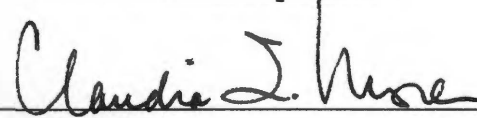


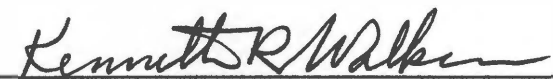
To the Graduate Council:

I am submitting herewith a thesis written by Sara Elizabeth Humbert entitled " Subaerial Paleokarst in Upper Pennington Formation (Upper Mississippian) Limestones at Leatherwood Ford, Big South Fork, Tennessee." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.


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We have read this thesis and
recommend its acceptance:


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Subaerial Paleokarst in the Upper Pennington Formation (Upper
Mississippian) Limestones At Leatherwood Ford, Big South Fork,
Tennessee

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Sara Elizabeth Humbert
May 2001

Dedication

This thesis is dedicated to my family:
Daddy, Mama, Christian, Neil,
Grandmother, Aunt Jo

Thank you.

Acknowledgments

This thesis could never have been written without the assistance of many different people. I wish to thank my advisor, Dr. Steven G. Driese, for his patience in this slow process, and Drs. Claudia I. Mora and Kenneth R. Walker, for their input as committee members. I would also like to thank my Clemson mentor, Dr. James Castle, who taught me to love 'soft rocks.' The staff at Big South Fork, particularly Mr. Robert Emmott, is also to be thanked for allowing me to do research in the park.

I appreciate the support I have received from the department, and wish to particularly to thank Marvin Bennett for his never failing help and encouragement; The secretaries, Denise, Teresa, and Melody, for whom I will always make an excuse to procrastinate, due to their constant and catching good humor; Dr. Misra for his pride in my accomplishments; and all of the computer gurus who spared me the pain of lost data and a lost mind.

Thanks to Pete Nester, who stands strong, even today, in the full blast of Hurricane Elizabeth (Of course, he always was a weather nerd). Thanks to Mike Wyatt for stories, allegories, and positive reinforcement. I thank my *hip-sister* – Janna Peevler – for helping me keep all my eggs in one basket, and my eye on the Target. I must also thank Dave King, Heather Gastineau, Amy Robinson, Dana Miller, Valerie Hale, Dee Dee Bruner, and Janee Ansley, for being such an indispensable support group. Without them I would never have finished this thesis (although without them, I might have finished sooner).

Finally, I wish to thank Parisian Department stores, who kindly gave me a job and who sent me screaming back toward grad school.

Abstract

The uppermost Pennington Formation (Mississippian - latest Chesterian) consists of limestone deposits, which, in some areas, contain evidence of paleokarst. A 100 m long continuous outcrop of the upper Pennington Formation was studied at Big South Fork National River and Recreation Area, in Scott County, Tennessee, using both field and petrographic methods, in order to test the hypothesis that the paleokarst is of subaerial origin.

The upper Pennington limestone section was subdivided into 4 depositional units, interpreted as recording sea-level change through the end of the Mississippian. Although there was an overall regression toward the end of the Mississippian, changes from unit 1 – a brecciated dolomicrite that reflects minor exposure, to unit 2 – a skeletal packstone that reflects a flooding surface, indicate a slight transgression that began lagoon development in this area. Unit 3 – a peloidal wackestone to packstone, reflects the growth and the entrenchment of the lagoon, whereas unit 4 – a peloidal-skeletal grainstone, reflects the demise of the lagoon due to regression, after which the upper Pennington limestone was subaerially exposed.

Paleokarst features associated with this period of subaerial exposure were mapped and catalogued according to three scales of features: macroscale, mesoscale, and microscale. Macroscale refers to major features expressed as paleotopographic variation along the exposure surface, such as paleo-dolines, the largest of which has a width of approximately 30m, and a depth of 4m. Other features include a shallow and flat-floored kamenitza with a width of 7m and a depth of only 0.5m. Mesoscale features include mantling limestone breccia-conglomerate, red and green claystone paleosols, limestone breccia clasts, and iron

oxide and oxy-hydroxide crusts. Microscale features include meteoric cements, grain micritization, reddening of the limestone, and extensive pore development.

Five phases of paleokarst are recognized: Phase 1 included the initial development of paleokarst features, particularly at the microscale. Phase 2 was the development of the macroscale paleo-dolines and paleo-kamenitzas. Phase 3 occurred as soil and vegetation developed on the karst plain. Phase 4 was marked by pulses of early Pennsylvanian sedimentation, in which paleo-channels developed, and mantling deposits, including a residual breccia-conglomerate, began to drape exposed limestone, and collapse at the paleo-exposure surface occurred. Finally, phase 5 involved the movement of reducing fluids along the unconformity and the precipitation of burial cements.

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I. Introduction

The Pennington Formation (Upper Mississippian, uppermost Chesterian) is a mixed siliciclastic-carbonate sequence, composed of dolostone, limestone, fine-grained sandstone, variegated (red, green, and gray) shale, and claystone beds, some of which are interpreted to be paleosols (Milici, 1974; Caudill et al., 1992, 1996). This Formation appears to represent a transitional depositional unit between Upper Mississippian carbonates deposited in a shallow-marine environment (Bangor Limestone) and Lower Pennsylvanian rocks consisting of shale that coarsens upward into thick Pennsylvanian fluvio-deltaic sandstones (Gizzard Group - includes Raccoon Mountain Formation and Warren Point Sandstone) (Fig. 1).

The focus of this study is an upper Pennington limestone member, which is as yet unnamed. This subtidal to intertidal marine carbonate sequence is approximately four to five meters thick, but generally crops out in thinner stratigraphic sections, or not at all, due to removal along an erosive unconformity that occurs between the Mississippian and Pennsylvanian lithofacies. This unconformity is the primary focus of this project. Below the unconformity the upper Pennington limestone shows paleokarst features, including paleo-dolines (sink-holes), paleo-kamenitzas (shallow solution pits), paleosols, as well as other features associated with a paleo-dissolution surface.

This study will examine the hypothesis that the paleokarst found at the erosional unconformity above the upper Pennington limestone member is subaerial in nature through:

1. Detailed study of the depositional history of the upper Pennington limestone, focusing on documentation of the sedimentology and stratigraphy.
2. Petrographic study of both depositional features and features associated with

Mississippian	Pennsylvanian	Morrowan	Gizzard Group	Sewanee Conglomerate
				Signal Point Shale
				Warren Point Sandstone
				Raccoon Mountain Formation
	Chesterian			? ? ? ? ? ?
				Pennington Formation
				Bangor Limestone
				Hartselle Sandstone
				Monteagle Limestone

Figure 1: Generalized stratigraphic column for east-central Tennessee. Question marks reflect the fact that the precise position of the boundary is not resolvable biostratigraphically.

subaerial exposure and early meteoric diagenesis.

3. Cataloguing each paleokarst feature at the unconformity in terms of dissolution type and scale.
4. Determination of a relative timing of events - from deposition and early diagenesis through subsequent subaerial exposure and karstification.

A. Study Area

The study area is located on the Cumberland Plateau (Fig. 2), in Scott County near Oneida, Tennessee. All of the research was conducted within the Big South Fork National River and Recreation Area located on the Kentucky-Tennessee border (Fig. 3). The outcrop section is found at the Leatherwood Ford locality, where Quaternary fluvial incision has cut through the relatively resistant Pennsylvanian sandstones and has exposed the underlying Upper Mississippian Pennington Formation. No additional outcrops with the features necessary to this study were identified, thus all of the research for this study was conducted at the Leatherwood Ford locality.

B. Research Relevance

This research was undertaken for several reasons. The primary motivation for the study involves uncertainty about the timing and duration of the systemic unconformity at the Mississippian-Pennsylvanian boundary. This includes problems pertaining to correlation of Upper Mississippian and Lower Pennsylvanian strata straddling the unconformity. The temporal and lithostratigraphic relationships between the upper Pennington paleokarst and the enclosing strata could lead to a new understanding of the Mississippian-Pennsylvanian unconformity in this area. The second reason for this study is the question of upper Pennington paleokarst origin. Paleokarst can form in several different ways, as is discussed

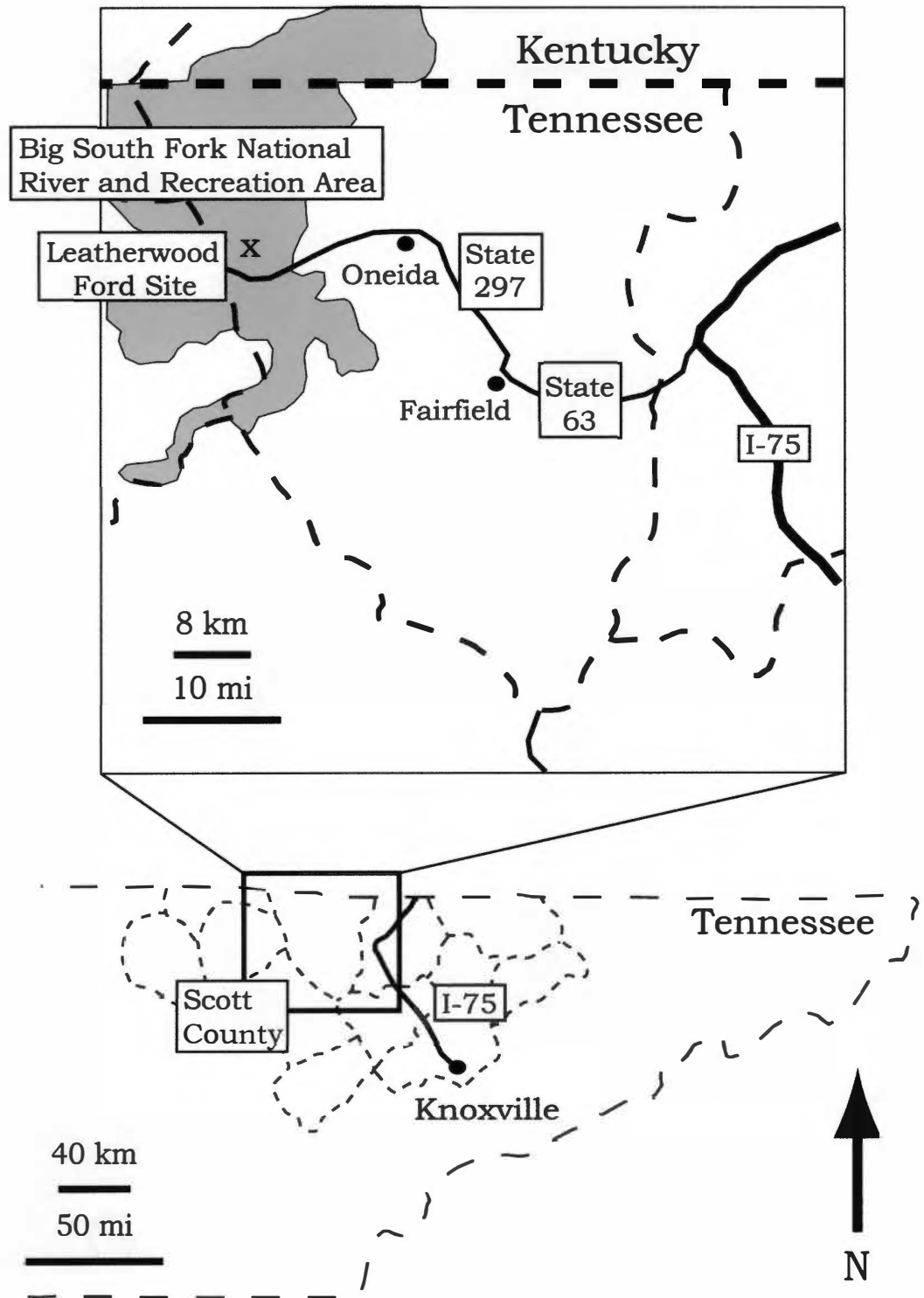


Figure 2: Location of field area, with respect to the State of Tennessee and Scott County. Dashed lines indicate state and county boundaries, plain lines indicate roads.

