., Hardwick Township, New Jersey, Leggette, Brashears & Graham, Inc., Ramsey, N.J., December 22, 1992, 22 p. with appendix.

Lord, D.G., Barringer, J.L., Johnsson, P.A., Schuster, P.F., Walker, J.E., Fairchild, J.E., Sroka, B.N., Jacobsen, E., 1990. Hydrogeochemical data from an acidic deposition study at McDonalds Branch Basin in the New Jersey Pinelands, 1983-86: United States Geological Survey Open-File Report 88-500, 132 p.

Manger, Edward, 1963, Porosity and bulk density of sedimentary rocks, US Geological Survey Bulletin 1144-E, US Government Printing Office, Washington DC, 55p.

Markewicz, Frank J. and Dalton, Richard, 1977, Stratigraphy and applied geology of the Lower Paleozoic carbonates in northwestern New Jersey, in, Guidebook for the 42nd annual conference of Pennsylvania Geologists, October 6-8, 1977, Field Conference of Pennsylvania Geologists, Harrisburg, Pa., 116 p.

Miller, Don and Skelton, John, 1979. Tracing subterranean flow of sewage-plant effluent in lower Gasconde Dolomite in the Lebanon area, Missouri, in Ground Water, v.17, no. 5, Sept.-Oct. 1979, p. 476-486.

Norris, Stanley E., 1976, Change in drawdown caused by enlarging a well in a dolomite aquifer, in Ground Water, v. 14, no. 4, July-Aug. 1976, p. 191-193.

Nutter, Larry J., 1973. Hydrgeology of the carbonate rocks, Frederick and Hagerstown valleys, Maryland, Report of Investigations No. 19, Maryland Geological Survey.

Palmer, Arthur N., 1987. Prediction of contaminant paths in karst aquifers, Proceedings, Conference on environmental problems in karst terranes and their solutions, Bowling Gren, KY, National Water Well Association, Dublin, OH, 1987, p. 32-53.

Parizek, Richard, White, William, and Langmuir, Donald, 1971, Hydrogeology and geochemistry of the folded and faulted rocks of the central Appalachian type and related land use problems, Penn State University Circular 82, Earth and Mineral Sciences Experiment Station, State College, Pa., 183 p.

Rauch, Henry W. and White, William B., 1970, Lithologic controls on the development of solution porosity in carbonate aquifers, in Water Resources Research, V.6, No. 4, August 1970,. p. 1175-1192.

Shuster, E.T. and White, W.B., 1971, Seasonal fluctuations in the chemistry of limestone springs: a possibke means of characterizing carbonate aquifers. J. of Hydrology 14, 93-128.

Serfes, M.S., in prep, Report concerning the natural ground-water qualilty of the major Paleozoic aquifers in New Jersey: New Jersey Geological Survey.

Smart, P.L. and Hobbs, S.L., 1987, Characterization of carbonate aquifers: A conceptual base, Proceedings, Conference on environmental problems in karst terranes and their solutions, Bowling Gren, KY, National Water Well Association, Dublin, OH, 1987, p. 1-14.

White, William B., 1963. Conceptual models for carbonate aquifers, in Bulletin of the National Speleological Society, v. 25, part 2, July 1963, p. 15-21.

White, William B. and Rauch, Henry W., 1970, Lithologic controls on the development of solution porosity in carbonate aquifers, Water Resources Research, v. 6, no. 4, August 1970, p. 1175-1192.

White, William B., Culver, David C., Herman, Janet S., Kane, Thomas C., and Mylroie, John E., 1995. Karst lands, in American Scientist, v. 83, p. 450-459.

THE USE OF SHALLOW SEISMIC REFLECTION TO LOCATE AND DEFINE INCIPIENT SINKHOLES, CHESTER AND MONTGOMERY COUNTIES, PENNSYLVANIA

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ABSTRACT:

High fold (12 and 24) shallow seismic reflection techniques, which include the use of closely spaced (2.5 feet to 5 feet) 40 hertz geophones and a 12 gauge shotgun source, are able to profile the shallow subsurface (less than 200 feet) even in areas with high background noise. This technique is used to identify the depth to the overburden/bedrock interface, subsurface structures such as fracturing/faulting and dissolution features in karst terrane.

To demonstrate this a seismic model for a generic geologic model which includes sinkholes and brittle faults was created. The shallow seismic reflection techniques were then successfully used in the field to profile a known sinkhole. Finally, the seismic reflection techniques are used in a potential karst terrane to identify faulting/fracturing and dissolution features. A soil boring confirmed the presence of an incipient sinkhole identified by the shallow seismic reflection technique.

Carbonate dissolution features can be identified on the seismic profile by changes in reflection amplitude, breaks in reflection continuity, in addition to the occurrence of fracture zones and/or closed structural depressions.

INTRODUCTION

A simplified hypothetical geologic cross section which included faulted limestone terrane overlain by unconsolidated sediments was created. A computer model seismic profile was analyzed for this generic geologic cross section. This model was designed to represent the geologic and geophysical conditions at two test areas.

Shallow seismic reflection profiles were generated at test areas in Chester and Montgomery Counties, Pennsylvania (Figure 1). The two test areas are located approximately 1.2 miles apart. Both areas are underlain by Ordovician limestones of the Conestoga Formation. This formation is estimated to be approximately 1000 feet thick and includes thin-bedded blue limestone, gray granular limestone with slaty partings, and coarse conglomerate at the base (Hall, 1934). Locally, the northeast-trending surface exposure of the Conestoga Formation is approximately 0.5 mile wide.

Test area 1 was located in Chester County and contained a known sinkhole. Two seismic reflection lines were generated in test area 1 in order to determine the feasibility of using the shallow seismic reflection method to locate and define dissolution cavities and incipient sinkholes. In addition, test area 1 provided an analog for the local seismic expression of limestone dissolution features.

Test area 2 was located in Montgomery County. As part of a geotechnical investigation for the rehabilitation effort of State Highway Route 202, four shallow seismic reflection profiles were generated in test area 2. The objective of the seismic reflection survey was to identify the thickness of the overburden and possible seismic signature of voids which will be encountered during excavation and construction of a new highway entrance/exit ramp.

A test boring was advanced at the location of a suspected incipient sinkhole identified by the shallow seismic reflection survey in test area 2. The results of the drilling lended support the use of the shallow seismic reflection for the location of dissolution features in carbonate terrain. Knowledge of the locations of potential sinkholes and other dissolution features provide the Pennsylvania Department of Transportation with very valuable subsurface information for cost effective engineering and planning of roads and roadway structures.

LOCAL GEOLOGY

The test areas lie within the Piedmont Physiographic Province. Locally, a 3-mile wide band of thrusted Paleozoic rocks trends approximately N70E (Hall, 1934). These rocks include the Ordovician Conestoga Formation, Conococheague-Elbrook limestone, Ledger dolomite, undifferentiated Trenton and Chazy limestones and calciferous sandstones; and Cambrian Antietam quartzite, Harpers phyllite, and Chickies

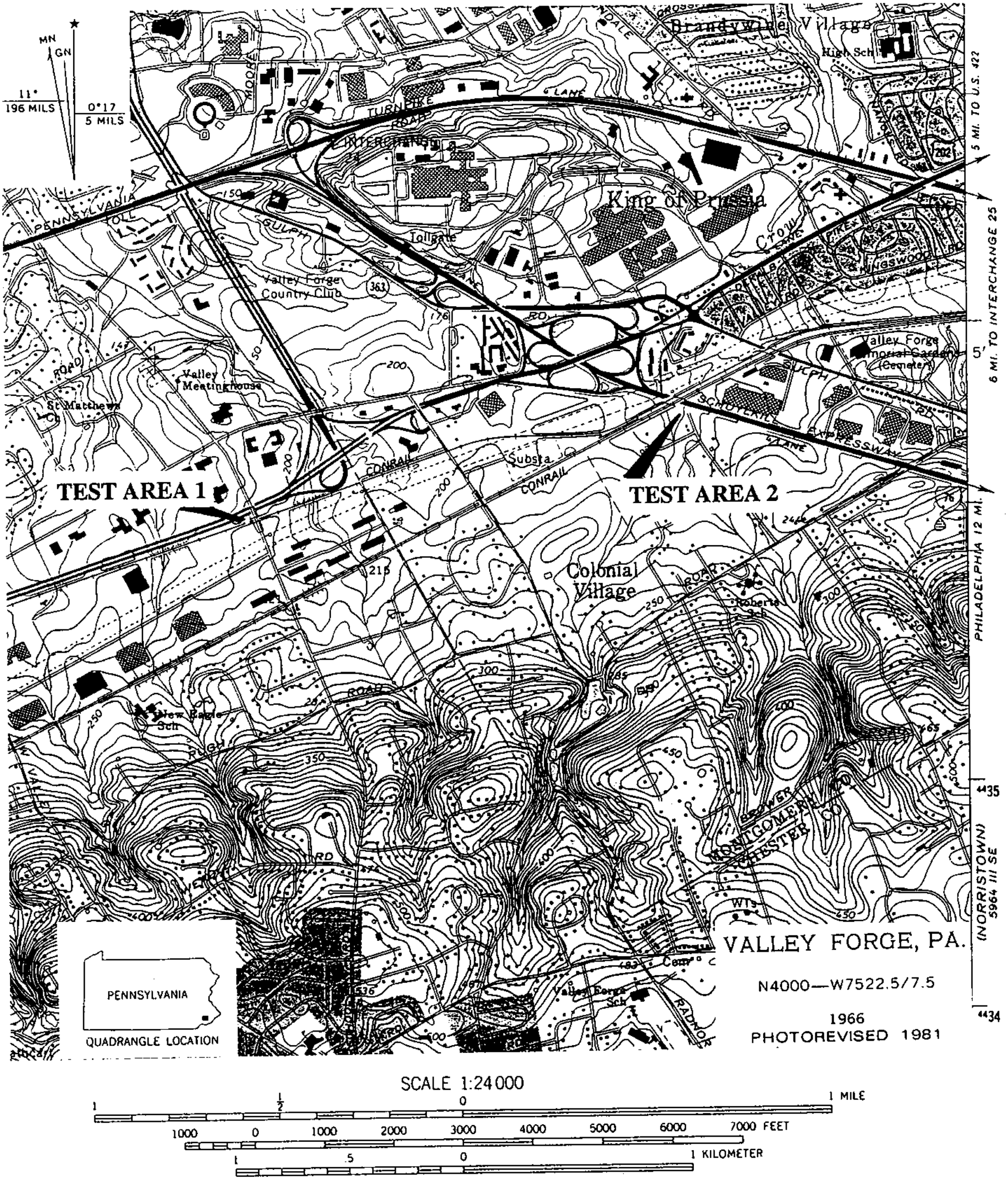


Figure 1: Test area location map

quartzite. This band of Paleozoic rocks is bounded on the southeast by the Wissahickon Formation of the Martic overthrust block. To the northwest, Proterozoic crystalline rocks which include granite, quartz diorite, quartz monzonite, granitic gneisses, gabbro, graphitic and other sedimentary gneisses are in unconformable or fault contact with the Paleozoic rocks. To the north, Mesozoic clastics including the sandstones of the Triassic Stockton Formation overlie the Paleozoic rocks.

METHODOLOGY

Data Acquisition:

Two different energy sources were tested. A custom-built 12 gauge blank shotgun device performed better than the 12 pound sledge hammer and steel plate. The 12 gauge source could overcome ambient traffic noise and provide a wider signal bandwidth for noise attenuation.

The selected receivers were 40 hertz vertical component geophones. Spacing between geophones (i.e. stations) varied for each line, and ranged between 2.5 feet and 5 feet. At test area 1, line GR95-1 was shot with a 2.5 feet station spacing, producing a subsurface sampling interval and horizontal resolution of 1.25 feet. The fold (i.e. the number of times the subsurface was sampled) was 24 and the spread length (i.e. distance between the first and last geophone for any shot) was 27 feet. Line GR95-2, positioned along a topographic high, was acquired with a 5 feet station spacing, producing a subsurface sampling interval of 2.5 feet. The fold was 24 and the spread length was 65 feet.

At test area 2, line GR95-3, GR95-4, and GR95-5 were shot with a 4 foot station spacing, producing a subsurface sampling interval of 2 feet. For these three lines, the fold was 24 and the spread length was 52 feet. Line GR95-6 was acquired with a 5 feet station spacing, and 12 fold.

A total of 825 records were collected in the two test areas. Each record was qualitatively reviewed at the time of collection in the field. The principle noise observed on all field records was ground roll (i.e. surface waves) produced as a result of the near surface conditions and the shot generated air wave. Background traffic noise was insignificant to absent; testing indicated that the recording of this ambient noise was minimized by the low levels of the field gain associated with the use of the shotgun source.

Upon completion of the data acquisition for each line, the surface elevation of each station was surveyed. Elevation data was used for topographic corrections during data processing.

Data Processing:

The data were processed using a common depth point (CDP) processing sequence. Field records were reformatted, edited, and filter tested.

The data were frequency filtered using a 95 hertz low cut filter to remove ground roll. The field records were first arrival muted (spatially varying) to remove the direct arrival, refracted waves, and air waves. The records were then sorted into CDP order. The data were corrected for the minor surface elevation changes present along the surveyed lines and corrected to the seismic reference elevations of 194 and 200 feet at test area 1, and 180 feet at test area 2. Normal move out (NMO) corrections were used to spread-correct the sorted data to remove the effect of geophone distance variation. The spread-correction was performed using a comprehensive constant velocity stack analysis. The data were "stacked" (i.e. vertically summed) so that the majority of traces presented on the final seismic cross-section are the sum of 24 (12 for line GR95-6) CDP field record traces of varying offset. This approach removed the majority of the random noise. A 150 hertz high cut filter suppressed minor background noise. All stacked seismic sections were scaled using a 180 millisecond (long gate) AGC. Because gentle dip was observed locally on the stacked sections, the data were not migrated.

Seismically defined average velocities were used to determine the depths to the top of the bedrock. Should accurate velocities be needed, a down hole velocity survey to the water table should be conducted. This survey would provide velocity and time/depth relations to be used in reflection identification and time to depth conversions.

RESULTS

Computer Model:

Computer modeling of the seismic response of carbonate dissolution indicates that major voids and sinkholes in limestone bedrock overlain by sediments should produce a discernible seismic response.

A generic geologic cross section (Figure 2a) was created to simulate the test areas. The section is 50 feet deep and 400 feet long. Thickened sediments are present over two sinkholes and one graben fault block. The velocity used for the sediments was 2000 feet/second (ft/sec). The velocity used for the limestone was 16000 ft/sec. The modeled seismic response (Figure 2b) indicated reflection amplitude and waveform continuity anomalies of magnitude that should be discernible.

Test Area 1: Old Eagle School Pass

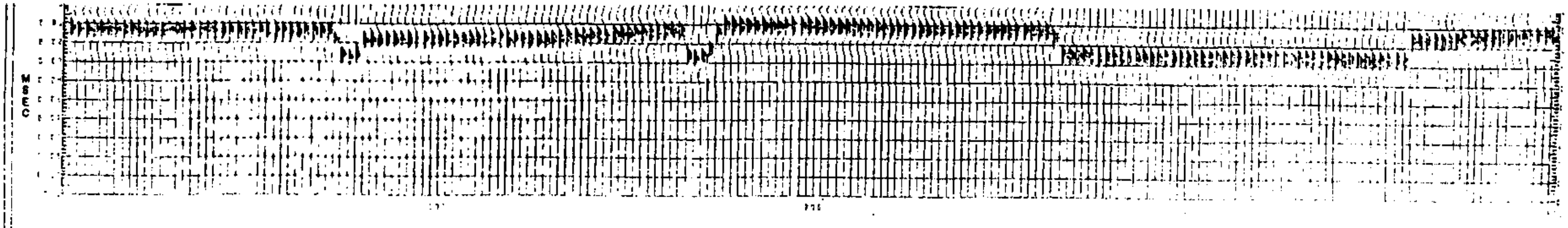
Data was collected along two seismic lines in test area 1 (Plate 1). GR95-1 was 400 feet long and contained the location of the known sinkhole. The seismic results obtained, together with interpreted fault/fracture and void locations, locations are indicated on Plate 2. A summary of seismic anomalies present on lines GR95-1 are presented in Table 1. GR95-2 was 300 feet long. There were no sinkholes known along GR95-2.

Depth to the top of bedrock ranged from approximately a few feet below ground surface along GR95-1 to 15 feet below the ground surface along line GR95-2 (using seismic velocity = approximately 2200 ft/sec; 9 milliseconds = 10 feet). The fractured carbonate surface dips gently to the south.

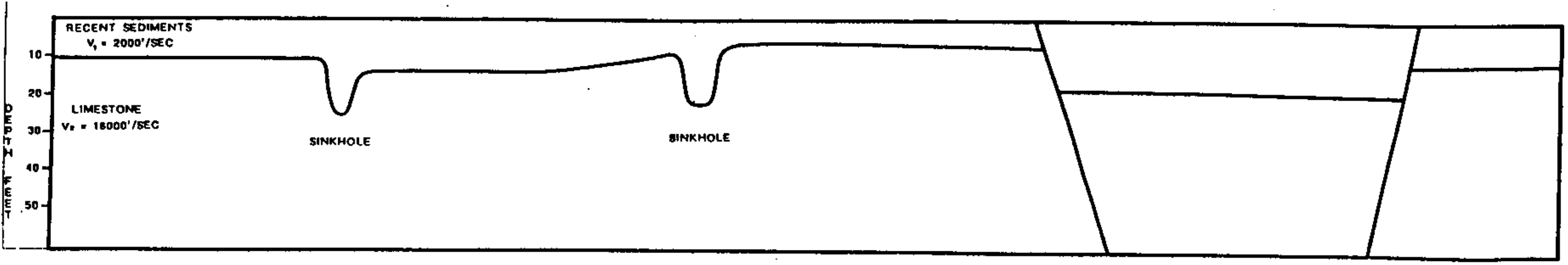
Line GR95-1

The following features were revealed along line GR95-1 (Plate 2). A fault bounded structural low is centered at common depth point (CDP) 245 station; surface station (SS) number 122.5 (CDP = 2X SS). A change in reflection amplitude is present at CDP 234 (SS 117). This may indicate the presence of a void. A similar character anomaly exists at CDP 276 (SS 138). Both features are associated with faulting/fracturing.

An anomaly which occurs at CDP 346 (SS 173), a similar anomaly at CDP 382 (SS 191), and the structural low which these locations bound represent the seismic expression of the known sinkhole on seismic line GR95-1. A prominent break in waveform continuity and change in reflection occur at CDP 346 (SS 173) and CDP 382 (SS 191). These locations are associated with the northeast and southwest downthrown (i.e. faulted/fractured) sides of a structural depression.



b) Seismic model



a) Generic geologic model

Figure 2: a) Generic geologic and b) seismic models

Table 1
Criteria for the Identification of Carbonate Dissolution Features

Line ID:	CDP #	Break in Continuity	Amplitude Anomaly	Faults/ Fractures	Proximal to Structural Low
GR95-1	234	X	X	X	X
	276	X		X	
	346	X	X	X	X
	382	X	X	X	X
	425	X	X	X	X
	474	X		X	
GR95-2	236	X		X	
	255			X	
	272	X		X	
	304	X		X	
GR95-3	222		X		
GR95-4	216	X			
	243	X			
GR95-5	227	X	X		
	247	X	X		
GR95-6	210			X	
	226			X	
	235	X	X	X	X

X = criteria is present

Another fault/fracture bounded character anomaly is present at CDP 425 (SS 212.5). In addition, a smaller break in continuity suggestive of a bedrock disturbance lies on the down side of fracturing at CDP 474 (SS 237).

Line GR95-2

Line GR95-2 (Plate 3) possesses a structural geometry and faults/fractures similar to line GR95-1. Possible dissolution features are present at CDP 236 (SS 118), CDP 272 (SS 136), and CDP 304 (SS 152). All three anomalies are characterized by breaks in waveform continuity and proximity to faults/fractures. A small depression on the down side of a fault/fracture is located at CDP 255 (SS 127.5). This structural low may be indicative of voids.

The data quality of this line is inferior to that of GR95-1 due to the differing field parameters used to acquire the data and the near surface conditions along the berm where line GR95-2 was shot.

Test Area 2: Abrahms Run Creek

The locations of seismic lines, faults/fractures, and postulated dissolution features are shown in Plate 4. In addition, boring information and seismic data were integrated to generate a depth to structure map for the top of the limestone bedrock (Plate 4). The carbonate surface is irregular and dips gently to the east-northeast. The depth to the top of bedrock proximal to the seismic grid ranges from 25 to 50 feet below grade (using seismic velocity = 3550 ft/sec; 11.3 milliseconds = 20 feet).

Line GR95-3

Line GR95-3 (Plate 5) shows an amplitude anomaly at CDP 222 (SS 111). This subtle deviation in the strength of the amplitude of the carbonate reflection may indicate the presence of a dissolution cavity.

Line GR95-4

Line GR95-4 (Plate 6) exhibits breaks in waveform continuity at CDP 216 (SS 108), CDP 238 (SS 119), and CDP 243 (SS 121.5) which suggests minor faults/fractures. Dissolution voids of the carbonate appears present at these two locations.

Line GR95-5

Line GR95-5 displays waveform continuity and amplitude anomalies at CDP 227 (SS 113.5) and CDP 247 (SS 123.5). Based on previously established criteria, dissolution is indicated at both sites.

Line GR95-6

Minor fracturing is indicated at CDP 210 (SS 105) and CDP 226 (SS113). An amplitude anomaly and obvious fault-bounded structural depression is located at CDP 235 (SS 117.5) on Line GR95-6 (Plate 7). The structural depression may be an induced time low or a "velocity sag" produced by a large lateral variation in the velocity of the undissolved and dissolved carbonate rock. This location was selected as the confirmatory test boring location.

Confirmatory Test Boring

The confirmatory test boring was advanced to a terminal depth of 45.25 feet below ground surface. A field boring log is presented as Figure 3. Continuous 1.5-foot split-spoon samples were collected to the top of bedrock at 34.0 feet below grade. The overburden was generally a dry firm to stiff silt and gravel mixture. A deeply weathered bedrock, identified by higher blow counts, was present between 31.0 feet and 34.0 feet. Split-spoon refusal and perched ground water indicated the top of a limestone cap at 34.0 feet. A roller bit was used to drill through the limestone cap to a depth of 35.0 feet. Between 35.0 feet and 38.5 feet a solution cavity filled with loose and wet sediments was encountered. The bedrock was cored between 39.5 feet and 45.25 feet. Two solution cavities were present in this core interval: 42.0 feet to 42.5 feet; and 44.0 to 44.25 feet.

FIGURE 3: BORING LOG
CONFIRMATORY TEST BORING: LINE GR95-6; CDP117.5
TEST AREA 2: ABRAHMS RUN CREEK, MONTGOMERY COUNTY, PENNSYLVANIA

depth (ft)	sample number	standard penetration 6"-6"-6" (N)	recovery (ft)	core recovery (%)	RQD (%)	description	comments
1.5	S-1	3-4-5 (9)	0.9			SILT, <u>ML</u>, med. brown, dry, firm to stiff	
3.0	S-2	3-2-3 (5)	0.9				
4.5	S-3	3-3-7 (10)	1.0				quartz fragment
6.0	S-4	4-5-5 (10)	0.9			SILT and GRAVEL, <u>GM</u>, med. brown, dry, stiff	
7.5	S-5	5-5-5 (10)	0.9				
9.0	S-6	3-3-5 (8)	1.3				limestone fragment
10.5	S-7	6-4-4 (8)	1.5			SILT, <u>ML</u>, med. brown, dry, firm	
12.0	S-8	6-3-3 (6)	1.5			SILT and CLAY, <u>CL</u>, med. brown, dry, firm	
13.5	S-9	3-5-6 (11)	1.4			CLAY, SILT, and GRAVEL, <u>GC-ML</u>, med. brown, dry, stiff to v. stiff	
15.0	S-10	7-11-9 (20)	1.5				
16.5	S-11	9-16-16 (32)	1.5				
18.0	S-12	5-3-4 (7)	1.2				
19.5	S-13	2-4-4 (8)	1.2			silty CLAY, SAND, and GRAVEL, <u>GM-CL</u>, med. brown, dry, soft to firm	
21.0	S-14	2-3-3 (6)	1.5				
22.5	S-15	3-2-3 (5)	1.5			SILT, CLAY, and GRAVEL, <u>GC-ML</u>, med. brown, dry, soft	
24.0	S-16	2-3-3 (6)	1.4			SILT and GRAVEL, <u>GM</u>, med. brown, dry, firm to stiff	limestone fragment
25.5	S-17	4-3-4 (7)	1.5				
27.0	S-18	5-7-6 (13)	1.5				
28.5	S-19	6-5-6 (11)	1.3			SILT, <u>ML</u>, med. brown, dry, stiff	
30.0	S-20	5-3-4 (7)	1.5			SILT, <u>ML</u>, med. to dk. brown, dry, firm to hard	
31.5	S-21	3-4-63 (67)	1.5				bottom of overburden(?) top of decomposed rock (?)
33.0	S-22	22-22-13 (35)	1.1			SILT, SAND, CLAY, and GRAVEL, <u>GM-CL</u>, dry, hard	
34.5	S-23	27-60/3" (60+)	0.8			silty CLAY, SAND, and GRAVEL, <u>GM-CL</u>, wet, hard	bottom of decomposed rock(?)
						LIMESTONE bedrock	Conestoga formation (Ord.) rollerbit 34.0' to 35.0'
36.0	S-24	4-3-4 (7)	1.1			SILT, SAND, and GRAVEL, <u>GM</u>, med. brown to gray, wet, loose	top of filled solution cavity(?)
37.5	S-25	1-2-3 (5)	1.0			CLAY, SILT, SAND, and GRAVEL, med. brown, wet, loose	bottom of filled solution cavity(?)
39.0	S-26	6-60/1" (60+)	0.6				
40.5 42.0 43.5 45.0	Run 1			87%	62%	LIMESTONE, hard, lt. gray to gray, fresh to slightly weathered	Conestoga formation (Ord.) fracture spacing moderate-close fracture dips 0-80 solution cavity 42.0' to 42.5' solution cavity 44.0' to 44.25' bottom of boring @ 45.25'

DISCUSSION

The evidence for dissolution voids on seismic line GR95-1 at Test Area 1 is most compelling at CDP 346, CDP 382, and CDP 425. A known sinkhole (approximately 45 feet wide) is bounded by CDP 345 and 382. The seismic profile indicates voids associated with faulting/fracturing at all three locations.

The confirmatory test boring on Line GR95-6 indicates the presence of solution features across a distance of approximately 25 feet suggested by the seismic profile. As indicated by the seismic profiles, sinkhole and/or solution cavities tend to develop where faults/fractures have been identified on the seismic data. There is approximately 2.5 feet of "displacement" associated with the disturbance between faults/fractures at CDP 230 and CDP 240.

CONCLUSIONS

Line GR95-1 demonstrates the analog response for a known sinkhole and dissolution features. The voids, which are potential sinkholes are recognized by waveform amplitude and continuity anomalies; whereas the sinkholes are additionally associated with fracturing and structural depressions. Therefore, changes in reflection amplitude, breaks in reflection continuity, and the occurrence of fracture zones and/or closed depressions are the principle criteria in identifying potentially damaging carbonate dissolution features. These observed seismic responses are consistent with computer modeling results.

Evaluation of the data from the two test areas indicate that in areas where the bedrock was within 25 feet of the ground surface, a station spacing of less than 3 feet and 24 fold data acquisition is required. Where bedrock was buried more than 25 feet, a station spacing of 4 to 5 feet and 12 fold coverage is adequate. Data quality is strongly influenced by the near surface conditions. The 12 gauge shotgun energy source is necessary to overcome the background random noise levels caused by passing traffic and to provide wider bandwidth for coherent noise attenuation.

The accuracy of the subsurface mapping was a function of the seismic data quality, the proximity of the test sites to boring locations, the structural complexity and the wavelength of structural variations, and the spacing of the seismic lines. In future seismic reflection studies intended to generate detailed subsurface maps of sinkhole prone areas, data should be acquired along a series of closely spaced parallel lines. In addition, several seismic velocity surveys should be conducted in selected borings.

These shallow seismic methods can be successfully and cost effectively utilized to identify dissolution voids and faults/fractures within a potentially sinkhole prone terrane. It is important to compliment these studies with a detailed survey of the local hydrology which includes present and future surface runoff patterns; and an engineering evaluation which includes a comprehensive boring program to evaluate soil permeabilities and the presence of groundwater.

ACKNOWLEDGEMENTS

We thank Dr. Andrew Michalski for his review of this manuscript; the Geological Association of New Jersey for the invitation to present this study; and CH2M HILL for financial and computer support in the preparation of this manuscript and reproduction of this guidebook.

REFERENCE

Hall, G.M., 1934, Groundwater in southeastern Pennsylvania, Pennsylvania Geological Survey, Water Resource Report No. 2, 255 p.

Karst Field Trip Road Log

Leaders - Richard Dalton, Donald Monteverde, Robert Canace, Michael Serfes

The field trip will examine various karst features in the Precambrian and Lower Palezoic rocks of northwestern New Jersey and southern New York. Figure 1 shows the location of the four stops on this trip.

The first stop will examine solution features in the Precambrian Franklin Marble and the second and third stops will look at karst features in progressively younger rocks. The last stop will examine an extensive karst drainage system which feeds the largest measured spring in New Jersey.

Mileage starts at the intersection of Routes 23 and 94, in the center of Hamburg, New Jersey.

Interval	Mileage	
0.0	0.0	Proceed north on Route 94 to McAfee.
2.7	2.7	Intersection of Routes 94 and Route 517 bear right and park in church parrking lot.