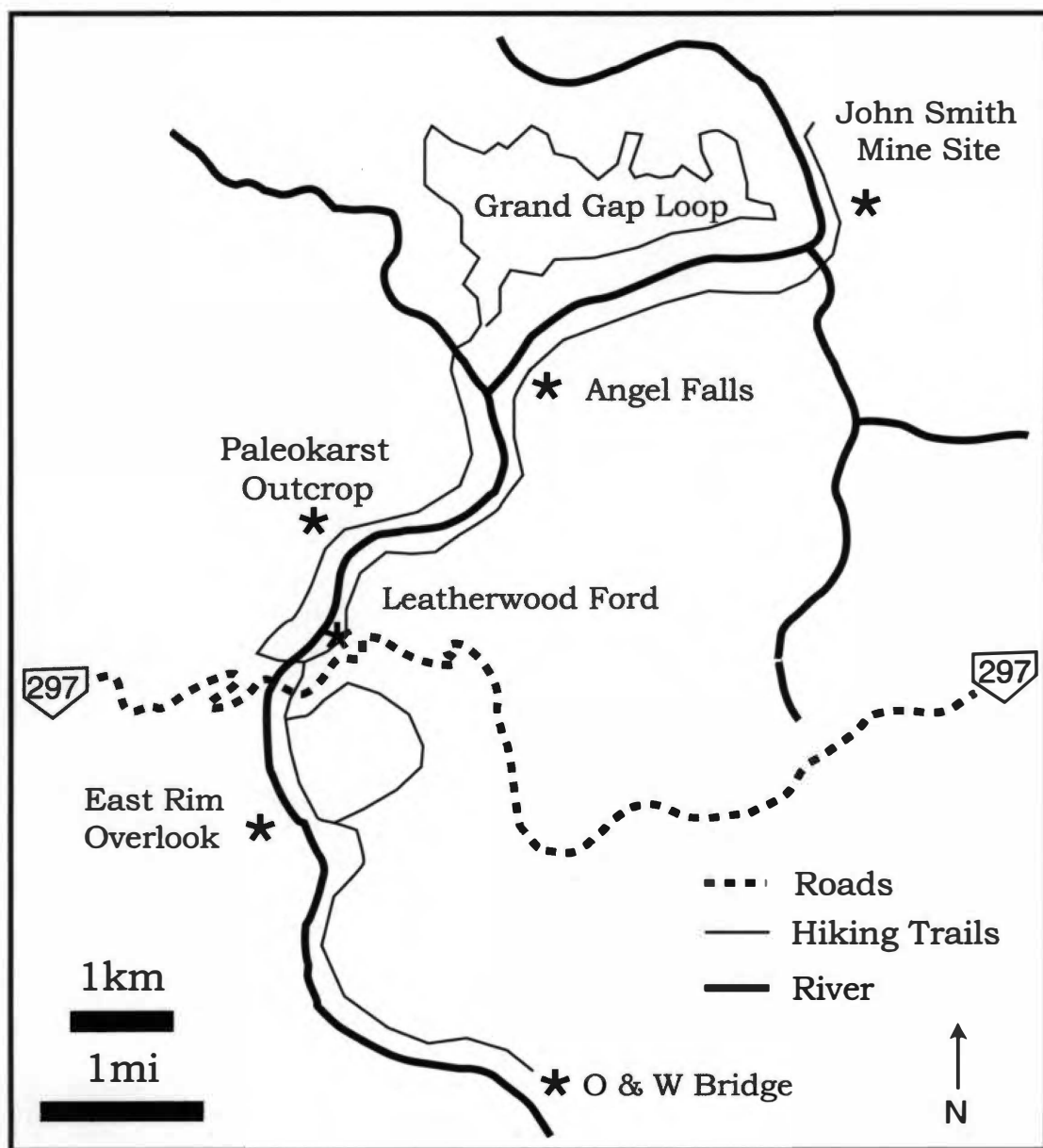


Figure 3: Location of outcrop within Big South Fork National River and Recreation Area. Adapted from Deaver and Smith (1999).

below. In order to differentiate between these mechanisms, it is necessary to document paleo-landforms and associated features, as well to utilize comparisons with other geologic areas of similar age or depositional conditions. Lastly, karstification and the development of an unconformity typically produce increased porosity (initially), which is of interest to petroleum exploration and production.

1. Mississippian-Pennsylvanian Boundary Quandary

The nature of the Mississippian-Pennsylvanian unconformity within the Appalachian Basin has long been controversial. There is a question as to whether or not this erosional surface is, in fact, a regional unconformity. Many studies support its interpretation as a systemic boundary associated with a global eustatic event, which caused sea level to drop. Worldwide subaerial exposure of Mississippian strata (Saunders and Ramsbottom, 1986) formed the systemic unconformity between Mississippian and Pennsylvanian strata. Other studies interpret the Pennington Formation as a “complexly intertongued sequence” (Ferm, 1971; 1974; Home, 1974), deposited in an area receiving continuous sedimentation throughout Late Mississippian and Early Pennsylvanian time.

More recent research supports the presence of a widespread unconformity, but considers the timing of exposure and the causal mechanisms of eustatic change to be completely different. Ettensohn and Chestnut (1989) and Ettensohn (1992) hypothesized that a tectonic fore-bulge developed in this area due to an early Pennsylvanian phase of the Alleghenian Orogeny. As the bulge migrated cratonward (to the northwest), it caused subaerial exposure and erosion of the Mississippian strata.

The distribution in space and time of a systemic unconformity should be directly related to basin configuration, as well as to interactions with local synsedimentary tectonic

processes (Fisher, 1978) (Fig. 4). According to certain authors (Englund, 1964; Englund and Delaney, 1966; Dennison and Wheeler, 1975), the central Appalachian basin experienced constant sedimentation during the Mississippian and Pennsylvanian, ensuring a conformable contact between the Pennington and overlying Pennsylvanian strata. Peripheral areas located on the edge of the basin, however, should have been more prone to exposure and erosion of the Upper Mississippian Pennington Formation (Colton, 1970; Pryor and Sable, 1974; Dennison and Wheeler, 1975).

Another major problem associated with defining the nature of this surface is the correlation of rocks on either side of the boundary in this area, particularly within the Upper Mississippian Pennington Formation and the Lower Pennsylvanian Gizzard Group. Variable stratigraphic thicknesses and the difficulties in correlating basal Pennsylvanian strata (Driese et al., 1998), may be directly related to the presence of an unconformity. Driese et al. (1998) suggested that subaerial exposure and subsequent karstification caused major variation in paleo-topographic relief, due to Mississippian carbonate removal and collapse. This would account for confusion about the stratigraphy of the rocks that straddle the Mississippian-Pennsylvanian boundary.

2. Intrastratal vs. Subaerial Karst

Paleokarst affecting rocks of the same age as the studied section (Upper Mississippian to Lower Pennsylvanian = Lower Carboniferous to Upper Carboniferous transition) occur in southern Wales, where they are interpreted to have had a different mode of formation. Whereas Upper Mississippian Pennington paleokarst is hypothesized to form by subaerial exposure, the southern Wales paleokarst appears to have formed due to intrastratal processes. There, water percolated through the overlying sandstone, and began

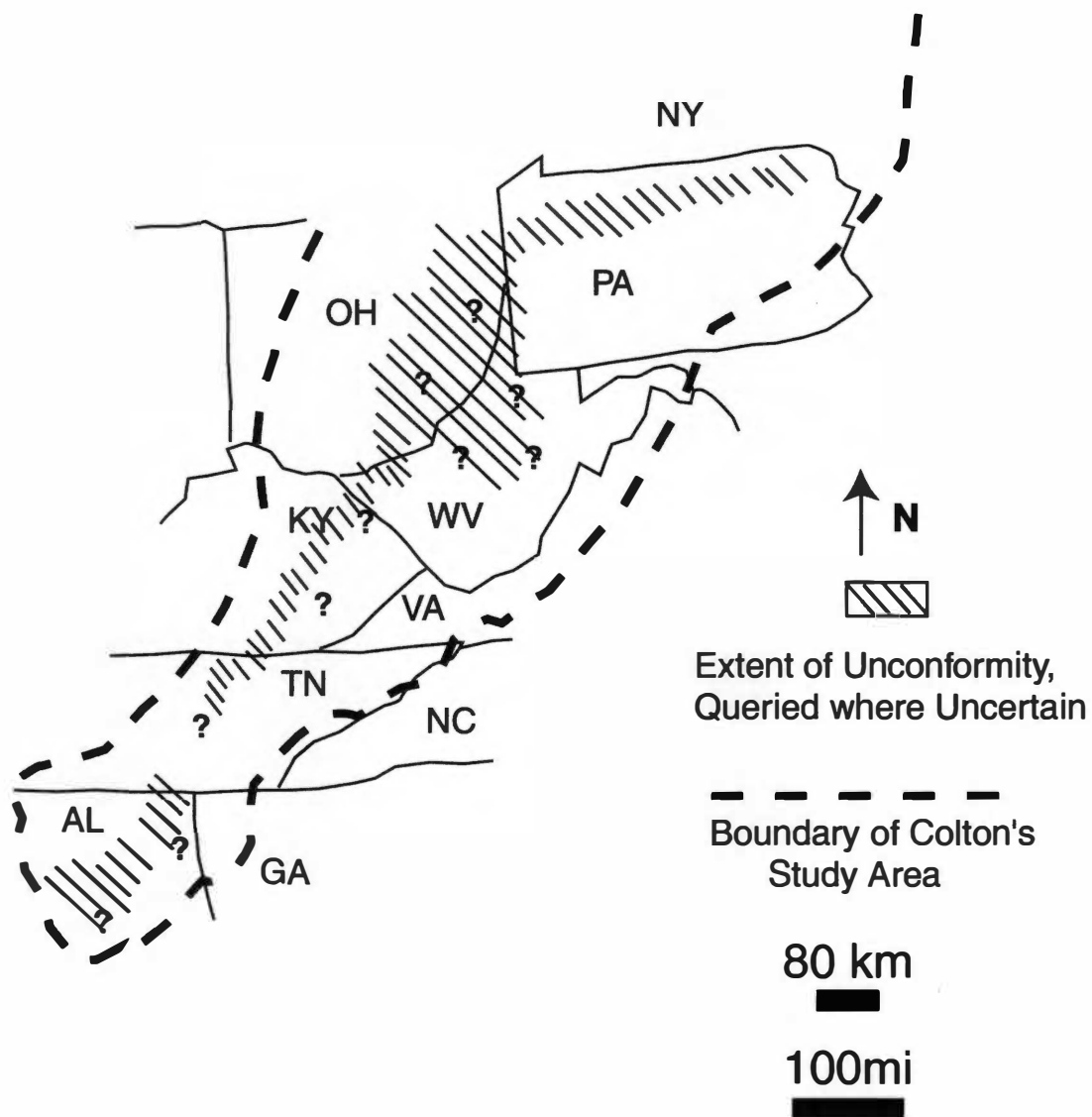


Figure 4: Extent of Mississippian-Pennsylvanian unconformity within the Appalachian Basin. Adapted from Colton (1970).

dissolution on limestones in the subsurface, at the contact between the two units (Burke, 1966).

Intrastratal karstification can be confused with subaerial karst due to a similar surface geomorphic expression. Sinkhole (doline) forms are common in both, with the intrastratal forms mimicking the features formed at the surface (Wright, 1982). The following are criteria suggested by Wright (1982), which aid in the differentiation of subaerial and intrastratal karst (Additional information is given in Table 1).

1. Subaerial exposure- related paleokarst would generally be overlain by paleosols or other alluvial deposits. Affected carbonates will show physical characteristics, such as vadose or meteoric cements, indicating exposure.
2. Subaerial paleokarst should be truncated by overlying beds, indicating dissolution before burial.
3. Subaerial paleokarst should be overlain by beds that show no sign of solution conduits connected to the paleokarst surface.
4. Subaerial paleokarst should be overlain by beds that show no sign of collapse into dissolutional features within affected carbonate.

3. Unconformities and Porosity

Unconformities are important to petroleum geologists due to common association of changes in porosity and permeability at and near the exposed surface. According to Budd et al. (1995), dissolution associated with subaerial exposure accounts for much of the secondary porosity in carbonate reservoirs comprising major oil and gas fields throughout the world. Although dissolution associated with subaerial exposure does not directly increase total subsurface porosity, it increases permeability by rearranging pore space (Saller et al., 1994).

Table 1 - Summary of possible features indicative of subaerial exposure.
(Adapted from Choquette and James (1988), and Driese et al. (1998)).

Indicators for Subaerial Exposure		
Stratigraphic - Geomorphic	Macroscale	Microscale
Dolines (sinks)	Rundkarren	Illuviated soil material in soil pores.
Towers (pinnacles)	Kamenitzas	
	Phytokarst	Etched cements
Unconformities	Caliche (calcrete)	Reddened and micritized grains
Shallowing - upward cycles	Terra Rossa - red claystone paleosol mantle	
	Red clay - iron oxide fracture fill and reddening of limestone at surface	Extensive dissolution, or enlarged, fabric selective pores.
	Mantling breccia	

C. Methods

Fieldwork began with preparation of a photomosaic of the approximately 100m horizontal outcrop section. Paleokarst features were measured and photographed in order to catalogue their geometry and type. Using a photomosaic and a rudimentary hand-leveled survey, a representative cross section was drawn (Figure 5). It shows varying thickness and relief of the limestone section, as well as the larger paleokarst features.

Six vertical transects (Figure 5), each 2 to 4 meters thickness, were measured, then sampled approximately every 0.5 meters. Figure 6 shows columns representing the five different stratigraphic columns measured and described, and indicates where each sample was collected. Samples were also taken from the base of the paleo-doline, from areas of collapse, and from areas with a limestone breccia mantle.

Approximately 50 oriented hand-samples were collected for laboratory analysis. Most samples were ~6 cm in diameter, although some were as large as 20 cm. From the hand samples, thin sections were prepared for 40 samples in order to discern vertical petrographic and lithologic changes within the Pennington Limestone. Twelve of these were stained using Alizarin Red S and Potassium Ferricyanide (Dickson, 1966) in order to differentiate calcite and dolomite.

General petrography, undertaken in order to gain information about mineralogy and allochemical composition, was supplemented by cathodoluminescence (CL) petrography. This technique was done on a Technosyn luminoscope, using an accelerating potential of 10-12 KeV and beam current of 150-200 μ a. Reflected light petrography was also used to identify opaque mineral phases.

Six samples were selected to discern terrigenous sand, silt, and clay percentages.

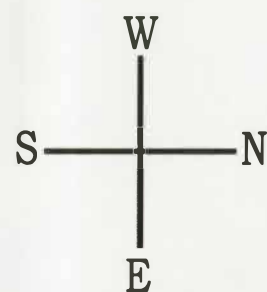
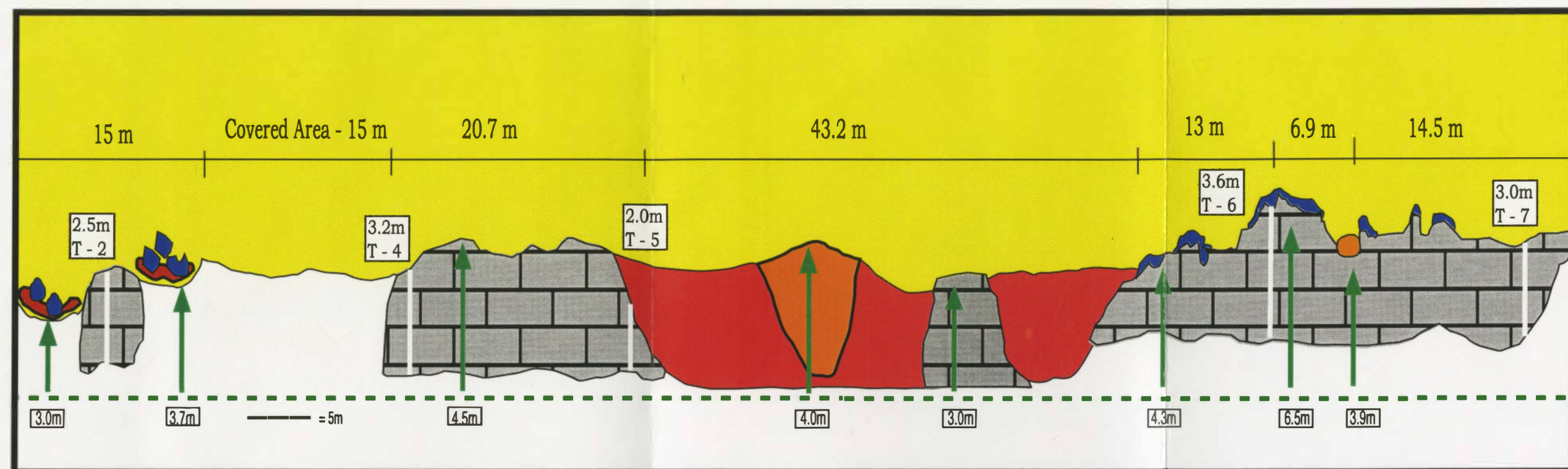
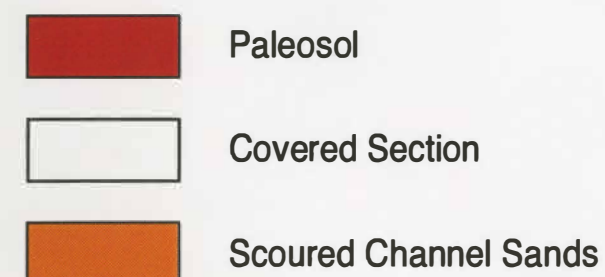
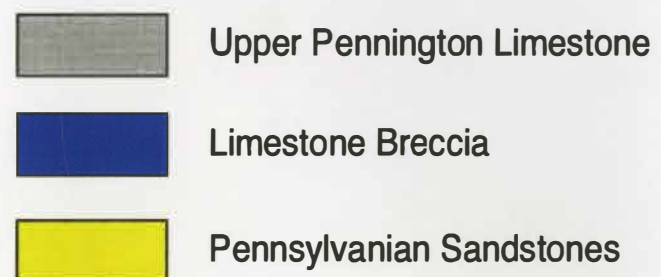
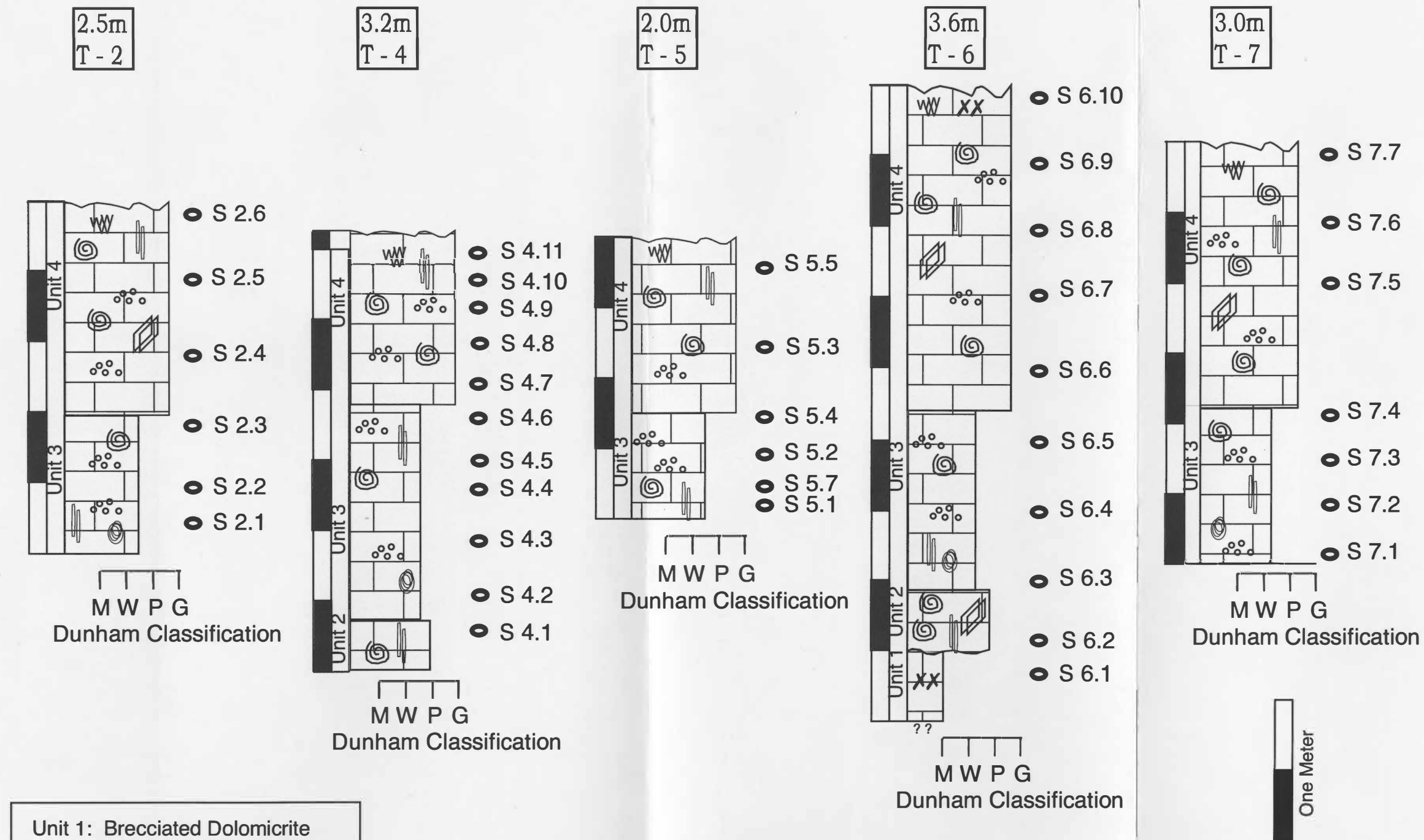


Figure 5: An interpretive illustration of the Leatherwood Ford outcrop in cross section; note the paleo-topographic variation and karst features. Horizontal plane to scale, some vertical exaggeration. Green arrows indicate thickness of upper Pennington limestone based on green dashed datum line. White lines indicate transects. Transect boxes include thickness of limestone sampled and transect number.





Unit 1: Brecciated Dolomicrite

Unit 2: Skeletal Packstone

Unit 3: Peloidal Pack-Wackestone

Unit 4: Peloidal / Fossiliferous
Pack-Grainstone

○ Oncoid

W Siderite/Hematite

|| Bioturbation

XX Brecciation

○○○ Peloids / Cortoids

◎ Skeletal Allochems

▧ Intraclasts

Figure 6: Stratigraphic columns for the Upper Pennington Limestone. Based on transects seen in Figure 5. Transect boxes include thickness of limestone sampled and transect number. For Dunham classification: M - mudstone, W - wackestone, P - packstone, G - grainstone.