Stop 1 - McAfee - Solution in the Franklin Marble

Leader - Richard Dalton

Quarrying operations at McAfee exposed three small caves in the Franklin Marble. Figure 2 is a simplified portion of the draft geologic map of the Hamburg quadrangle (Dalton and others, in prep). The site is located in a band of Franklin Marble which extends from Hamburg north into New York State. Several hundred feet east of the quarry is the Hamburg Fault, a steep southeast dipping normal fault. To the north and south of McAfee this fault brings Lower Paleozoic carbonate rocks into contact with the Franklin Marble. In the town of McAfee the marble bounds the fault. West of the quarry there is a shear zone running parallel to Route 519 and about 400 feet further west is the Pochuck Fault. This fault parallels the Hamburg Fault and is also dipping steeply to the southeast.

Regionally, the Franklin Marble is a metamorphosed limestone and in places a dolomitic limestone that contains layers of gneiss; locally, it is intruded by granite pegmatite.

Marble at this stop is white to buff weathering, medium-to coarse-crystalline, massive textured, and indistinctly to moderately foliated. It is composed predominantly of calcite and accessory graphite, pholgopite, and minor amounts of chondrodite and pyrite. Joints in the marble are typically irregularly spaced and poorly developed. Three distinct joint trends occur within the marble

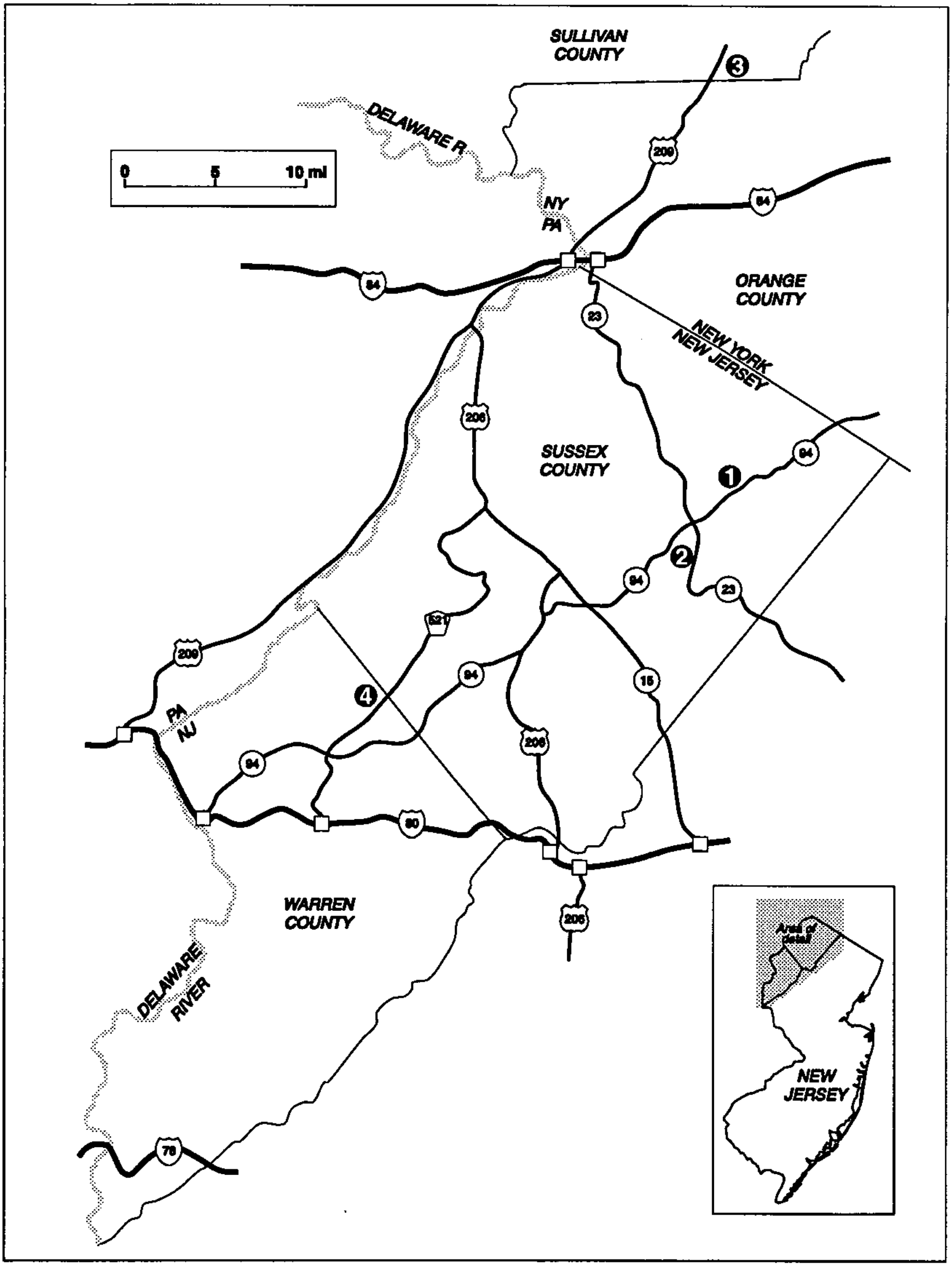


Figure 1.– Map showing field-trip stops.

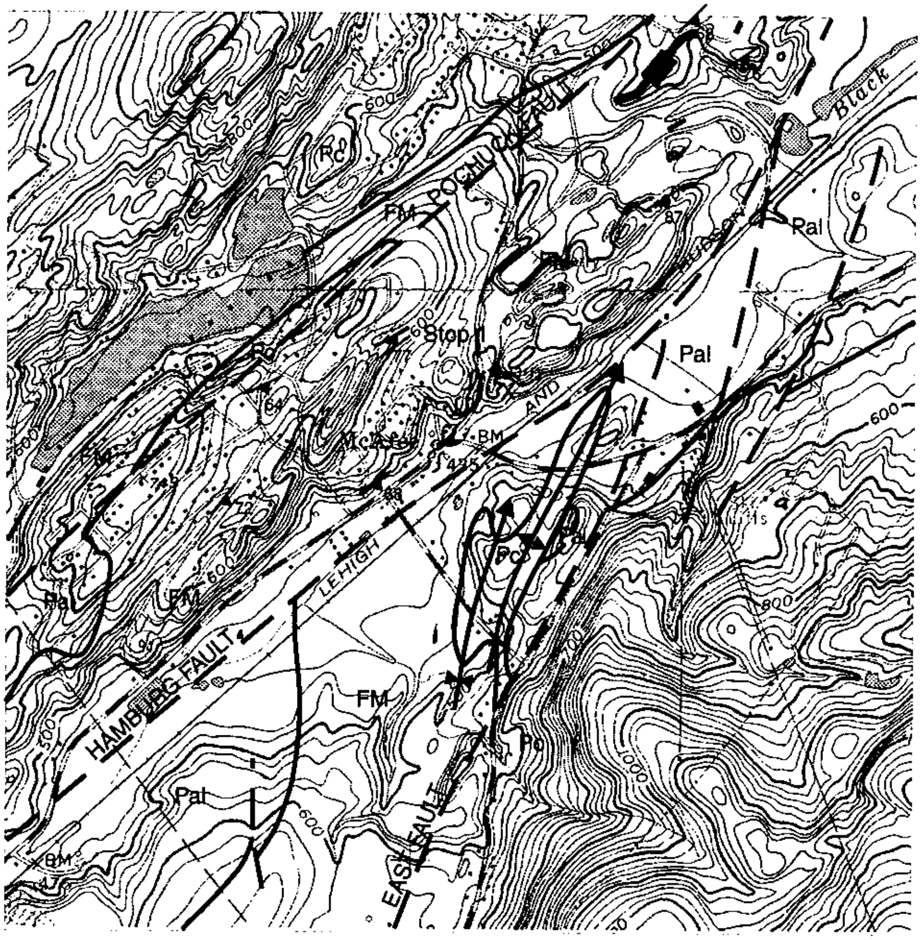


Figure 2.-- Site geologic map of stop 1. FM- Franklin Marble; Pc- Precambrian rock (undifferentiated); Pal- Paleozoic rock (undifferentiated). Topography from Hamburg USGS 7.5-minute quadrangle.

of this valley. They are: N. 45°-52° W. dipping steeply southwest and less often northeast; N. 04°-21° W. dipping steeply southwest and northeast; and N. 71° E. to N. 74° W. dipping steeply north and south (R.A. Volkert, unpublished data). Metamorphic foliation averages N. 41° E. 65° SE. here, as well as regionally, but the dip locally steepens to near vertical along strike.

The three small caves which were exposed during the quarrying operations were likely part of an extensive, steeply dipping karst drainage system. At the upper end of the system is Arch Roof Cave, located high on the north wall of the quarry; it is a single steeply dipping solution tube about 4 feet high and 20 feet long.

The other two caves are at the floor of the quarry in the south wall (fig. 3), and are connected by a N. 44° W. trending fissure which is too small to enter. The southeastern most cave, know as Kerreganot, is a single long fissure up to 6 feet high with minor offsets. The passage trends S. 40° W. and then bends to S. 24° W. for most of its length; it plunges toward the southwest at approximately 40 degrees. About 10 feet from the entrance is the connecting fissure to Wormscrew Cave.

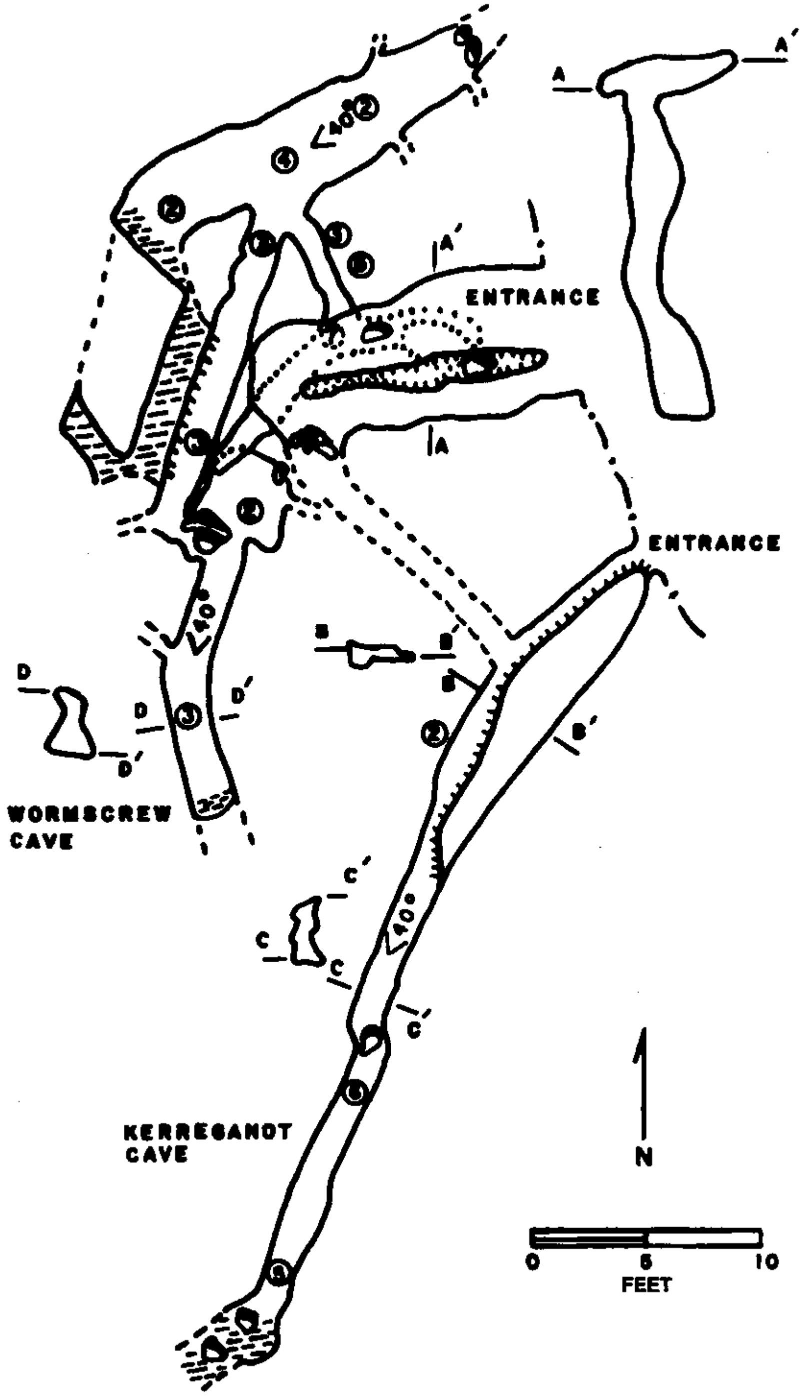


Figure 3.-- Diagram of Kerreganot-Wormscrew cave system (from Dalton, 1976).

Wormscrew is a complex cave. The entrance passage which trends S. 80° W. forms a 20 foot pit which connects to a lower level. The main lower level passage trends S. 60° W. and then bends around to S. 14° E. The lower level passage plunges approximately 40° in a southerly direction. The northwestern passage complex is over 20 feet below the central and southern parts of the cave.

The map illustrates that there are several trends of passages: N. 20° E., N. 60°-80° E. and N. 20°-40° W. The small, short passages are oriented along the N. 25° W. trends and the long passages on the N. 20° E. trend. The wide passage segments are mainly on the N. 60°-80° E. trend. A comparison of passage trends to joint orientations indicates that most of the solution occurs on joints or fractures parallel to the foliation. The slope of the passages seems to be controlled by the plunge of the small bodies of gneiss.

Features to note:

1. The coarseness of the marble.
2. The gneiss blocks.
3. The yellowish pods in north wall and on the floor of quarry.
4. The flutting on the walls of Arch Roof.
5. The overall plunge of the system.
6. The large parting surface that forms the floor of Arch Roof.

Turn around and proceed south on Route 94 through intersection with Route 23. Continue on Route 94 to the intersection with Route 631.

Interval	Mileage	
5.3	8.0	Turn left onto Route 631.
1.1	9.1	Turn left onto Scott Road.
0.4	9.5	Turn left into the yard of Franklin Precast Tanks and park.

Stop 2 - Paulison's Sinks

Leader - Richard Dalton and Donald Monteverde

The Paulison's Sinks (stop 2, fig. 4) are a group of sinkholes which opened up in the early 1950's as the result of the owner cutting trees to clear the edge of a field. Rainfall runoff flows from the upper fields to the river by a natural trough. When the trees were cut along the drainage, some of this water percolated down near the rotting stumps into the underlying bedrock. In time a series of at least seven sinkholes opened (fig. 5). In 1955, local cavers dug open three of the sinkholes and revealed a complex network of cave passages. Hundreds of hours of digging removed tons of glacial debris from the three caves. Unfortunately, severe rains from a hurricane in the summer of 1956 closed one of them. The other two were opened periodically and digging continued intermittently in both for years. This was carried out mainly by Larry Chapman who was trying to find the first New Jersey cave over 500 feet long. The largest of the caves is nearly 500 feet long and another about 200 feet long.

Presently, the Central New Jersey Grotto is working with the assistance of the landowner to install better access to the cave system. Originally, three 55 gallon drums were welded together

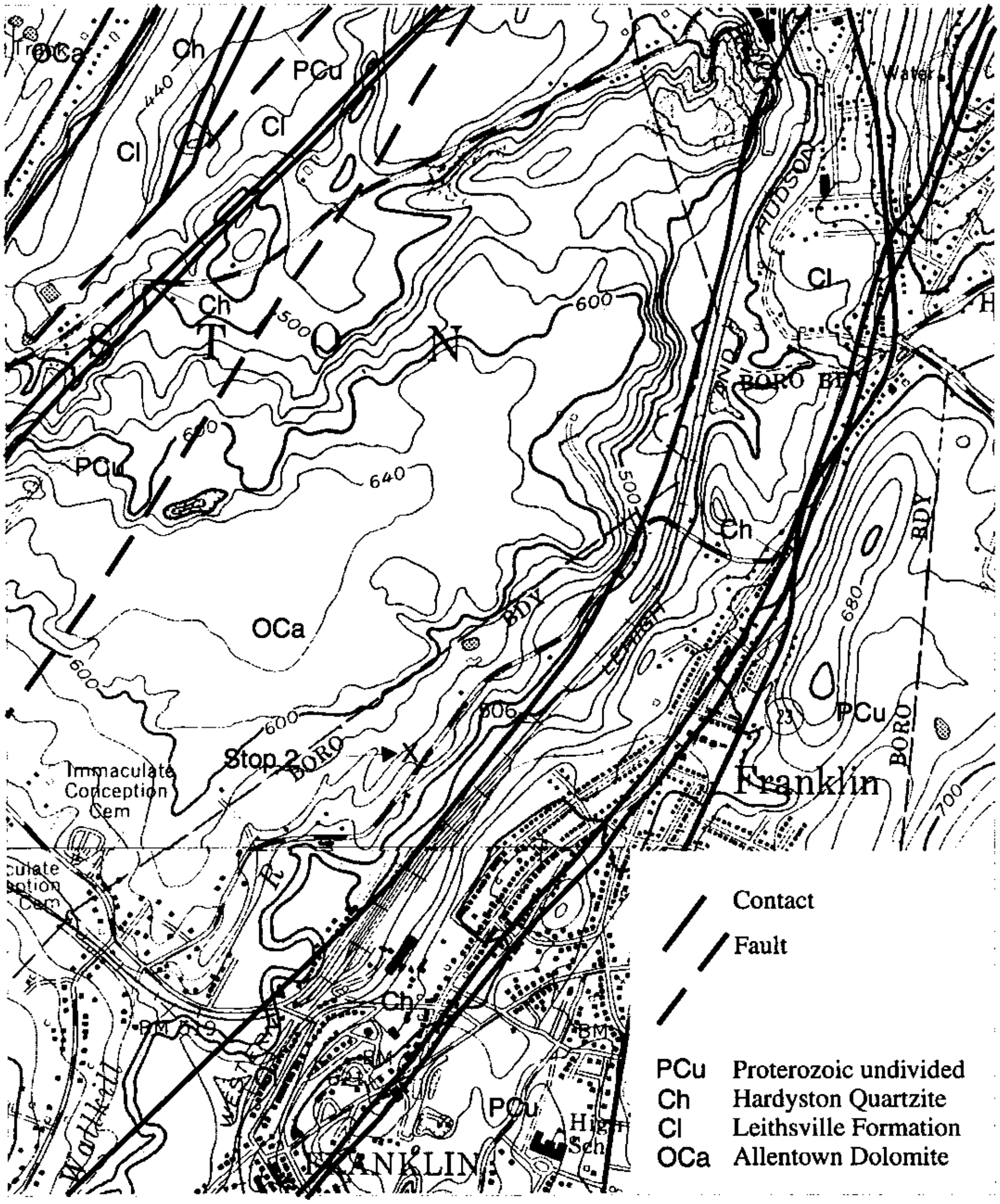


Figure 4.-- Site geologic map of stop 2. Topography from Hamburg and Franklin USGS 7.5-minute quadrangles.

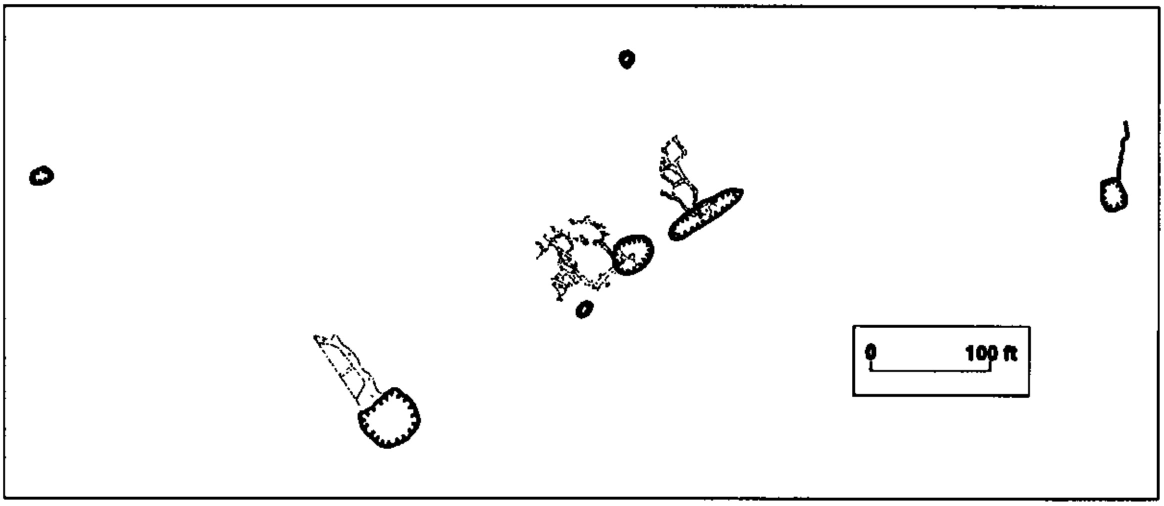


Figure 5.– Caves at Paulison's Sinks (modified from Dalton, 1976).

and set in the bottom of the sinkhole to stabilize the entrance of the largest cave. The new access will consist of 15 to 20 feet of concrete rings and a gate. The other sinkholes have gradually been filled by previous land owners, a common practice in karst regions.

During the numerous digging trips, running water has been heard in the lower reaches of the cave, behind the glacial fill. Although the cave system formed below the water table, it was later modified by running water when water levels dropped. This is evident by the glacial debris found in many passages. Another indication of later modification by water is the keyhole shaped passages found in the cave (fig. 6). Keyhole passages develop when the primary solution passage is filled with sediment. Later vadose (subsurface but above the water table) streams enter the passageway and cut into the walls of the cave above the fill. In time they downcut and remove the fill, leaving a slot-shaped passage resembling a keyhole.

Regional Stratigraphy

Rocks of the Allentown Dolomite form the host unit for the Paulison's Sinks caves (Dalton, 1976). This formation is approximately 1800 feet thick and makes up the middle part of the Kittatinny Supergroup which is approximately 3500 feet thick. The Supergroup also includes the Leithsville Formation which lies below the Allentown, and the Ordovician Beekmantown Group which lies above it. These carbonates, along with the older Hardyston Quartzite, represent the New Jersey portion of the Lower Paleozoic passive carbonate margin found throughout the Appalachians.

Clastics of the Hardyston Quartzite mark the initial deposition of the passive margin sediments on the Proterozoic basement rocks. Outcrops of an arkosic sandstone occur on the east side of the Wallkill River in Hamburg and strike northeast with a moderate northwest dip (fig. 4). The

Figure 6.-- Photograph of keyhole passageway from Paulison's Sinks Cave 3 (from Dalton, 1976).

Leithsville Formation, lying conformably to nonconformably above the Hardyston, marks the beginning of carbonate deposition. It contains three members (Markewicz and Dalton, 1977); a central package of dolomitic sandstone and shales bounded on both sides by a medium- to coarse-grained dolomite. The Leithsville crops out to the west of the Hardyston, up to the Wallkill River. The contact of the Leithsville with the overlying Allentown occurs beneath the Wallkill River, and close to the caves. The Limeport Member and an unnamed upper member divide the Allentown in two units (Markewicz and Dalton, 1977). The Limeport makes up one of the most distinctive units of the Kittatinny Supergroup because of its characteristic sedimentology including oolites, stromatolites, mudcracks, paleosols, quartz sand beds and edgewise conglomerate. These features indicate a supratidal and intertidal depositional environment. Paulison's Sinks caves occur within this member. Till and meltwater sediment laid down during the late Wisconsin glaciation cover most of the bedrock. In some places these materials may be very thick (Stanford and Harper, 1985; Stanford and others, 1995).

The Limeport Member crops out in the sand and gravel pits to the northwest and along Scott Road. It consists entirely of dolomite with minor beds of thin argillaceous dolomite and quartz sand lenses. Dolomite occurs both as a primary sediment and a secondary replacement of limestone. Near the cave, the unit is a thin- to medium-bedded, aphantic to medium-grained, dolomite. Subrounded quartz sand occurs as both lenses and as individual floating grains. A general alternating pattern of light and dark beds is present. In the commercial sand and gravel pits to the west and north, glacially polished exposures of dolomite crop out that contain oolites as both beds and lenses, edgewise conglomerate and stromatolites. Primary porosity is very low, yielding a dense rock only broken by secondary fractures.

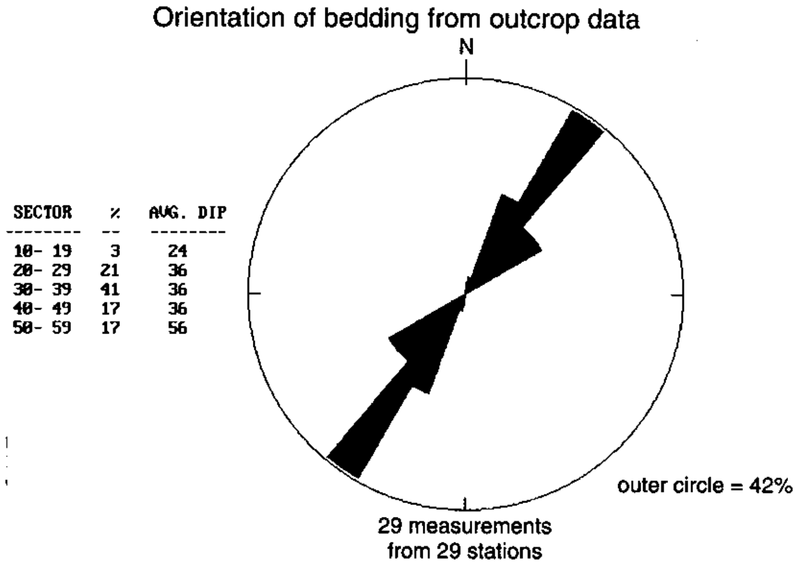
Structural impacts on the region

The rocks of this area have a history of extensive deformation. Both compressive and extensional events are recorded in the regional geology. The Jenny Jump-Crooked Swamp Thrust System that formed during the Alleghenian Orogeny (Herman and Monteverde, 1989) imparted a strong compressive signature to the entire region. Locally, to the south and northeast of Hamburg and Franklin, high-angle normal faults developed due to localized extension in the same deformational event. Later Mesozoic rifting may have reactivated both types of these earlier faults. These various deformation events imparted strongly developed joint patterns in the dolomitic rocks.

Regional geologic mapping for the new 1:100,000 state geologic map of New Jersey allowed an initial understanding of the structural complexities of the cave area, and 1:24,000 scale mapping formed the basis for a more detailed analysis of the structural features. Structural data were collected at the outcrop and all joint orientations measured and spacings identified; later these were input on a personal computer (PC). Due to the complexities of the faulting, the study used only outcrop-scale data collected within a specific area (see Herman and Monteverde, 1989, and Herman, 1992, for a discussion of the regional fault patterns). Boundaries of the block are the Hardyston unconformity to the east, the fault contact to the west, and approximately one mile to the north and south. Data were compiled and plotted on rose diagrams for further study.

Preliminary analysis portrays a consistent orientation of both bedding and joints (D. Monteverde and G. Herman, unpublished data). Compilation of 29 bedding orientations showed a constant trend (fig. 7) with a dominant northeast strike between N. 30^{o}-39^{o} E. degrees and a steady northwest dip. Rose diagrams of 50 joint readings also exhibit a well developed pattern (fig. 8A) with a cross strike oriented (in relation to bedding) maximum centered on the N. 60^{o}-70^{o} W. degrees. Subsidiary maxima occur between N. 10^{o}-30^{o} E. degrees and N. 10^{o}-30^{o} W. degrees.

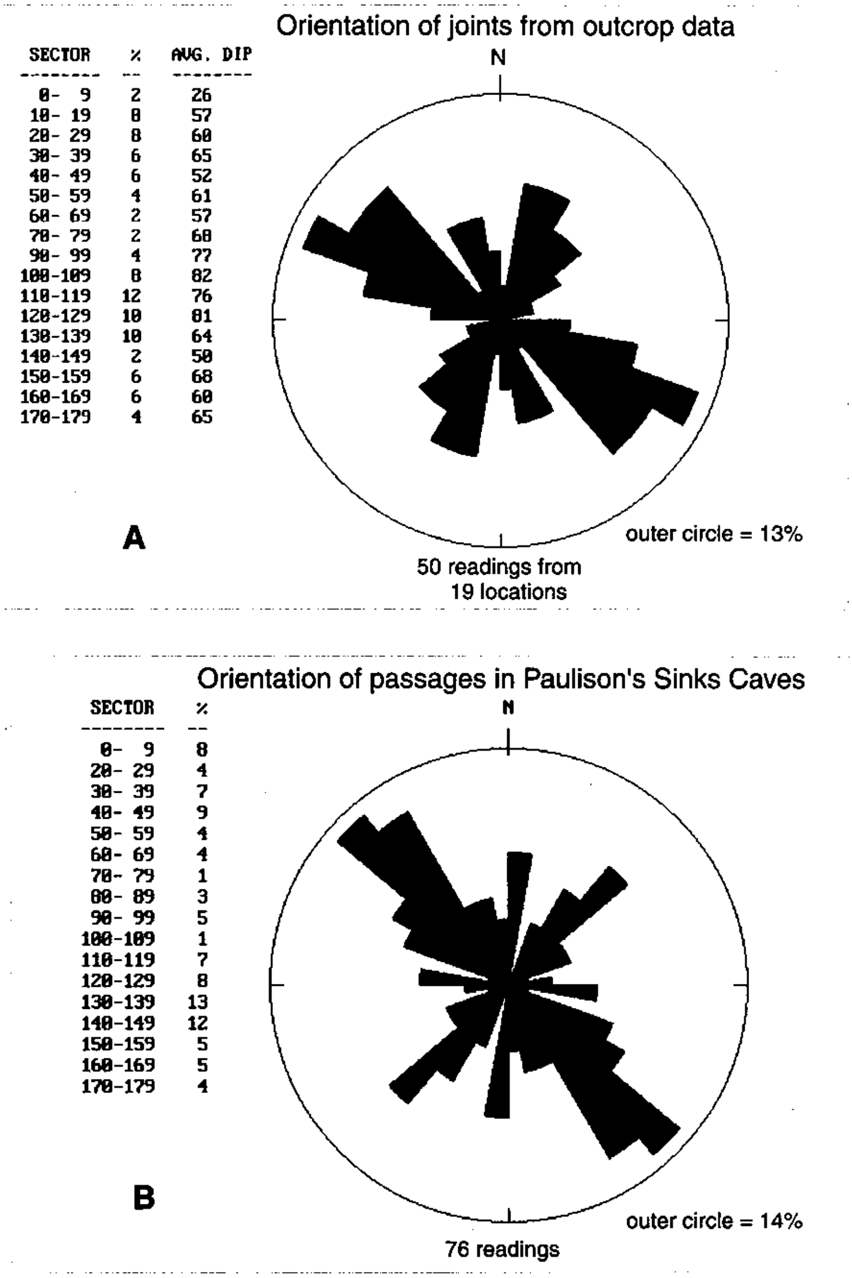
Orientation data on karst features was analyzed to decipher the impact of the outcrop-scale joint trends measured. Mapped passageways of the Paulison's Sinks Caves were selected for this purpose. These caves were mapped in 1955 by Larry Chapman and other members of the Northern New Jersey Grotto. Cave passage maps commonly have grades which depict the degree of accuracy of the mapping. Scales follow the British Cave Research Association Survey Grades as described by Ellis (1976). They range from a sketch of low accuracy without measurements (Grade 1) to a magnetic survey with horizontal and vertical angles accurate to one degree and distances accurate to ten centimeters (Grade 5). The Paulison's Sink Cave map has an accuracy level of Grade 3 (rough magnetic survey with horizontal and vertical angles measured to 2.5 degrees and distances to 50 centimeters). Original compass readings of passageways were unobtainable, so trend lines were drawn on cave passage maps to approximately parallel the cave wall traces. Data analysis commenced after inputting 76 cave passage orientations on the PC for rose diagram construction.