These samples were selected from each of the four identified lithologic units within transect 6 (refer to Figs. 5 and 6). Samples were ground to a fine powder using a mortar and pestle, then treated repeatedly with a ten- percent hydrochloric acid solution. After dissolving all available carbonate, the solutions were filtered using glass fiber filters, capturing insoluble particles $>0.25\ \mu\text{m}$. The filters were weighed before and after the collection of particles on an Ohaus triple beam balance. Samples chosen for dissolution, and accompanying results are seen in Table 2.

D. Previous Work and Geologic Setting

The Pennington Formation was originally named the Pennington Shale by Campbell (1893), who documented exposures in Pennington Gap, Lee County, Virginia. These exposures were never officially measured, and the reference section - designated as units between the Newman Limestone (Bangor Equivalent) and the Lee Conglomerate of Pennsylvanian age - is actually found at Big Stone Gap, Wise County, Virginia, where the Pennington is 312.6 m thick (Campbell, 1893). The usage of the name was extended to Tennessee's Valley and Ridge in 1894 by Campbell, and in 1899 to rocks Keith (1896) deemed equivalent on the eastern rim of the Cumberland Plateau.

The Pennington Formation is exposed in two outcrop belts, which trend through West Virginia, Virginia, Tennessee, Kentucky, and Alabama (Fig. 7). The belts are subparallel to each other, and are separated by as much as 200 km width of Pennsylvanian rocks. The Pennington Formation is a heterogeneous unit dominated by shales, and lesser amounts of sandstone, siltstone, dolostone, and limestone (Ettensohn and Chestnut, 1985). The age is considered to be late Chesterian, palynology by Ettensohn and Peppers (1979).

Table 2: Table of carbonate insoluble percentages and insoluble material type from six samples within the Upper Pennington Limestone.

Dissolution Analyses of Six Samples				
Sample	Unit	Weight of entire sample	Weight % of insoluble material	Description of insoluble material
6.1	1	1.18g	23%	78% clays 15% quartz silt 7% iron oxides
6.2	2	0.60g	12%	75% clay 20% quartz 5% iron oxides
6.3	3	0.43g	8.6%	85% clay 13% quartz 2% iron oxides
6.5	3	0.15g	3.0%	87% clay 7% quartz 6% iron oxides
6.7	4	0.38g	7.6%	89% clay 08% iron oxides 3% quartz
6.9	4	0.22g	4.4%	55% iron oxides 43% clay 2% quartz

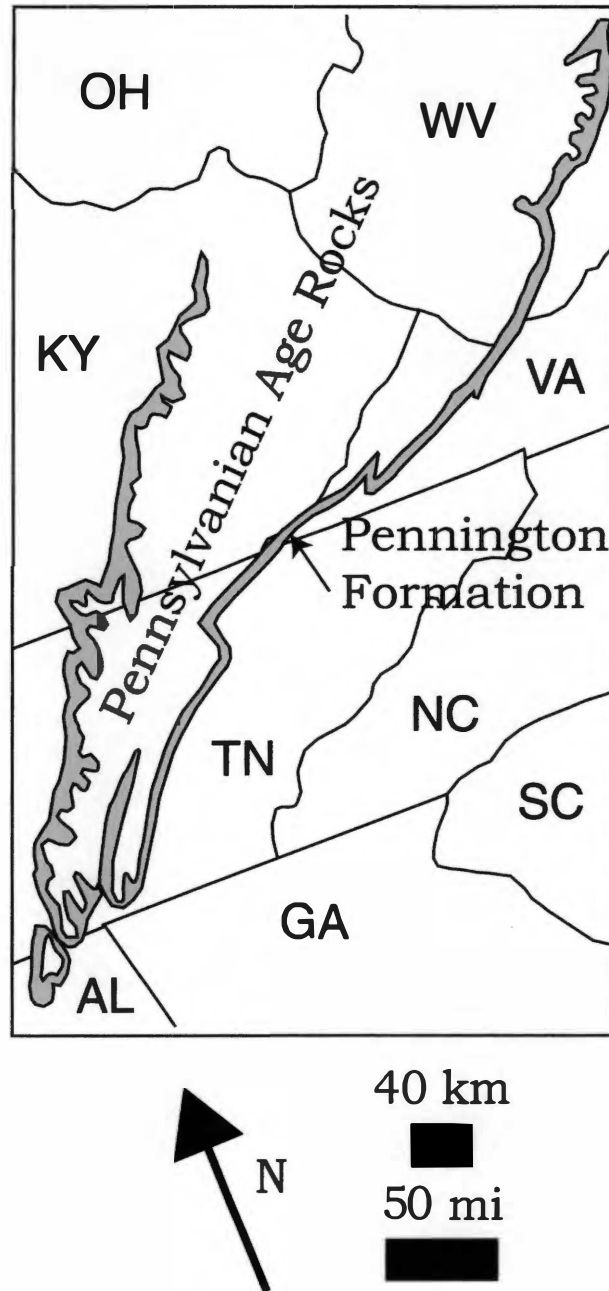


Figure 7: Pennington outcrop belts. (Adapted from Ettensohn et al., 1985.)

The Pennington is correlative with the Mauch Chunk Formation of Pennsylvania and West Virginia (Dennison and Wheeler, 1972). Generally outcrops are poor, due to the abundance of easily eroded shales and the presence of many discontinuous lithologic units. In upper East Tennessee, the Pennington Formation gradationally overlies the Bangor Limestone (Algeo and Rich, 1992), with a thickness that ranges from 30 to 150 m (Milici et al., 1979). The regional lithostratigraphic variation is manifest by thinning deposits seen from east to west, as the carbonate shelf to the west was slowly smothered by terrigenous clastics derived from an eastern source. The Pennington Formation is disconformably overlain by the Warren Point Sandstone, and locally by Pennsylvanian Raccoon Mountain Formation shale and silty sandstone (Hurd and Stapor, 1997).

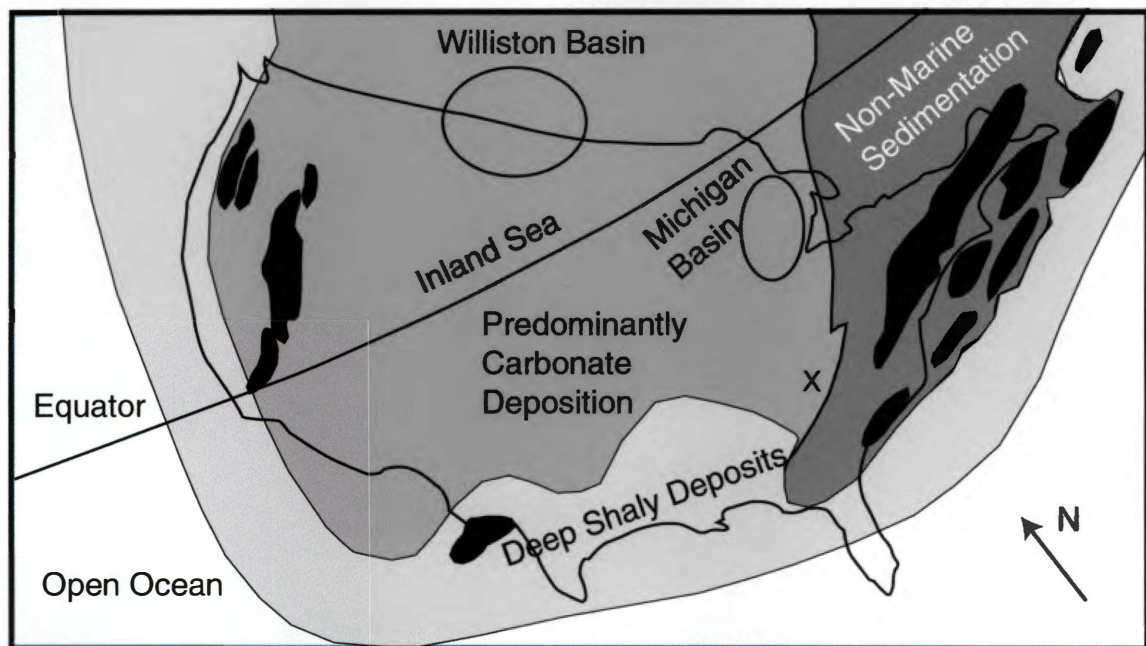
The Pennington Formation represents a wide array of paleo-environments. According to Ettensohn (1985), the Pennington Formation represents the distal edge of a clastic progradation in the very late Mississippian (Chesterian). He subdivided the Pennington into four members, which consist of a lower dark shale member followed by a clastic or dolostone member, overlain by a limestone member, and finally an upper shale member. These members are interpreted to record changes from a rather deep, quiet lagoon facies to a tidal flat assemblage. Although a transgression is reflected in the limestone member, the limestone is capped by muddy clastic tidal flat deposits, indicative of increased terrigenous sediment transport from the east.

The carbonate lithofacies, which are of special interest in this project, represent a variety of environments, which are punctuated by repeated periods of subaerial exposure and pedogenesis (Bergenback et al., 1972, Milici et al., 1979, Caudill et al., 1992, 1996). Frazier (1973) detailed the petrography and environmental synthesis for the Pennington Formation

carbonate deposits. He identified five specific environments for the deposits, including supratidal flat, lagoon, marsh, shallow marine, and littoral or intertidal environments.

Clearly, the Pennington Formation is an excellent example of a transitional mixed carbonate-siliciclastic sequence, which reflects environmental changes triggered by changing tectonic regimes throughout Middle and Late Mississippian time, into the Pennsylvanian. The Acadian Orogeny had ended by the Middle Mississippian, allowing for carbonate deposition to spread from the Appalachian Basin onto the craton (Williams and Hatcher, 1982). By latest Mississippian time, the beginning of the Alleghenian Orogeny is recorded by increased subsidence and progradation of the Mauch Chunk-Pennington clastic wedge. Late Mississippian paleogeographic reconstruction of North America is shown in Figure 8.

Tectonic activity played an active role in both deposition of the Pennington Formation and removal. The associated unconformity separates the Mississippian Pennington Formation and overlying Pennsylvanian strata. The unconformity does not have a simple explanation, and due to poor biostratigraphic constraint, questions persist as to its age and genesis. Ettensohn (1989) suggested that the unconformity is a product of Early Pennsylvanian erosion, produced by a northwest migrating peripheral bulge associated with early stages of the Alleghenian orogeny. Others contend that the unconformity is associated with a major worldwide mid-Carboniferous eustatic event (Saunders and Ramsbottom, 1986). Though not all agree as to the formation and timing of the unconformity, an erosive surface is indisputably seen at the top of the exposed Pennington Formation. It was therefore earlier suggested that this is a subaerial exposure surface that is associated with paleokarst (Driese et al., 1998).



120 km

 150 mi

Figure 8: Paleogeography of United States during Mississippian times. X indicates study area locality (OTS Heavy Oil Science Center, 1999).

II. Depositional Systems: Upper Pennington Limestone

A. Introduction

Although this thesis is primarily concerned with the formation of hypothesized subaerial exposure features in the Upper Pennington limestone, it is necessary to take a closer look at the limestone itself. This affords a better understanding of the depositional systems that led to subaerial exposure and karstification. Detailed facies examination of the 4m thick limestone section provides paleoenvironmental interpretations that constrain paleokarst interpretations. It will be shown in this section, through descriptions, interpretations, and finally a synthesis, that this package of limestone deposits illustrates a shallowing-upward trend. The stage is set by depositional unit 1, which is included to show the complex nature of deposition and repeated subaerial exposure during the late Mississippian. As a transitional sequence, the Pennington Formation was easily influenced by small-scale changes in sedimentation and sea level. The small portion of the Pennington studied in this research illustrates the nature of these changes through a drop in clastic sedimentation, a rise in sea level, and a resumption of carbonate production.

In this study of the Upper Pennington limestone, fluctuations in the aforementioned factors are small, but enough to change depositional patterns radically. Figure 6 shows the interpreted lithostratigraphy. Appendix 1 is included from field notes taken at the Leatherwood outcrop, and Appendix 2 is specific percentages of allochems and orthochems determined for each sample using petrography. In some cases, units were delineated by microfacies due to difficulty in hand sample lithologic differentiation

B. Description of Depositional Units and Lithofacies

1. Unit 1 – Dolomitic Mudstone

Depositional Unit 1, a brecciated dolomitic mudstone, occurs beneath the Upper Pennington limestone member. Total thickness is unknown because less than 0.2m is exposed (Fig. 9a) due to basal coverage. Although Unit 1 is not genetically related to the upper Pennington limestone section and is physically separated by an erosional sequence boundary, it sets the stage for the deposition of the upper Pennington limestone.

Unit 1 consists of a highly brecciated, non-ferroan dolomicrite, which is olive green in color. The dolomicritic matrix is massive and crosscut by brecciation (Fig. 9b), evidenced as cracks in the matrix. These occur throughout the sample in lengths ranging from 0.5 to 1.0 mm, and are occasionally lined or filled with clay or silt (Fig. 9c). The fractures tend to follow horizontal planes, although intersecting vertical fractures are not uncommon. Iron oxide staining (Fig 9d), when present, follows the fractures almost exclusively. Fractures are generally filled by a blocky, ferroan, dolospar cement, which has straight crystal faces, non-undulose extinction, and a drusy fabric.

Unit 1 does not contain any obvious skeletal allochems. Intra-clasts (within the brecciated matrix) and rounded dolomitic peloidal nodules are present. The intraclasts consist of a dolomicritic material that is darker than the brecciated matrix (Fig. 9e), and are selectively brecciated. The intraclasts range from 0.15 - 0.5 mm in diameter, and the secondary fracturing cuts across the thinnest portion of the clast in parallel, regularly spaced intervals. The peloidal nodules, which are 0.1 - 0.25 mm in diameter, are the same color and texture as the dolomitic matrix, making the two difficult to differentiate. The pellet-nodules are more easily identified when they are rimmed by circumgranular dolo-microspar (Fig. 9f

Figure 9 - Photograph and Photomicrographs of petrographic features taken in plane light of Unit 1, a brecciated dolomicrite exposure surface. Photos a, b, c, d, e, f, and g.

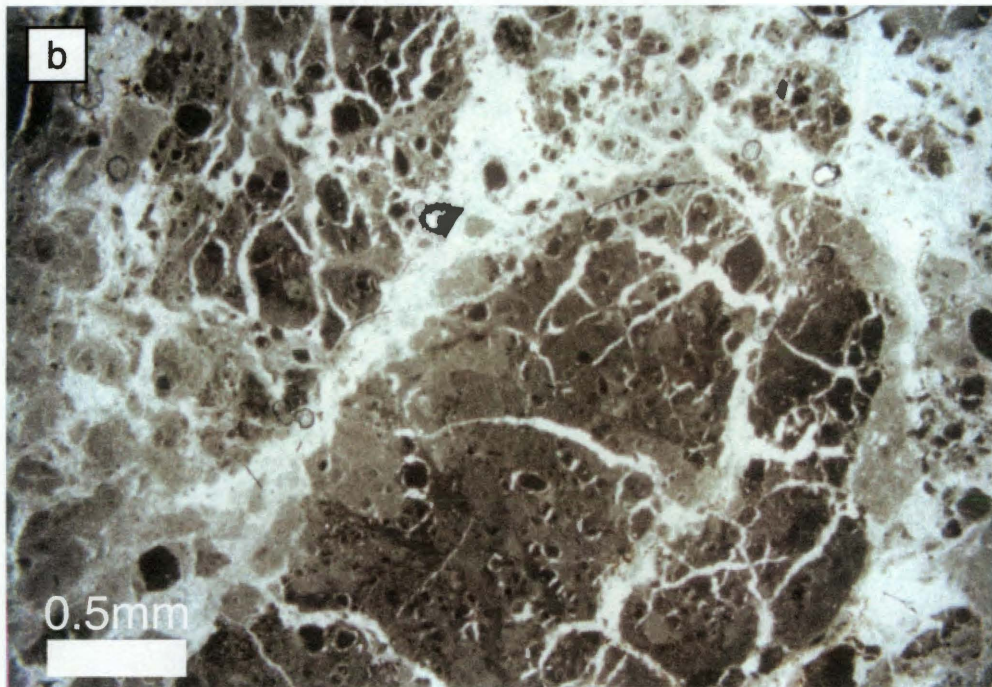


Figure 9 - Photograph and photomicrographs of petrographic features taken in plane light of Unit 1. Figure 9a - Unit 1: Exposure of brecciated dolomitic mudstone, occurring beneath Upper Pennington Limestone in transect 6. Figure 9b - Unit1: Pre-upper Pennington Limestone section dolomiticrite. Photomicrograph shows extreme brecciation of large clasts, which are internally brecciated as well.

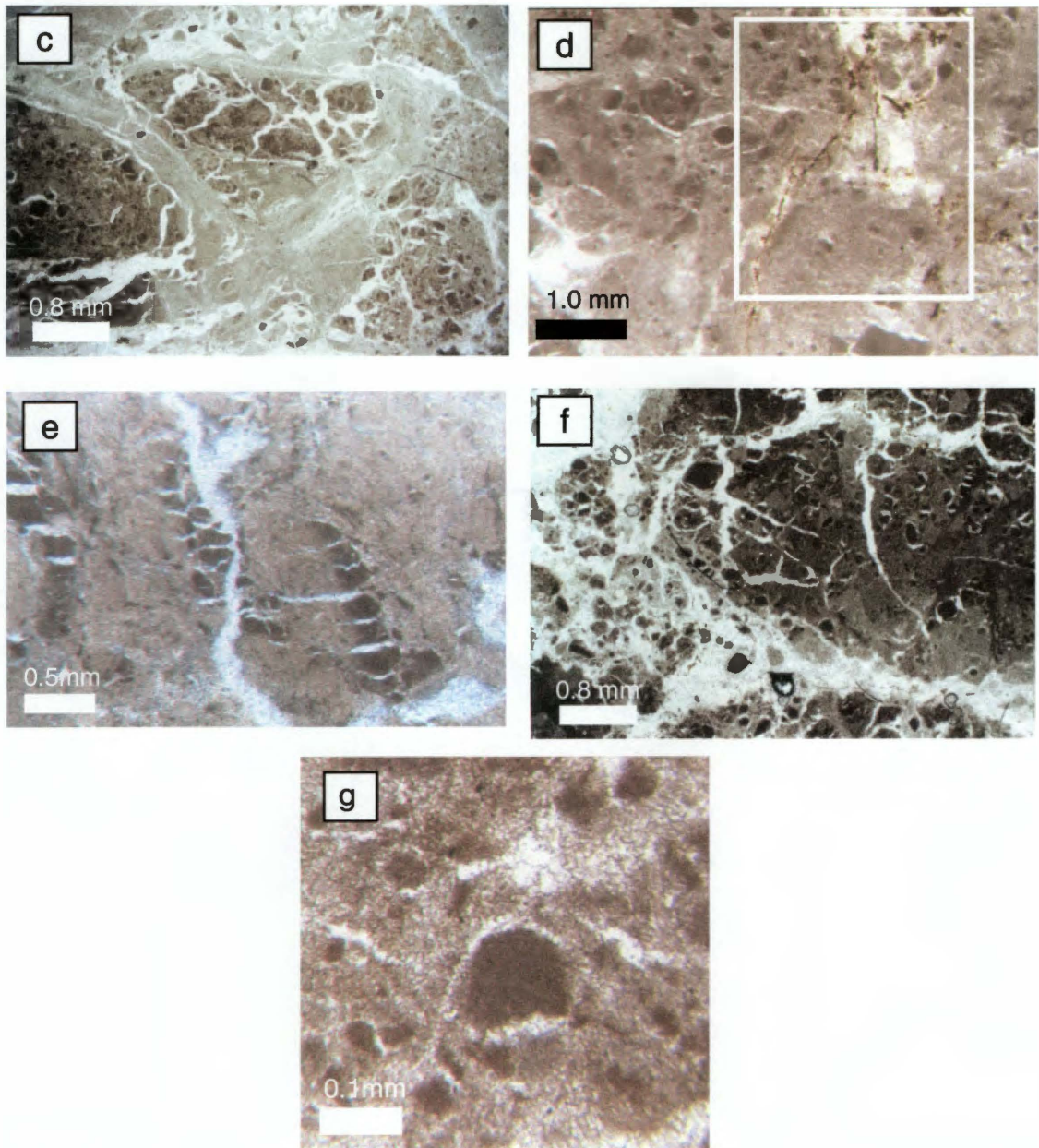


Figure 9 cont. - Photograph and photomicrographs of petrographic features taken in plane light of Unit 1. Figure 9c - Unit 1: Clay fill in cracks surrounding dolomicritic breccia clasts. Figure 9d - Unit 1: Note iron oxide staining following fracture in dolomicritic matrix. Figure 9e - Unit 1: Selectively brecciated intraclasts found within the dolomicritic matrix. Figure 9f - Unit 1: Note upper right edge of picture, and the peloidal nodules within the matrix of larger breccia clast. They are surrounded by circumgranular spar. Figure 9g - Unit 1: Close up of circumgranular spar, surrounding peloidal nodules. All photomicrographs taken in plane polarized light.

and 9g).

Dissolution of a 5g- powdered sample of sample 6.1 produced 1.18g insoluble material, which is close to 23% of sample weight (Table 2). Insoluble material is largely a clay-sized fraction (nearly 78% clay), although quartz silt grains (15%) and iron oxides (07%) are present as well.

2. Unit 2 – *Skeletal Packstone-Wackestone*

The first 0.42 m of the upper Pennington limestone section comprises depositional Unit 2, a skeletal packstone to wackestone. It is a medium-bedded limestone with dark gray to black color on a fresh surface. Unit 2 contains downward-tapering vertical fissures, also called grikes, which are now filled by calcite (Fig. 10a). Iron oxide staining, when present, follows these openings. Unit 2 also contains tiny clay seams, which are now open porosity. These horizontal features commonly show oriented grain fabric in the surrounding matrix.

Unit 2 is approximately 34-38% skeletal allochems, including abundant echinoderms, brachiopods, bryozoans, mollusks (mainly pelecypods), and arthropods (mainly ostracodes) (Fig 10b). (For specific percentages of allochems, refer to Appendix 2). Many of these fossils show breakage and abrasion; only moderately-resistant echinoderm grains maintain original form and composition. Other diagnostic fossils include foraminifera, which are present as miliolids and fusilinids (Fig 10c and 10d). A second type of microfossil is the calcisphere, which is a perfectly spherical spar filled sheath, approximately 0.125-0.25 mm in diameter. Algal tubules, thought to represent *Girvanella*, are also common throughout Unit 2 (Fig. 10e). These hollow elongate sheaths, observable only under high magnification, occur in the matrix and appear as a nested web of filaments.