SECTOR	%	AVG. DIP
10- 19	3	24
20- 29	21	36
30- 39	41	36
40- 49	17	36
50- 59	17	56

Figure 7.-- Rose diagram of bedding readings collected during bedrock mapping.

The impact of bedding cannot be easily correlated to the development of passageways due to their projection to the horizontal on the cave map. Comparison can only be made to the strike of bedding. The rose diagram of the passages does show a secondary correlation to the strike of beds at N. 30^o-39^o E. degrees (figs. 7 and 8B). To verify if the passages follow down the dip of bedding the projection must be into a vertical section 90^o to the bedding strike, in other words, a dip section. This cannot be done with these data. Photographic evidence and field relations suggest that bedding plays an important role in controlling location of karst features. Figure 6, a photograph taken within the Paulison's Sinks Cave 3, portrays a bedding bounded passage. Outcrops of dolomite north of the caves which project below the cave entrances provide further evidence of bedding control on karstification in this area. Figure 9A shows this outcrop where a high degree of solutioning occured at the expense of an individual bed as opposed to the entire outcrop. At this site, rain runoff from a feed storage shed drops onto the dolomite outcrop. The dark-gray, medium-grained bed weathers faster than the other beds as shown by deep pitting in



SECTOR	%	AVG. DIP
0- 9	2	26
10- 19	8	57
20- 29	8	60
30- 39	6	65
40- 49	6	52
50- 59	4	61
60- 69	2	57
70- 79	2	60
90- 99	4	77
100-109	8	82
110-119	12	76
120-129	10	81
130-139	10	64
140-149	2	50
150-159	6	68
160-169	6	60
170-179	4	65

SECTOR	%
0- 9	8
20- 29	4
30- 39	7
40- 49	9
50- 59	4
60- 69	4
70- 79	1
80- 89	3
90- 99	5
100-109	1
110-119	7
120-129	8
130-139	13
140-149	12
150-159	5
160-169	5
170-179	4

Figure 8.-- Rose diagram of structural components of rock outcrops and Paulison's Sinks. A- orientations of joints collected at outcrops near Paulison's Sinks; B- orientations of cave passages collected during bedrock mapping.

the weathered layer (fig. 9B). This suggests that within the Limeport Member certain beds of dolomite are more conducive to karstification then others.

Preliminary analysis shows a good correlation between the joint and passageway trends. This is seen by the agreement in the general shape and contour interval of the two rose diagrams (figs. 8A and 8B), and suggests that the dominant joint traces in the rocks controlled the ground water flow in these carbonate rocks. If figure 6 shows the bedding control on these features then the in-

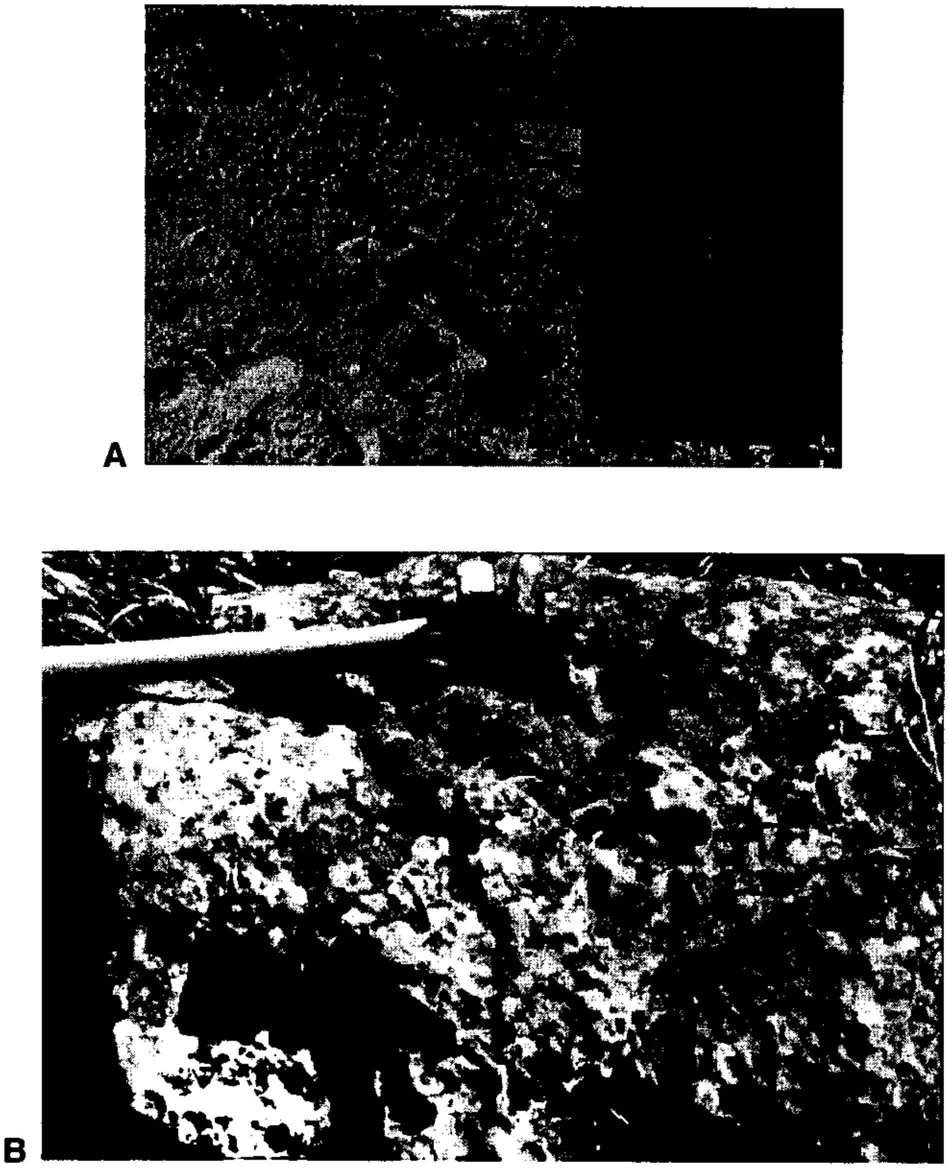


Figure 9.-- Photographs of solution features of Allentown Dolomite outcrop just north of Paulison's Sinks. A- runoff from roof of hayshed descends on outcrop. One bed of dolomite shows preferred solutioning compared to others; B- close-up of solution features.

ter-relationship of jointing within the more soluble layers controls karst development. Therefore, the more dominant joint trends within the area concentrate the flow of ground water, and develop parallel karst features. Further statistical analysis is necessary to validate these preliminary findings.

Return to Route 631.

Interval	Mileage	
0.4	9.9	Turn right onto Route 631.
1.1	11.0	Turn right onto Route 94 and proceed north to Hamburg.
2.5	13.5	Turn left onto Route 23. Follow Route 23 north through Sussex, over Kittatinny Mountain and past High Point State Park. Continue down the mountain to junction with Route 521 near Port Jervis.
18.1	31.6	Turn left onto New York Route 6 and proceed into the center of Port Jervis.
1.2	32.8	Turn right onto Route 209 and proceed north to Westbrookville.
11.6	44.4	Turn right onto Route 61 and cross the Basher Kill.
0.5	44.9	Turn left onto South Street and proceed north.
0.8	45.7	Turn left into large parking area.

Stop 3 - **Mystery-Rhodes Cave Area**

Leaders - Richard Dalton, Donald Monteverde

Cavers in the late 1950's investigated this unique karst area (fig.10) and found one medium-sized cave they called Rhodes Cave (fig. 11). In 1965-1966 cavers from the Northern New Jersey Grotto discovered a second cave which has been called by various names including Fall Brook, Surprise and Mystery Cave (fig. 12). Exploration has yielded a very large cave for the region, which has over 1.5 miles of mapped passages with many pits and dome pits extending to a depth of 171 feet below the entrance. The largest room in the cave, the Roundroom, is over 50 feet wide and one passage from the room has ceiling heights of 60 or more feet. Most of the passageways are walkable. At least five separate streams enter the cave. The main stream below the entrance room flows north along strike for about 400 feet from the New Discovery toward the entrance, where it joints a south flowing stream from the Scrub Passage (fig. 12). The main stream continues north for another 200 feet to just before the Roundroom where it turns more westerly; it then flows down a series of dip passage and exits the cave in the Lakeroom Maze area. Another stream enters from the Shower Dome and may join part of the main stream before it also exists in the Lakeroom Maze.

Two other streams join at the Helldome. One of them is an upper level stream that flows from the south and drops about 30 feet down the Helldome and joins a south flowing stream. When

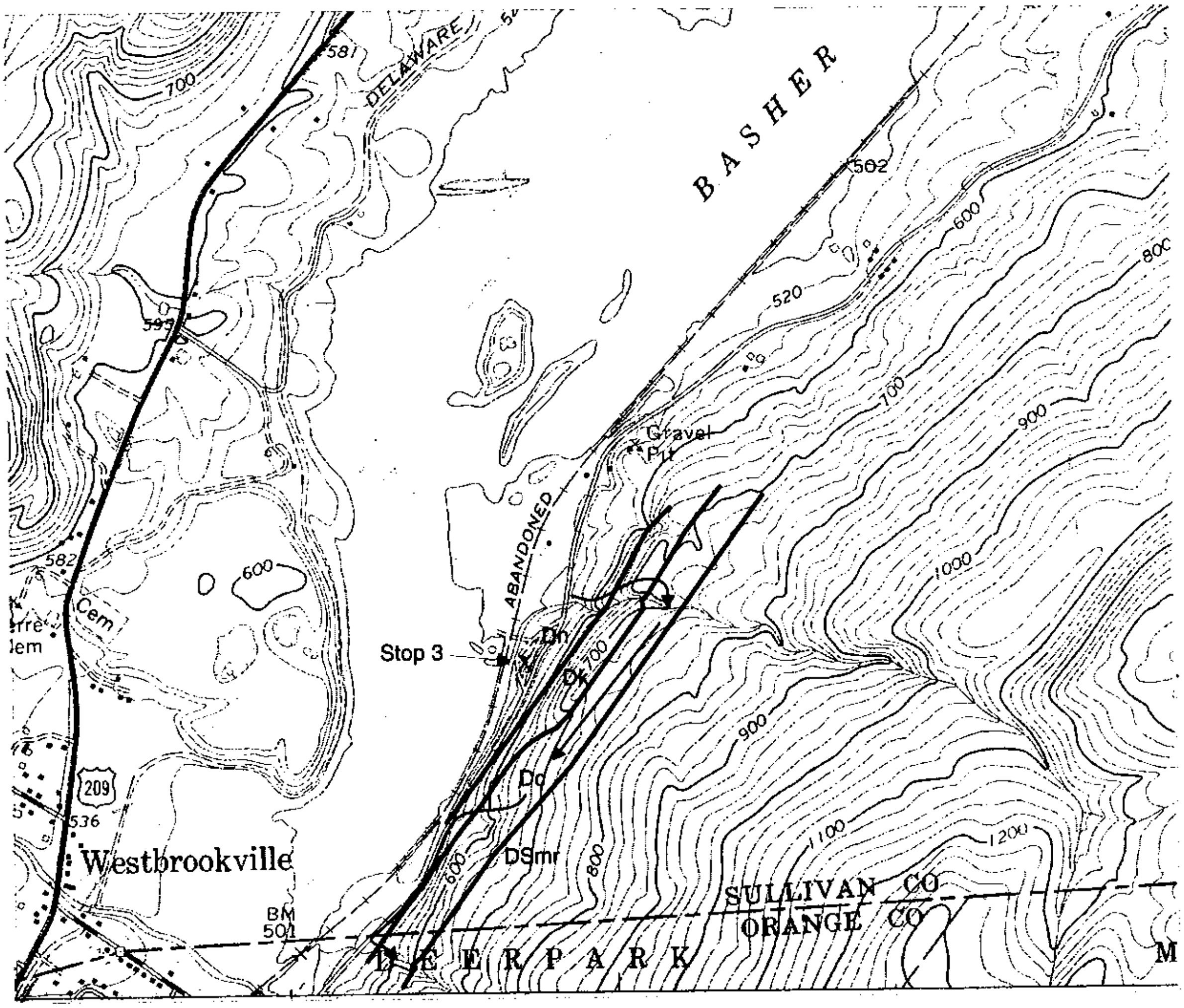


Figure 10.-- Site geologic map of stop 3. Solid lines indicate approximate location of unit contacts. Arrows show path of field trip. Dn- New Scotland Formation; Dk- Kalkberg Limestone; Dc- Coeymans Limestone; DSmr- Manlius Limestone and Rondout Formation. Geology from D. Monteverde and J. Epstein, unpublished data. Topography from Yankee Lake, NY USGS 7.5 minute quadrangle.

they merge, the stream turns back on itself and flows north for over 300 feet where it also turns west and flows down the dip. This stream exits the cave from the lower reaches of the Lasso Passages about 20 to 30 feet higher than the main stream exit. A surface stream flows right over the cave and continues down the dip slope to the Basher Kill.