Peloids and intraclasts are also present in the fossiliferous packstone. The peloids

Figure 10 - Photomicrographs of upper Pennington Formation, Unit 2, showing petrographic features taken in plane light. Photos a, b, c, d, e, f, g, h, and i.

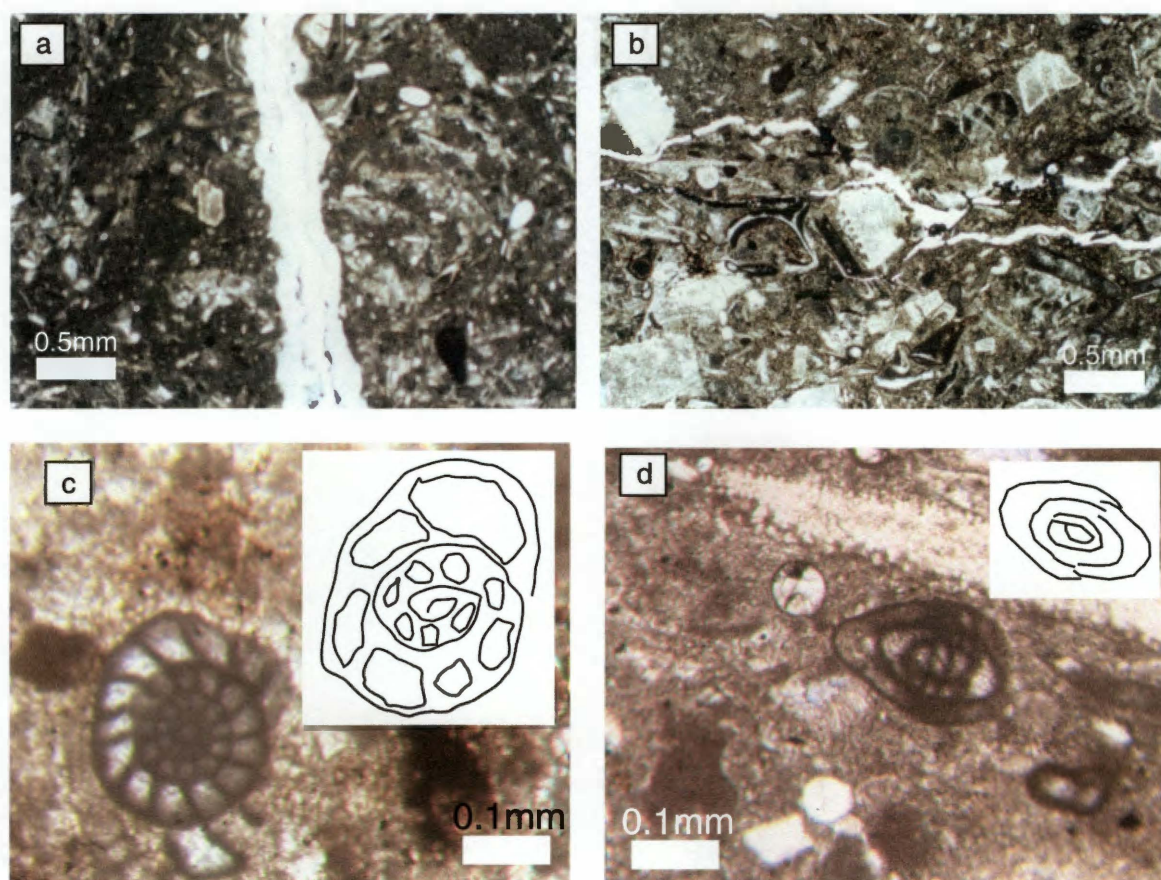


Figure 10 - Photomicrographs of upper Pennington Formation limestone Unit 2, showing petrographic features taken in plane light. Figure 10a - Unit 2: A vertical fissure, or grike, extends down through the unit. Notice the fringing non-ferroan calcite cements. Figure 10b - Unit 2: A varied assortment of fossils are found in this unit, the most common of which are echinoderm plates, brachiopods, bryozoans, mollusks, ostracodes, foraminifera, and algal remains. Many of the larger fossils are highly abraded, except for the resistant echinoderm grains. Also seen in this photomicrograph are horizontal clay seams, filled by iron oxides. Surrounding grains show horizontal orientation trend. Figure 10c - Unit 2: Foraminifera begin to be common in this unit, with the appearance of fusulinids, a coiled globular body type. The interpretive illustration is added to clarify the photomicrograph. Figure 10d - Unit 3: Another foraminiferal type called a miliolid. These forms are less globular, and more streamlined. The interpretive illustration is used for added clarity.

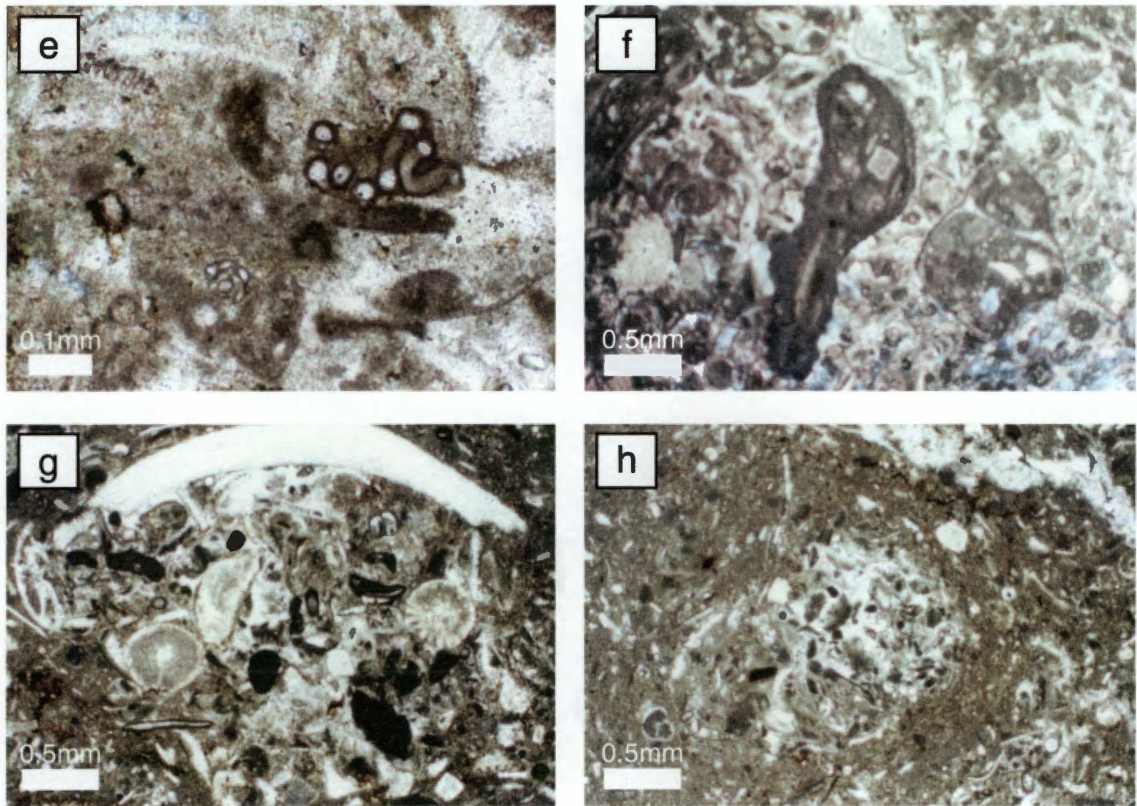


Figure 10 cont. - Photomicrographs of upper Pennington Formation limestone Unit 2, showing petrographic features taken in plane light. Figure 10e - Unit 2: Algal tubules are found in the micritic matrix, throughout the unit. Figure 10f - Unit 2: Micritic intraclast containing abraded skeletal material. Figure 10g - Unit 2: Increased shelter porosity found beneath large brachiopod and associated grains including echinoderms, peloids, and shell hash. It is cemented by non-ferroan calcite. Figure 10h - Unit 2: A cross section through a horizontal burrow is evidence for bioturbation. Thin section oriented perpendicular to bedding.

are 0.1-0.2 mm in diameter, and occasionally show remnant structures resembling small foraminifera that have been extensively micritized. The intraclasts average 1.0 - 1.5 mm in diameter, are micritic, and contain occasional skeletal allochems (Fig. 10f). Peloids account for about 10-17% of the lithology, whereas intraclasts account for less than 5%.

Lithologically, Unit 2 shows variable micritization. The peloids appear to be the allochem most affected by persistent micritization, while skeletal allochems, particularly the larger ones, show little or no grain micritization. Thin, poorly developed, micritic envelopes are present on the larger grains, but are generally less than 0.125 mm thick.

Micrite is the most common orthochemical constituent. It is present in percentages from 33-35%. Sparite is present in amounts ranging from 10-13%, as pore filling, intergranular cements, and syntaxial overgrowths. Calcite spar appears as a moldic pore-filling, particularly in association with mollusks. The pore-filling cements consist of both a bladed rim of non-ferroan calcite, which surrounds the perimeter of the mold, and an equant drusy mosaic of ferroan calcite in the central pore. Spar is also present in sheltered areas (Fig. 10g), fractures, and areas of extreme bioturbation. Non-ferroan calcite is the most common type of sparite, especially as intergranular cement and syntaxial overgrowth, whereas high-iron cements occur most commonly as central pore- and late fracture-fillings.

Bioturbation is common throughout this lithology, and occurs as sharp-walled burrows (Fig. 10h), which give Unit 2 a slightly mottled appearance. The bioturbation increased local depositional porosity, which in turn allowed far more room for the precipitation of high amounts of intergranular calcite spar cement. The burrows are commonly circular in cross-section, thus horizontal in nature, which indicates minimal effects of compaction. Absence of compaction is also indicated in areas where shelter pores

have protected underlying grains. The only real evidence of any burial compaction is seen in rare horizontal clay seams (Fig. 10b). Grains on either side of the seams show a relative lithostatic stress-induced orientation.

Dissolution of a 5 g powdered sample of sample 6.2 produced 0.6 g of insoluble material, which is 12% of total weight (Table 2). The specific percentages include 75% clay, 20% quartz, and 5% iron oxides.

3. Unit 3 – Peloidal Wackestone-Packstone

Unit 3 is a medium-bedded limestone, which occurs as a buff-colored peloidal wackestone to packstone. Thickness of Unit 3 ranges from 0.7 - 1.28 m. Horizontal clay seams are rare, but occur occasionally throughout the unit at less than 1 mm thick. Unit 3 is easily recognized in the field due to the presence of large oncolitic allochems, which are abundant in specific beds (Fig. 11a).

Although the oncoids are the most obvious of the allochems, the dominant allochem type in Unit 3 is actually peloids. These 0.1 mm diameter micritic spheres are approximately 30-50% of the lithology, although percentages vary due to a well-developed grumeleuse structure, which can obscure boundaries between grains and matrix (Fig. 11b). Intraclasts are rare in Unit 3, with percentages averaging 2%. When present, the intraclasts are micritic and have well-defined borders.

Skeletal allochems are also present in Unit 3, ranging from 21-23%. The most common allochems are echinoderms, gastropods, ostracodes, and foraminifera, again with the miliolid varieties most common. Pelecypods and brachiopods occur in smaller percentages. Calcspheres (Fig. 11c), bryozoans, and algal tubes are also present in small amounts. Many of the skeletal allochems are highly micritized or are surrounded by a

Figure 11 - Photomicrographs of upper Pennington Formation limestone, Unit 3, showing petrographic features taken in plane light. Photos a, b, c, d, e, and f.

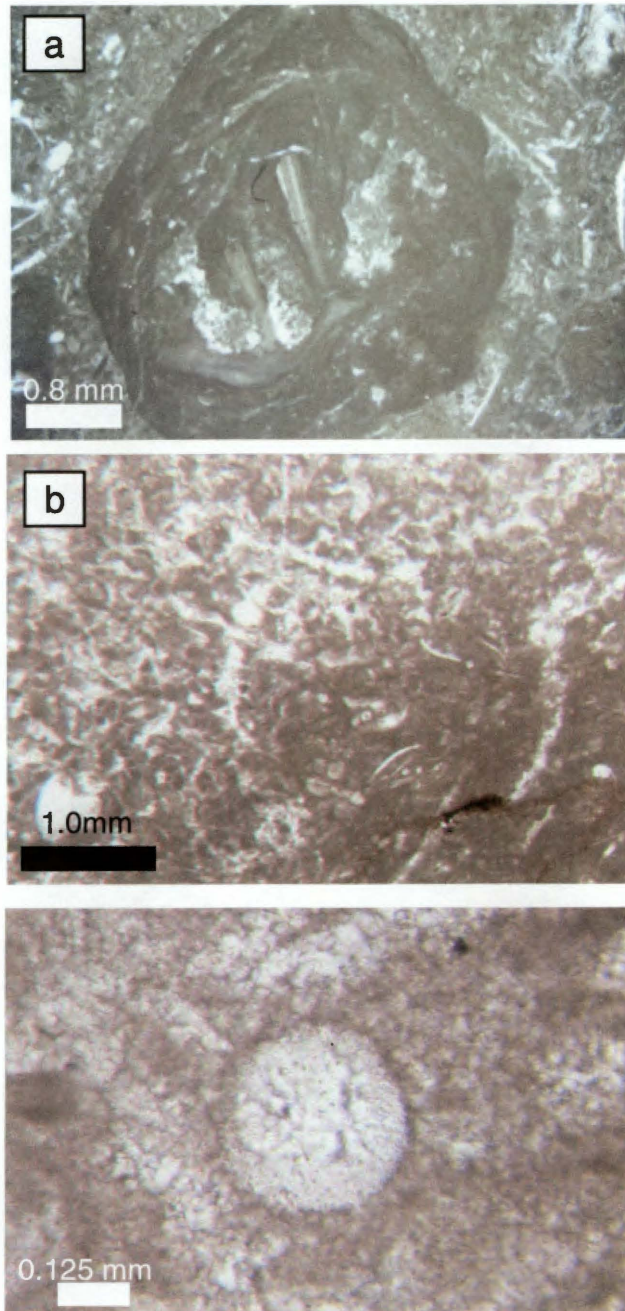


Figure 11 - Photomicrographs of upper Pennington limestone Unit 3, showing petrographic features in plane light. Figure 11a - Unit 3: Microbial oncoids are common in particular layers within unit 3. This oncoid is built around a mollusk grain. Figure 11b - Unit 3: The predominant grains in this unit, pellets, are obscured by a grumeleuse texture, which obscures the boundaries between grains and matrix. Figure 11c - Unit 3: Calcispheres, spherical spar filled sheaths, are common throughout this unit.

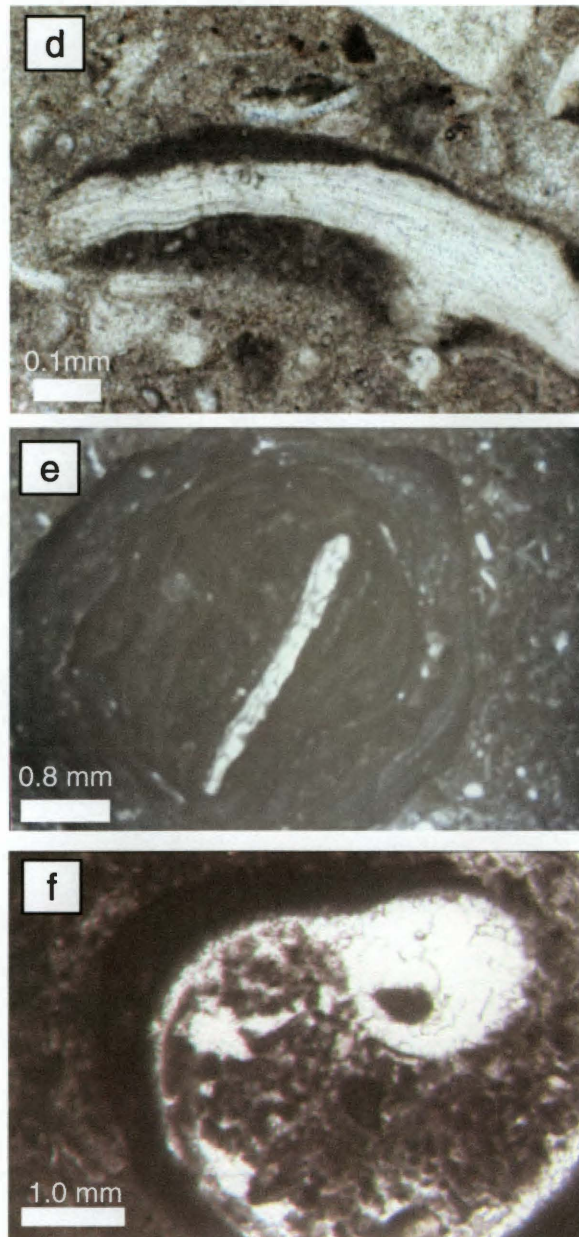


Figure 11 cont. - Photomicrographs of upper Pennington limestone Unit 3, showing petrographic features in plane light. Figure 11d - Unit 3: A brachiopod shell surrounded by a micritic envelope. Development is poor on this particular grain, with less than 0.125 mm of crust. Figure 11e - Unit 3: An example of an oncoid based on a fragment of a brachiopod grain. Figure 11f - Unit 3: Moldic pores commonly form from gastropod fossils. The base of the pore is filled by pelleted sediment. Notice differences in cement forms throughout the pore - a fringing cement rims the edges, whereas a drusy calcite cement occurs in the center.

micritic envelope (Fig. 11d).

Although the base of Unit 3 contains grains with poorly developed micritic envelopes (<0.125 mm thick), the upper section has envelopes which are as much as 0.5-1 mm thick. These micritic envelopes are commonly so thick that the grain could be classified as an oncoid, a grain surrounded by thick irregular micritic laminae (Fig. 11e). To take the classification a step further, these types of grains could be more specifically referred to as cortoids, namely, a grain coated by a thick micritic envelope that is presumed to have formed by endolithic microorganisms. They are not strictly coated grains, although they may form partially through accretionary action, because the envelope is a direct result of alteration of the grain surface (Tucker and Wright, 1990).

Unit 3 contains an orthochemical component, which is difficult to categorize. Because of the intense micritization, many of the allochems are difficult to differentiate from the matrix. There does appear to be calcite spar cement in many of the interstices between grains, but much of it is overprinted by micrite. Micrite is approximately 15% of this unit, whereas calcite spar cement ranges from 10% at the base of the unit, to 5% at the top.

Preserved porosity in Unit 3 is very low, but one can see there was once primary porosity as evidenced by geopetal fabrics, shelter pores, moldic pores of dissolved bioclasts (Fig. 11f), and intergranular porosity. The first cement phase is that of a fringing non-ferroan calcite that rims the edges of the pore. This is followed by a central pore-filling of ferroan calcite. As was the case in Unit 2, the non-ferroan calcite dominates, and occurs as both intergranular cement and syntaxial overgrowths. The ferroan calcite also occurs in late cross-cutting fractures.

Rare burrowing is indicated by mottled textures, and by a lighter color. These

burrows are much less densely packed with allochems, and therefore, contain a higher percentage of sparry calcite pore-filling cement. The compaction in Unit 3 appears to be quite variable. Though many of the shelter pores and burrows do not appear distorted, horizontal clay seams are present in the unit. These vary in thickness from 0.5 - 1.5 mm.

Dissolution of 5 g powdered samples of sample 6.3 and 6.5 produced 0.43 g and 0.15 g, respectively, of insoluble material (Table 2). This equals 8.6% and 3% of total weight for each sample. The specific percentages for sample 6.3 include 85% clay, 13% quartz, and 2% iron oxides. The specific percentages for sample 6.5 include 87% clay, 7% quartz, and 6% iron oxides.

4. *Unit 4 – Skeletal Grainstone-Packstone*

Unit 4 is a skeletal grainstone to packstone. It is light gray on a fresh surface, but approaching the exposure surface, increasing amounts of iron oxides tint the limestone a light red-orange to a deep reddish purple color (Fig. 12a). This medium-bedded limestone is 1.5 - 1.7 m thick in outcrop, and is bounded at the top by an unconformity.

Unit 4 is almost entirely grain-supported, with a high percentage of skeletal allochems. The dominant allochems are echinoderms, with lesser amounts of mollusks (dominantly pelecypods) and arthropods (dominantly ostracodes). Also present in high percentages are foraminifera, but in this unit miliolids and fusilinds are not the dominant forms. In Unit 4 the overwhelming majority of forams are a biserial form, which is reminiscent of a gastropod in cross section (Fig 12b). Algal tubules and calcispheres are also present, but in small percentages.

Other allochems are present in large amounts throughout Unit 4. Peloids are common, in amounts ranging from 20 to 45%, whereas intraclasts occur sporadically, in

Figure 12 - Photomicrographs of upper Pennington Formation limestone, Unit 4, showing petrographic features taken in plane light. Photos a, b, c, d, e, f, g, h, i, j, and k.

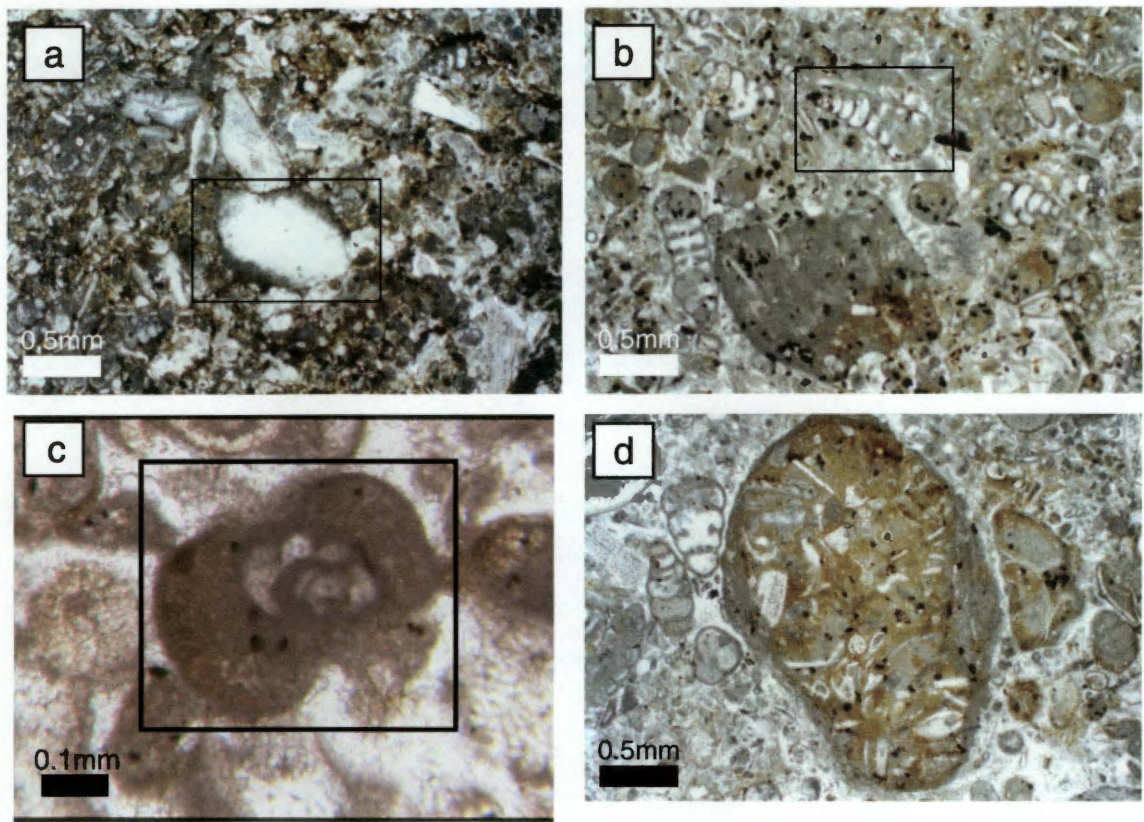


Figure 12 - Photomicrographs of upper Pennington limestone Unit 4, showing petrographic features in plane light. Figure 12a - Unit 4: Limestone near the unconformity surface has undergone a number of changes due to subaerial exposure. These include a staining of the rock by iron oxides, and micritization of grains, as seen in the central echinoderm grain. Figure 12b - Unit 4: A different type of foraminifera is found throughout unit 4. This biserial form is reminiscent of a gastropod in cross section. Figure 12c - Unit 4: Peloids in this unit commonly show remnant skeletal structure, particularly that of foraminifera. The box indicates a fusilinid that has been highly micritized. Figure 12d - Unit 4: Intraclasts within this unit commonly show skeletal allochems in the micritic matrix.