A path going up the hill along the stream, leads to a broad bench on the flank of the Shawangunk Mountains about 180 to 200 feet above the valley floor. The topographic map of the area shows two prominent streams that field examination suggests are intermittent. They only flow across the bench and reach the Basher Kill in times of high rainfall, such as in the spring.

Between these two stream valleys numerous sinkholes occur. Many sinkholes cluster right over the cave on both sides of the stream. In between the stream and the next drainage, about 1000 feet to the north, the number of sinks decreases rapidly. About half way is a broad flat area hun-

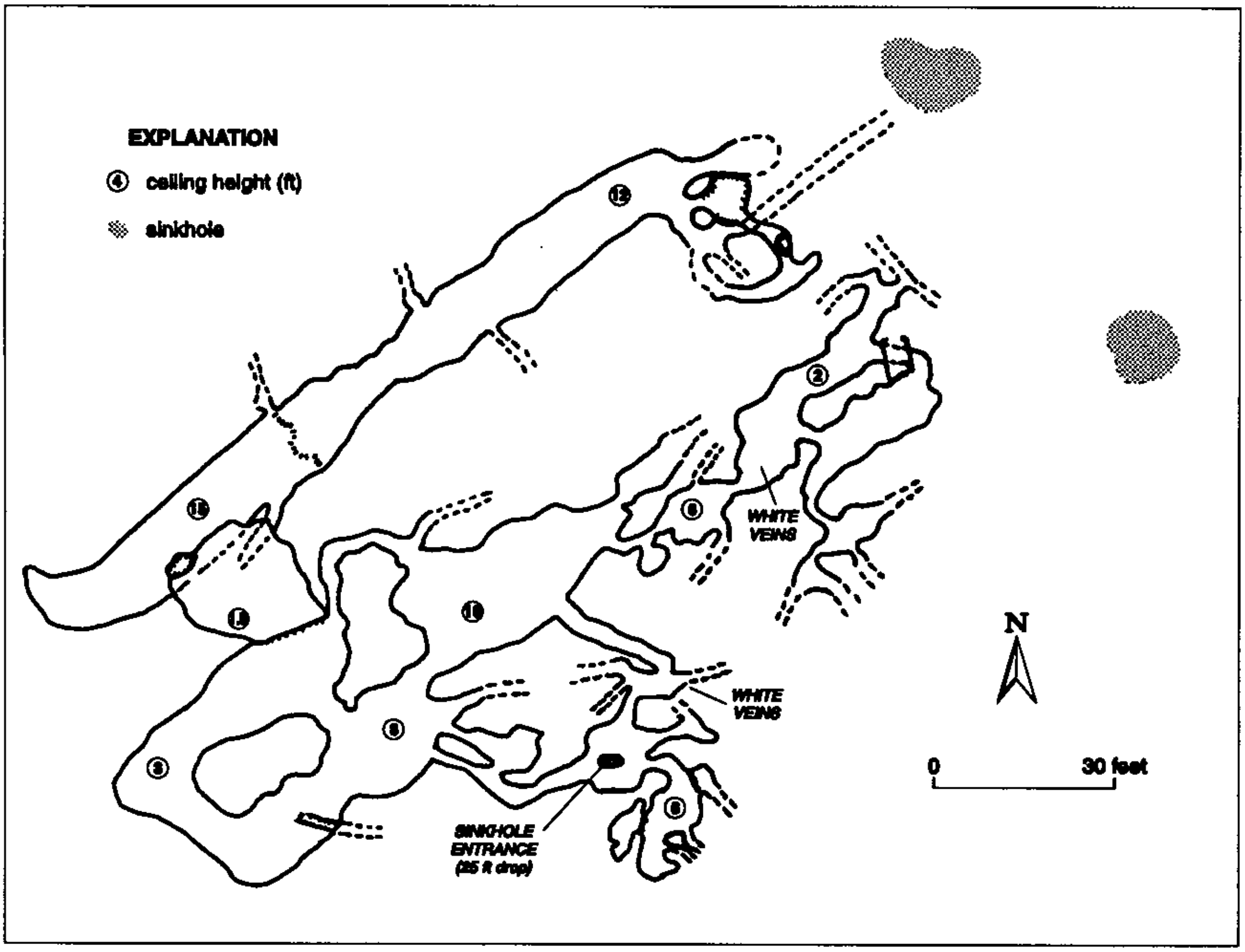


Figure 11.– Map of Rhodes Cave (modified from an unpubished map by Jayne, W.M. and Anderson, R.R., 1959).

dreds of feet wide which has almost no sinkholes. At the next drainage, large deep sinkholes become common again.

In a southerly direction the bench descends in elevation where there is a prominent drainage and another minor one between the surface stream at Mystery and the stream at Rhodes Cave. As each drainage area is approached the number and size of the sinkholes increases. At the major drainage two dry valleys join and wet weather springs can be observed feeding the stream which flows a few tens of feet and then sinks. Down stream of the junction of the two dry valleys there are large bank collapses on both sides of the stream. There is also a rock lined shaft about ten feet deep in the bed of the stream.

About 1000 feet further south is the Rhodes Cave stream. Sinkholes become very common on both sides of the stream. Two of the three entrances to the cave are in the stream bed and the third is a 25 foot shaft in the bank. Here again, springs rise upstream above the cave; the water flows a short distance and then sinks into the streambed.

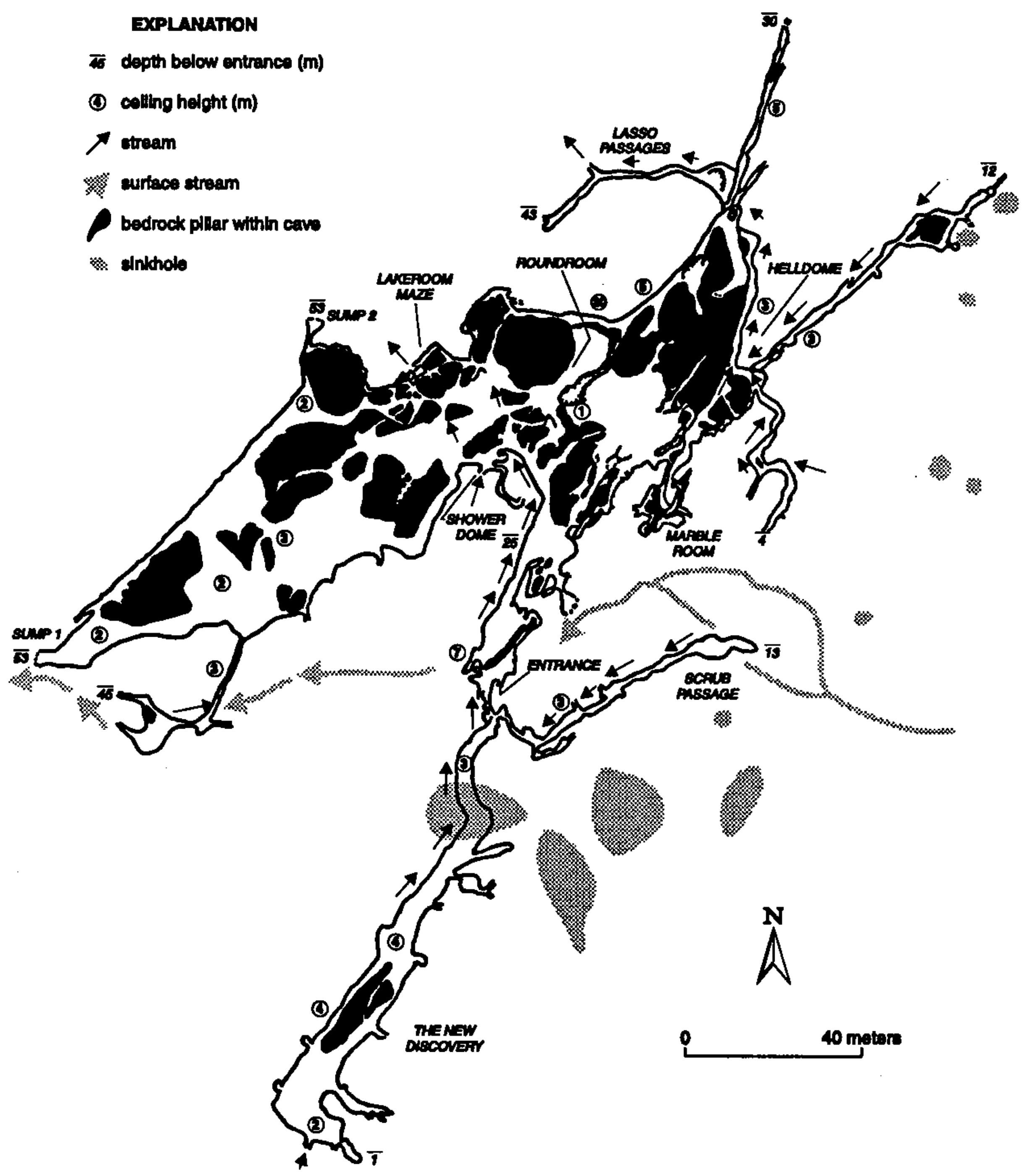


Figure 12.– Map of Mystery Cave (modified from Jelen, 1984).

Several major springs rise along the road below Mystery Cave and Rhodes Cave. Dye placed in the lower sump of Mystery Cave surfaced north of the Mystery Cave stream in the Baskerkill Valley (Febroriello, 1984).

A comparison of the orientation of the cave passages from figures 11 to 12 to local strike of the bedding indicates the long axes of the caves are strike parallel and the passages are offset down the dip of the bedding. In the upper reaches of both caves there is a lot of calcite veining; it is noted in two places on the Rhodes Cave map (fig. 11) and in the Marble Room area of Mystery Cave (fig. 12). The veining seems to be selectively confined to one or more beds. There may be a structural control of the veining, but this has not been investigated.

Reconnaissance geologic mapping (fig. 10) shows how the different limestone units of the region control karst activity. As seen on the upward climb towards the cave entrance, this surface is a dip slope. The stream can be seen to descend bedding planes with several jumps up-section. Since the average bedding in the area strikes N. 35° E. and dips 30° NW., one traverses progressively older units by climbing upwards and eastwards. The lower reaches of the stream are in the New Scotland Formation. Here the unit is a thin- to medium-bedded alternating fine-grained light-medium-gray limestone and dark-gray argillaceous limestone. The argillaceous limestone is the more resistant of the two and upholds the long continuous bedding planes the stream flows over. At the first major stream bench, the argillaceous limestone becomes less common. This lower and therefore older unit is the Kalkberg Limestone and contains a more uniform thin- to medium-bedded, fine-grained, light-medium-gray limestone. Select dark-gray, pod-like bodies weather in relief due to a higher silica percentage. They become more apparent on the second dip slope further up stream. Continuing higher on the climb, a second bench forms near the cave entrance. Here, medium- to dark-gray chert can be found in thin layers and lenses. At this upper bench the Coeymans Limestone occurs. It is a slightly coarser, dark-gray limestone. Continuing upstream, there is a lack of bedrock exposure because surficial material from the late Wisconsian glaciation and recent alluvium and colluvium cover the region.

The limestone geology of this main stream matches well with that in the two streams along strike located to the southwest. In the southern two streams a slighlty older limestone than the Coeymans, that of the Manilus Limestone, can be seen up on the slope. This is a uniformly thin-bedded, fine-grained limestone. Downstream and above the Manlius, exposures of the Coeymans Limestone crop out. The coarser grained nature of these units are readily observable here.

All the limestones show a well developed fracturing. The dominant feature is a spaced cleavage striking N. 48° E. and dipping 55° NW. on average (D. Monteverde, unpublished data). Joints also can be found in the limestones. From a limited sampling of the immediate area there appears a clustering of data between N. 61°-81° W. (D. Monteverde, unpublished data). They are discontinuous but do traverse the stream beds for greater than 15 feet. There is an interplay of the joints and the spaced cleavage which allows the removal of large blocks of bedrock by the stream (fig. 13). This appears on the large dip slopes in the stream and as the "stepups" where the stream climbs upsection.

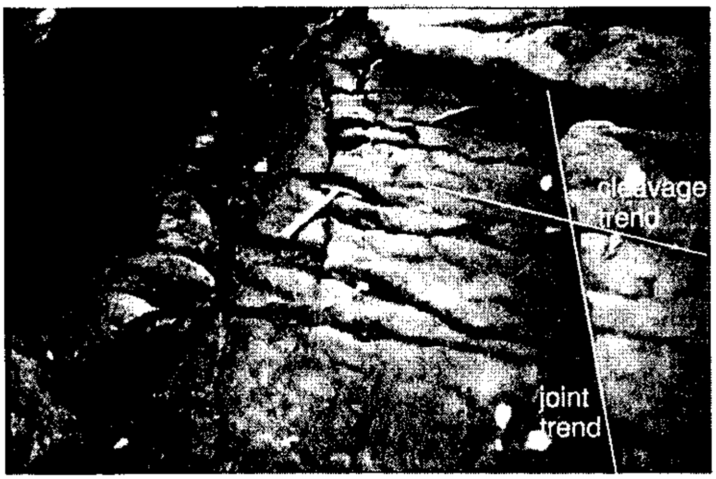


Figure 13.-- This photograph shows the influence of the joint and spaced cleavage trends on karst development; it looks down on the dip slope of the carbonate rock in the stream bed. Enhanced dissolution of the carbonate occurs along these two planes, allowing the erosion action of the stream flow to remove large blocks of rock.

The main purpose at this stop is to point out the relationship between the surface drainage and sinkhole development. Even though most of the bench, slope and valley bottom is limestone, the sinkholes tend to cluster on one unit, the Coeymans Limestone (fig. 14). If there is some flow in the streams, then springs and sinking streams can be observed.

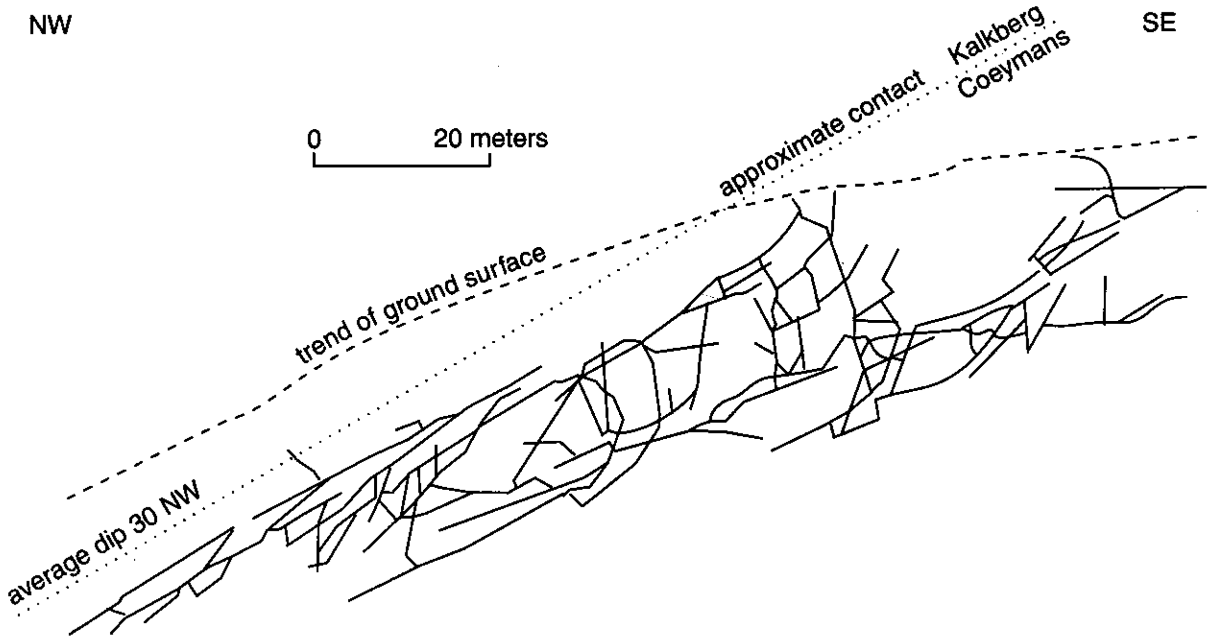


Figure 14.-- Passageways from Mystery Cave projected into a cross section trending perpendicular to bedding. This shows how the bedding trend confines the orientation of the passages. It appears that the cave is restricted to the Coeymans Limestone. (modified from Jelen, 1984)

It is also important to note the relationship of the mapped cave passages to the surface locations of the sinkholes (figs. 11 and 12).

Turn right from parking lot and proceed back to Westbrookville and Route 209.

Interval	Mileage	
0.8	46.5	Turn right onto Route 61.
0.5	47.0	Turn left onto Route 209 and proceed south through Port Jervis to Milford, Pennsylvania. Continue through Milford to the intersection with Route 206 and the bridge for New Jersey.
20.1	67.1	Turn left onto Route 206, cross the Delaware River, and go past Stokes State Forest to Culvers Gap.
9.8	76.9	Turn right onto Route 521 and proceed south past Swartzwood Lake to Stillwater.
16.7	93.6	Bonnie Brook Spring is on right side of the road. It is identified by a very small pond between the road and the hill. There is a spring house against the base of the hill. The pond which is created by a stonewall dam and the road has two outlets which flow under the road into the valley of the Paulins kill.
1.0	94.6	Turn right onto a wide lane.
0.2	94.8	Park at gate.

Stop 4 - Schuster Pond Karst Area

Leaders - **Robert** Canace, Donald Monteverde, Michael Serfes

The area around Schuster Pond in Hardwick Township, Warren County, provides a classic model of karst hydrology in New Jersey. It illustrates some of the complexities associated with understanding the dynamics of an integrated karst surface- and ground-water system. Karst hydrogeology is characterized by diffuse recharge by way of weathered joints and strata, by concentrated recharge to sinkholes, disappearing streams, box canyons, undergound streams, and by natural springs. All of these features are found or are suspected in the study area (fig. 15). Several significant springs occur in the area, including Bonnie Brook spring, which appears to be hydraulically connected to Shuster Pond. Nutter (1973) suggests that abundant springs are one of the most important features of carbonate rock terranes and that these discharge signficant quantities of water from the karst ground-water system.

Station 1. Mountain Wood Spring Water Company

Shuster Pond is a natural water body covering approximately 10 acres. It is fed by a high-discharge spring and by a stream coming from a second large spring. Shuster Pond spring provides water for the Mountain Wood Spring Water Company. About 50,000 gallons of water per day are pumped from the spring house, across the pond, to the former bottling plant. No longer bottled on site, the water is now taken by trucks to off site bottling plants. It is sold under the labels, Mountain Wood Natural Spring Water, Springtime 100% Pure Natural Spring Water, and Mountain Spring Water. The owner of the company, Mr. Bill Egan, kindly permitted us access to the property to examine the spring and related karst features.

Station 2. Shuster Pond spring

The spring at Shuster Pond emanates from solution-enlarged fractures in the Allentown Dolomite; these are visible in the spring house at the northwest edge of the pond. A large spring at an elevation slightly above Shuster Pond feeds a stream that enters the west side of the pond. Together, this stream and the spring fill the pond.

The discharge volume from the spring at Schuster Pond varies significantly. Getchell (1992) measured discharge at the spring between September 1991 and October 1992. These measurements ranged from less than 100 gallons per minute (gpm) [0.22 cubic feet per second (cfs)] or 0.144 million gallons per day (mgd), to slightly more than 4000 gpm (8.91 cfs) or 5.76 mgd. Getchell points out that the period studied had below average rainfall, and that these measurements should be viewed conservatively. New Jersey Geological Survey (NJGS) measurements of the spring discharge on August 6, 1996 indicated an instantaneous discharge of 1,630 gpm (3.73 cubic feet per second). This corresponds to a daily discharge of 2.3 million gallons.

The high volume and variable-discharge characteristics of Shuster Pond spring suggest that it is part of a conduit-dominated ground-water system. Karst ground-water systems have been characterized as lying along a contiuum between diffuse flow and conduit or free-flow systems (White, 1963; Smart and Hobbs, 1987). Most bedrock aquifers are diffuse-flow systems. In these, ground-water storage and movement occurs in a variably connected network of open fractures that are relatively narrow. Conduit systems occur in solution-channeled carbonate aquifers. Solution-enlarged fractures dominate this kind of flow system. Typically, conduit systems drain through a small number of high discharge springs (Rauch and White, 1970). The springs act as sinks that drain ground water from saturated fractures in the surrounding bedrock and from conduits at higher elevations. The main water-bearing conduits apparently flow at or slightly below regional base level (White, 1963). Conduit systems are generally characterized by a low hydraulic gradient, sustained by highly permeable conduits. Ground-water flow rates can be significant in these systems. Springs fed by conduit systems have a short residence time, are occasionally

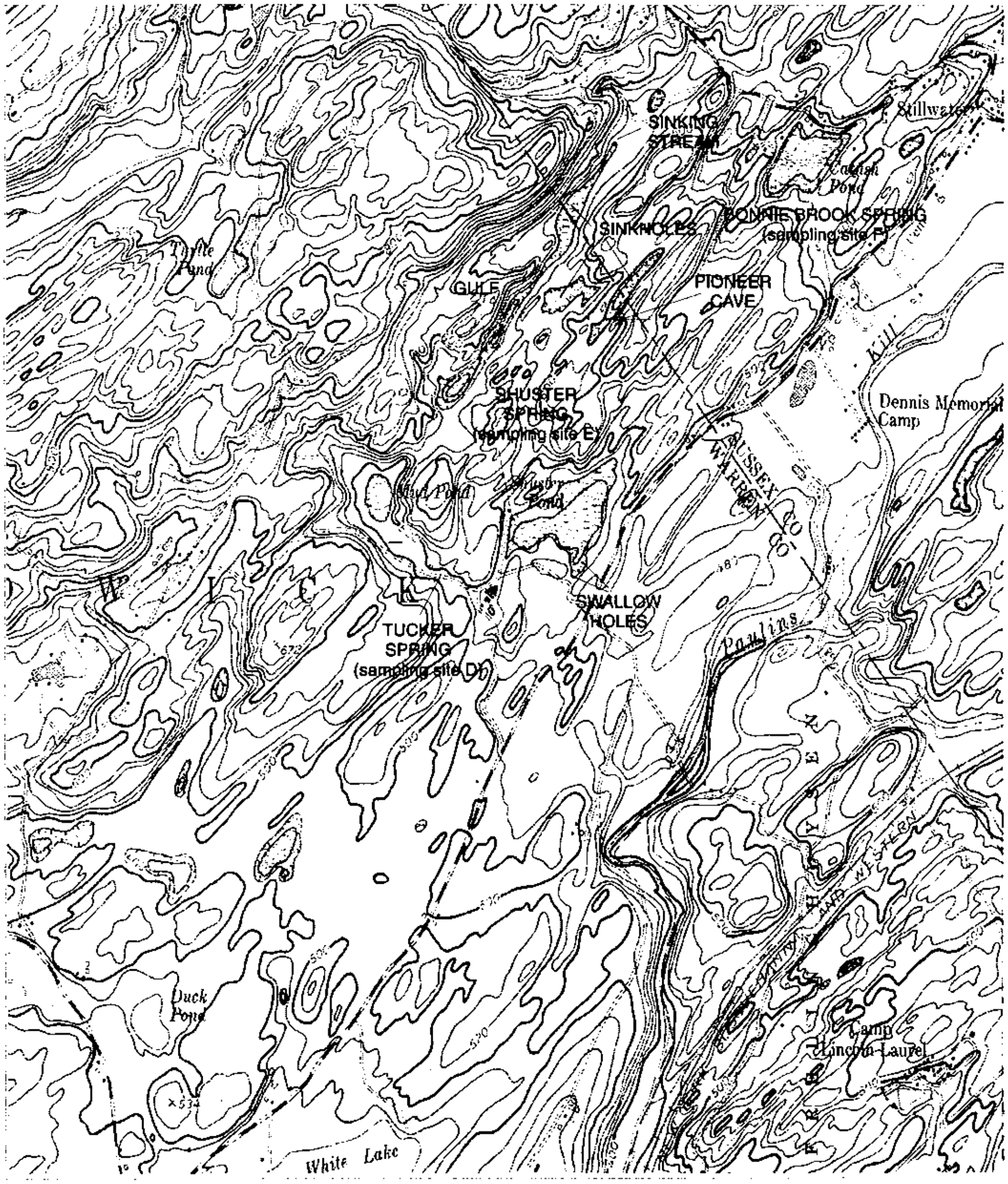


Figure 15.-- Karst features and spring water sampling sites at stop 4. Shaded areas are suspected large-scale subsidence features (sinkholes). Topography from Flatbrookville USGS 7.5-minute quadrangle.

turbid, and experience large variations in chemistry and discharge. Flow in conduits is often turbulent. Ground-water levels exhibit marked variations in response to sudden, high-volume inputs from sinking streams and sinkholes.

Ground-water discharge from the carbonate aquifer feeds the Shuster Pond spring. Flow characteristics and the hydrogeology of the area suggest that it is also fed by a sinking stream draining the shale upland north of the pond. Recharge from flooded sinkholes also contributes to the spring. In order for the upland sinking stream to reach Shuster spring, ground water must flow across the strike of bedding and dominant joints. There are structures in the carbonate bedrock that accomodate this flow pattern.

Flow characteristics and water quality measured at Shuster Pond spring suggest it is part of a conduit system fed by significant surface-water inputs, such as might be provided by the sinking stream and flow into large sinkholes above the spring. Sinkhole flooding has been observed in the area during seasons of high precipitation with water-level fluctuations in sinkholes in excess of 15 feet.

Recent field measurements of temperature, specific conductance, pH and alkalinity were collected at streams, springs, sinkholes and swallow holes to determine possible ground-water flow paths in this complex karst drainage system. The results provide insights into the nature of the carbonate ground-water system and the interaction of surface- and ground-water flow.

Gaseous carbon dioxide (CO_2) from the atmosphere (.03 percent CO_2 by volume), soil air (up to 50 to 100 times higher than the atmosphere) and other sources dissolve in the ground water to produce carbonic acid (H_2CO_3). Carbonic acid increases the acidity of water and reacts with calcite and dolomite to produce the soluble bicarbonate. This interaction produces the dissolution features characteristic of karst landscapes.

Atmospheric precipitation can be characterized as a dilute, acidic, oxidizing solution. When it contacts carbonate rock directly, or after passing through the unsaturated zone, progressive increases in the pH, total dissolved solids (TDS), alkalinity and other parameters occur as calcite and dolomite dissolve. The water temperature approaches that of the aquifer it is flowing through until stabilizing when chemical and thermal equilibrium are established. Comparisons of certain physical and chemical parameters are useful in assessing potential flow paths, evaluating regional versus local flow systems, and determining the types of openings ground water is flowing through.

Ground water from wells in the Kittatinny Supergroup (mostly dolomite) will generally have a longer residence time, and therefore should be more chemically mature, than the water discharging from springs in the Shuster Pond area. The Shuster Pond spring has a lower conductivity (median value 313 uS/cm) than Kittatinny ground water (median value 586 uS/cm). Alkalinity values increase from precipitation to spring water to ground water. Bonnie Brook Spring has an alkalinity (median value 162 mg/L as $CaCO_3$) more similar to ground water (median value 165 mg/L as $CaCO_3$). This and other water-quality data suggest that the spring water from Bonnie Brook Spring is more chemically evolved than water from the Shuster Pond spring.

Temperature has been used to differentiate between conduit versus diffuse flow types at springs (Shuster and White, 1971). Water from springs that are mainly recharged by conduit flow systems show seasonal temperature variations, while those from diffuse systems show steady temperatures similar to ground water. Temperature measurements in this study were taken during the summer so conduit fed spring water should be warmer than local ground water. The spring water at Tucker spring (sampling site D, fig. 15) had a temperature of 14.5°C, indicating that it is recharged by conduit flow. At Shuster Pond spring (sampling site F, fig. 15) the temperature was 10.1°C in June and 10°C in August. These temperatures are similar to the coolest ground water and indicate that this spring is fed by a diffuse recharge system. Bonnie Brook spring (sampling site F, fig. 15) had a temperature of 13.9°C in June and 15.3°C in August which indicates recharge from a conduit flow system since it is warmer than the ground water.

Station 3. Outcrop of Allentown Dolomite

Shuster Pond lies in the Allentown Dolomite (fig. 16) which strikes northeast and dips to the northwest. Ground-water flow in carbonate rocks like the Allentown is transmitted by secondary pores, consisting of bedding-plane partings, joints, cleavage, and shear fractures. Many of these features are enlarged by the dissolution of the rock. According to White (1963), solution modified conduits usually follow the dominant joint systems. Davies (1958), in his study of caves in West Virginia, concluded that joints determine the patttems of caves. He found bedding planes and faults of secondary importance in controlling cave directions. Joints connecting with faults showed more cave development.

An analysis of the secondary features within the carbonate rocks in the study area was performed to understand their orientations and relate them to ground water flow (fig. 17). Bedding in the carbonate rocks has a dominant northeast trend, ranging from N. 40-70° E. with an average dip of between 20 and 30 degrees to the northwest. Joint orientations portray a major bidirectional trend with other minor trends. One major trend N. 40-50° E. mimics bedding but has a steep southeast dip. The second dominant trend, E. W. to N. 70° W., is across the strike of bedding. A third trend is oriented nearly north-south.

Joint spacing and aperture are variable. Tightly spaced joints, more appropriately characterized as spaced cleavage, are evident in the immediate vicinity of both Shuster and Bonnie Brook springs. Both north-south and a northeast oritented sets have been identified. The cleavage sets are open and are solution enlarged. Solution cavities observed in outcrop follow beds, individual joints, and bedding/cleavage intersections.

Recharge to the bedrock also occurs through exposed, solution-enlarged joints. High-angle, solution-enlarged joints in the dolomite bedrock in the study area most likely function as the vadose pores of Palmer (1987). Several interconnected joint sets are visible in outcrop, all of which dip at a high angle. These solution joints appear to be well connected to bedding-parallel solution-enlarged fractures. The interconnection between solution-enlarged joints and bedding planes can readily be seen on the dip-slope above Schuster Spring. The most prominent orientation of these joints is north-south and their dip is near vertical.

Station 4. Sinkholes in karst valley

Recharge that occurs within the carbonate terrain has been referred to as autogenic recharge. Autogenic recharge occurs through unconsolidated overburden on top of the carbonate rock, through exposed, open joints and beds, and through sinkholes.

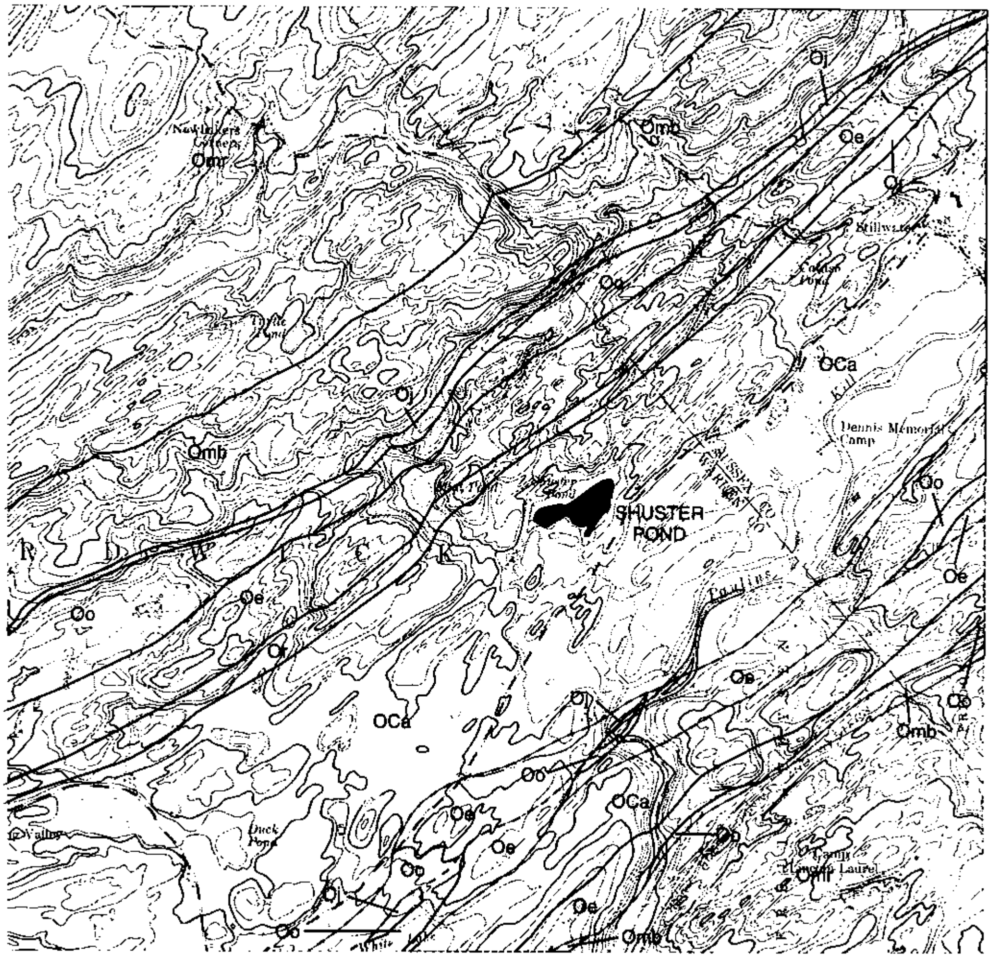


Figure 16.-- Site geologic map of Shuster Pond region from unpublished data of D. Monteverde and G. Herman. Solid lines are unit contacts, dashed lines are faults. OCa- Allentown Dolomite; Or- Rickenbach Dolomite; Oe- Epler Formation; Oo- Ontelaunee Formation; Oj- Jacksonburg Limestone; Omb- Bushkill Member of the Martinsburg Formation; Omr- Ramseyburg Member of the Martinsburg Formation. Topography from Flatbrookville USGS 7.5-minute quadrangle.

Dissolution of carbonate rocks by carbonic acid and humic acid contained in infiltrating water brings about karstification of the bedrock. Through this process the bedrock surface of carbonate aquifers is often characterized by grooves, pinnacles and clefts covered by soil.

The part of the study area underlain by carbonate bedrock has no visible surface streams. A "dry valley" can be seen at the northern end of Schuster Pond. Such dry valleys are typical of karst landscapes. This valley has numerous sinkholes that intercepts surface runoff and provides recharge directly to the conduit systems, which in turn recharge the spring or the pond. Overburden at Shuster Pond consists of a thin layer of late-Wisconsinan glacial till. Thus, it is not likely to store or contribute signficant recharge to the bedrock aquifer.

Several large sinkholes are visible in the valley. These occur along a line that parallels bedrock strike and the trend of the dominant joint set. The sinkholes appear to coalesce. The formation,

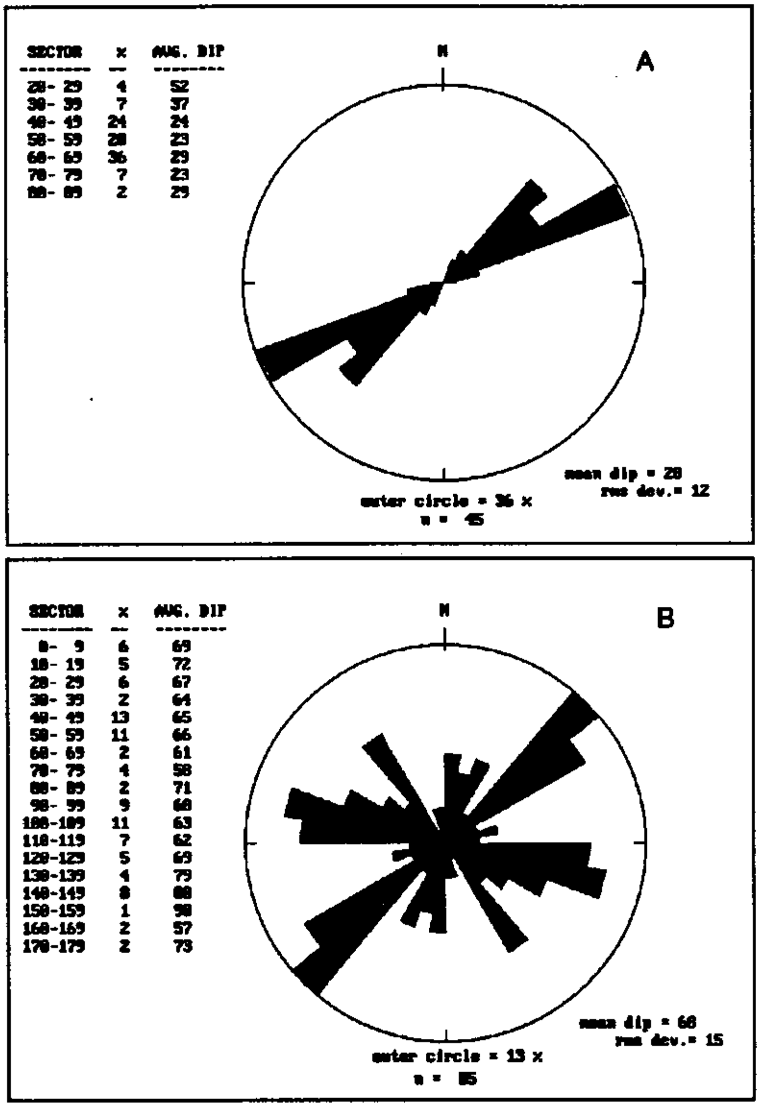


Figure 17.-- Rose diagrams of structural orientation data from the Shuster Pond area collected at the outcrop scale during geologic mapping. A- Bedding trends from the surrounding carbonate rocks. B- Compilation of joint, spaced cleavage and vein trends from the carbonate rocks.

development, and merging of the sinkholes is the dominant erosional mechanism forming this karst valley. This process may provide insights into the formation of Shuster Pond.

Station 5. Pond swallow holes

Shuster Pond drains into a box canyon formed by a resistant ridge of dolomite at its southern end. There, the drainage sinks into the dolomite by way of several swallow holes in the overlying glacial till. Geologic factors suggest that this drainage re-emerges at Bonnie Brook spring, approximately 5000 feet to the northeast of the swallow holes. This connection has been demonstrated by the results of a ground-water tracer test (Dalton, 1976).

The distance from stream disappearance to spring emergence varies greatly in eastern North America, typically ranging from one to a few tens of kilometers (White, 1970). Subsurface flow rates in carbonate aquifers can be substantial. Miller and Skelton (1979) estimated underground flow rates from dye-tracing in an Ordovician dolomite in Missouri. They calculated straight-line velocities of 0.6 to 0.8 kilometers per day from points of submergence to emergence. They point out that the likely presence of tortuous ground-water flow paths probably means that velocities are significantly higher than those calculated. Nutter (1973) suggests flow rates of up to 2000 feet per day in the Nittanny Valley.

Shuster Pond appears to represent a large sinkhole pond formed through the coalescing of karst subsidence features, including sinkholes and possible cavern collapse. The dynamics of this process are evident at the edges of the pond where it is being undermined and the pond is expanding by subsidence of the glacial till mantle. Active sinkholes form at the pond's edge, capturing pond runoff. These sinks enlarge at a relatively rapid rate once the pond begins to drain into them. For example, one of the two principal discharge areas for the pond is a swallow hole at its southeastern edge. Three years ago this swallow hole consisted of a mound of winnowed glacial cobbles. At the date of this publication, the cobble mound has exhibited significant collapse. Several new sinkholes have opened along the pond's southern edge during this period as well.

High-water marks on trees near the swallow holes attest to the severe water-level fluctuations experienced in conduit carbonate systems. Water levels in wells in the carbonate Nittanny Valley of Pennsylvania may rise 30 feet or more to accomodate a single period of snow melt or rain as surface water is recharged via sinkholes (Parizek and others, 1971). At Shuster Pond, the water level in the pond measured on August 6, 1996, was 10.3 feet lower than the high-water mark visible on trees. This high water mark is a result of the flooding caused by melt-off in the spring of 1996.

Bibliography

Anonymous, Report on hydrogeologic conditions associated with Bonnie Brook spring in Stillwater Township, Sussex County, NJ: on file at the offices of the New Jersey Geological Survey, Trenton, N.J. Report may have been performed for Coca-Cola Co., authorship pre-dates 1974, 32 p.

Dalton, R.F., 1976, Caves of New Jersey: New Jersey Geological Survey, Bulletin 70, 51 p.

Dalton, R.F., Canace, R.J., Volkert, R.A., Monteverde, D.H., and Herman, G.C., in press, Bedrock geologic map of the Hamburg quadrangle, Sussex County, New Jersey: New Jersey Geological Survey Open-file Map OFM-xx, scale 1:24,000.

Davies, W.E., 1965, Caverns of West Virginia: West Virginia Geological and Economic Survey, v. XIXA, 330 p., w. supplement.

Ellis, B.M., 1975, The BCRA system of grading cave surveys for probable accuracy: British Cave Research Association Bulletin 6, p. 7

Febroriello, Peter, 1984, Mystery Cave history, policy, and updates: The Northeastern Caver, v. 15, no. 3, p. 45-56.

Getchell, F.L., 1992, Summary of hydrogeologic assessment of the Shuster Pond spring, Mountainwood Spring Water Company, Inc., Hardwick Township, New Jersey: Leggette, Brashears & Graham, Inc., Ramsey, NJ, 14 p., w. appendices.

Jelen, B.P., 1984, Interactive computer graphics and the Mystery Cave survey: The Northeastern Caver, v. 15, no. 3, p. 57-61.

Herman, G.C, 1992, Deep crustal structure and seismic expression of the central Appalachian orogenic belt: Geology, v. 20, p. 275-278.

Herman, G.C., and Monteverde, D.H., 1989, Bedrock structure and balanced cross sections of the Valley and Ridge Province and southwest Highlands area: in, Grossman, I.G., editor, Paleozoic geology of the Kittatinny Valley and southwest Highlands area, N.J., Sixth annual meeting of the Geological Association of New Jersey, Easton, PA, p. 1-57.

Markewicz, F.J., and Dalton, Richard, 1977, Stratigraphy and applied geology of the Lower Paleozoic carbonates in northwestern New Jersey: in, 42nd Annual field conference of Pennsylvania geologists guidebook, Harrisburg, Pa, 117 p.

Miller, Don and Skelton, John, 1979. Tracing subterranean flow of sewage-plant effluent in lower Gasconde Dolomite in the Lebanon area, Missouri: Ground Water, v. 17, no. 5.

Nutter, L.J., 1973. Hydrogeology of the carbonate rocks, Frederick and Hagerstown valleys, Maryland: Maryland Geological Survey, Report of Investigations no. 19.

Palmer, A.N., 1987, Prediction of contaminant paths in karst aquifers: Proceedings, conference on environmental problems in karst terranes and their solutions, Bowling Green, KY, National Water Well Association, Dublin, OH, p. 32-53.

Parizek, R.R., and others, 1971, Hydrogeology and geochemistry of the folded and faulted rocks of the central Appalachian type and related land use problems: Pennsylvania State University Circular 82, Earth and Mineral Sciences Experiment Station, State College, PA.

Rauch, H.W. and White, W.B., 1970, Lithologic controls on the development of solution porosity in carbonate aquifers: Water Resources Research, v. 6, no. 4, p. 1175-1192.

Shuster, E.T. and White, W.B., 1971, Seasonal fluctuations in the chemistry of limestone springs: a possible means of characterizing carbonate aquifers: Journal of Hydrology, v. 14, p. 93-128.

Smart, P.L. and Hobbs, S.L., 1987, Characterization of carbonate aquifers: A conceptual base: Proceedings, Conference on environmental problems in karst terranes and their solutions, Bowling Green, KY, National Water Well Association, Dublin, OH, p. 1-14.

Stanford, S.D., and Harper, D.P., 1985, Reconnaissance map of the glacial geology of the Hamburg quadrangle, New Jersey: New Jersey Geological Survey, Geologic Map Series, GMS 85-1, scale 1:24,000.

Stanford, S.D., Witte, R.W., and Harper, D.P., 1990, Hydrogeologic character and thickness of the glacial sediment of New Jersey: New Jersey Geological Survey, Open-file Map Series, OFM-3, scale 1:100,000.

White, W.B., 1963, Conceptual models for carbonate aquifers: National Speleological Society Bulletin, v. 25, part 2, p. 15-21.

White, W.B. and Rauch, H.W., 1970, Lithologic controls on the development of solution porosity in carbonate aquifers: Water Resources Research, v. 6, no. 4, p. 1175-1192.