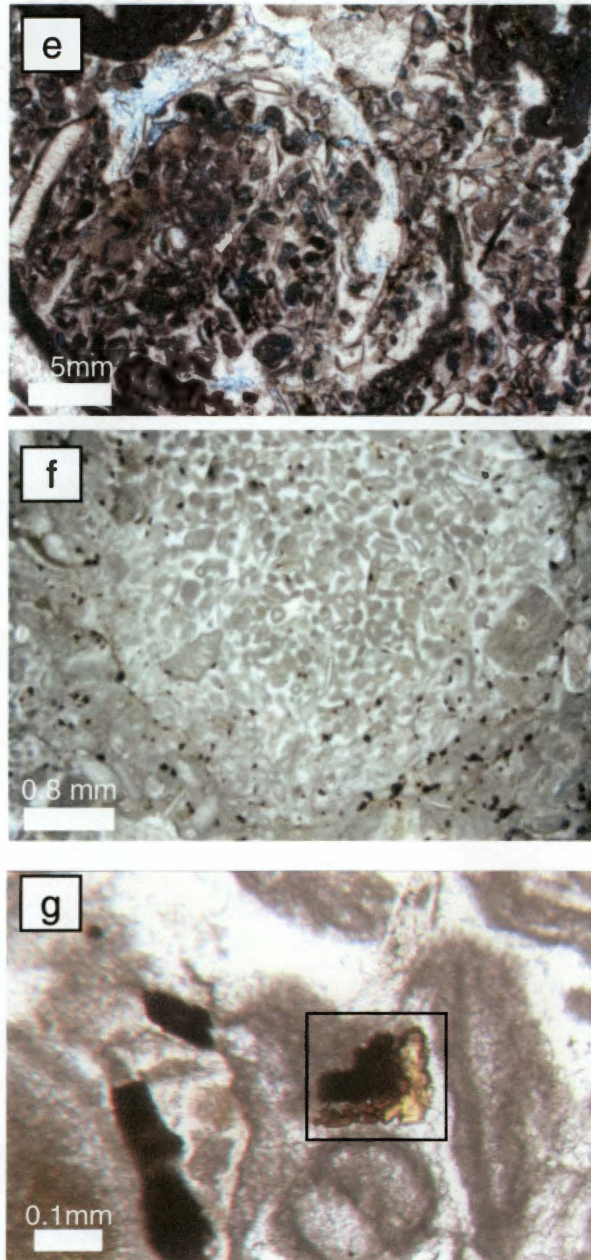


Figure 12 cont. - Photomicrographs of upper Pennington limestone Unit 4, showing petrographic features in plane light. Figure 12e - Unit 4: Ferroan calcite is most common near the top of the unit as intragranular, intergranular, and central pore-filling cements. The blue color in the pores of the thin section above is indicative of the presence of ferroan calcite. Figure 12f - Unit 4: Burrows within this unit are filled by a round laminated grain, called a cortoid. Figure 12g - Unit 4: Siderite rhombs are seen throughout the matrix of this unit. Opaque rhombs have been replaced by hematite. The rhomb indicated is still ankeritic siderite.

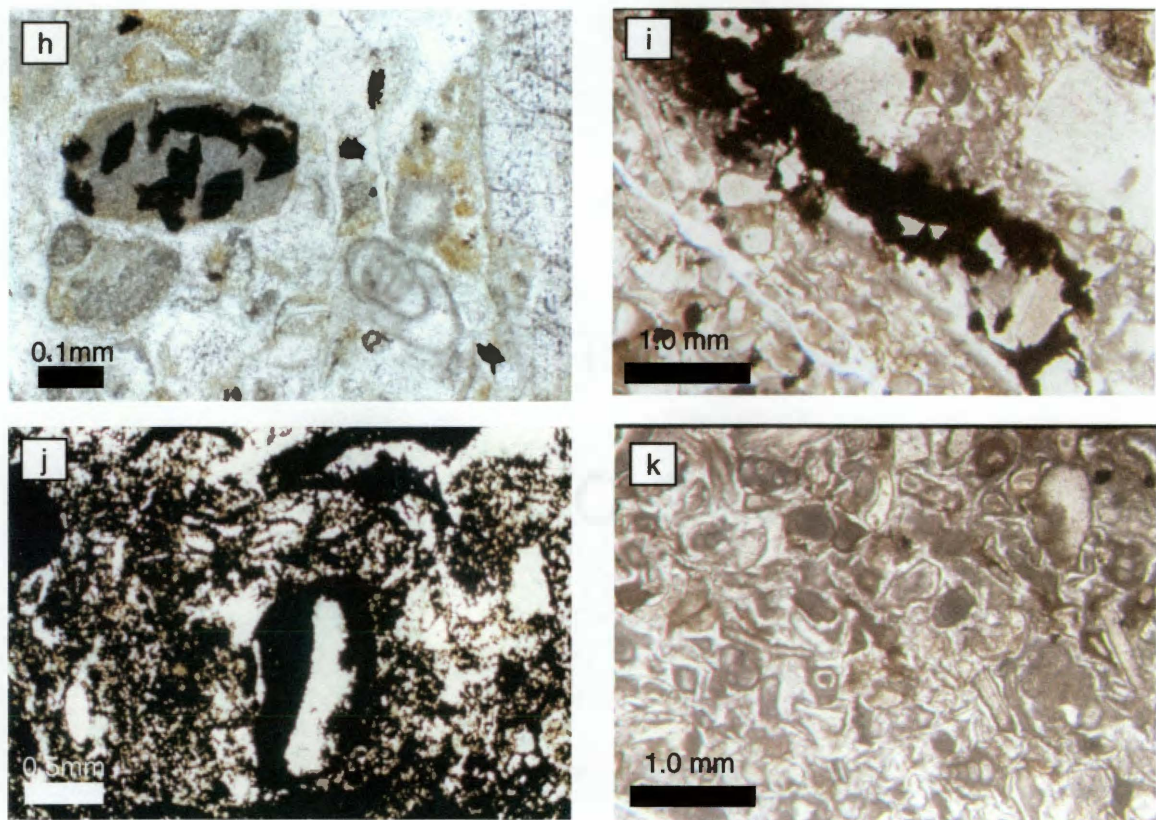


Figure 12 cont. - Photomicrographs of upper Pennington limestone Unit 4, showing petrographic features in plane light. Figure 12h - Unit 4: Intraclasts are commonly host to an assemblage of siderite rhombs. Figure 12i - Unit 4: Siderite rhombs, replacive hematite, and iron-oxide staining are common following grikes, or open dissolutional fractures. Figure 12j - Unit 4: Hematite is most common along exposure surfaces. In these areas, the hematite acts as both a cement and a allochem replacive agent. Figure 12k - Unit 4: The uppermost sample taken from the Upper Pennington Limestone has microstylolites, which cause pervasive grain reorientation. Though not as obvious as a clay seam, they impart an oriented undulating texture.

amounts averaging 3%. The peloids are generally quite distinct, with sharp boundaries. As was the case in underlying units, peloids show remnant skeletal structure preserved within the allochem (Fig. 12c). Intraclasts are micritic with well-defined borders, and contain rare skeletal allochems (Fig 12d).

Micritization of allochems is common in this unit, with micritic envelopes developed around many of the larger skeletal allochems, and commonly complete micritization of the grains (Fig 12a). Intensity of micritization increases sharply up-section in Unit 4, over thicknesses of as little as half a meter. This trend is also seen in the increase of diffuse peloidal boundaries and grumeleuse textures with a micritic matrix.

Orthochemical constituents in Unit 4 differ from other units. Although non-ferroan calcite is the most common cement, occluding porosity as a moldic fringing rim cement and an intergranular cement, ferroan calcite is increasingly common toward the top of the unit. Ferroan calcite is present not only as central pore fill in moldic pores, but also as an intragranular and intergranular cement (Fig. 12e). The iron-rich calcite also occurs as late fracture-filling cement. Micrite is much less common, although there are some obvious exceptions, particularly in the highest portions of the section where micritization appears to have been pervasive.

Bioturbation is common throughout Unit 4. Burrows are sharp-walled and filled with an allochem type that is not seen anywhere else in the unit (Fig. 12f). The allochems are small, well-rounded cortoids of equal size. Although they are the same size as the peloids, they contain a better-organized internal structure, which suggests lamination and/or oolitic coatings. The outer layers of micrite have a perforate appearance, with small holes seen regularly through the matrix. The cortoids are cemented by non-ferroan intergranular calcite

spar.

Unit 4 contains high amounts of iron, which is often scattered through the matrix as siderite (ankerite) rhombs (Fig 12g). The rhombs are most common in micritic intraclasts, or following grikes (Fig 12h and 12i). Generally, the siderite has been converted to, or replaced by hematite. Hematite also plays an important role as cement and as a replacive agent of allochems through the unit (Fig. 12j). In some cases almost all of the carbonate has been removed, except for rare echinoderm grains, and replaced by purple-red hematitic cement.

In sample 6.10, which is the highest sample in Unit 4, a swarm of micro-stylolites distorts the original texture of the rock (Fig. 12k). This feature causes pervasive grain re-orientation. Although broad clay seams occur occasionally in lower portions of Unit 4, these specific micro-stylolites (or clay seam swarms) were not observed in any other sample.

Dissolution of 5 g powdered samples of samples 6.7 and 6.9 produced 0.38 g and 0.22 g, respectively, of insoluble material (Table 2). This equals 7.6% and 4.4% of total weight for each sample. Specific percentages for sample 6.7 include 89% clay, 8% iron oxides, and 3% quartz. Specific percentages for sample 6.9 include 55% iron oxides, 43% clay, and 2% quartz.

5. Diagenetic Constituents of the Upper Pennington Limestone

The upper Pennington Formation has obviously experienced extensive diagenetic modification. The limestone is well cemented and many phases of cementation are apparent, manifested by different types of carbonate cement. The first phase of cementation is interpreted to be early marine or meteoric origin. Microprobe analyses of the cement revealed very low to undetectable concentrations of Fe and Mn (Driese et al., 1998, and in

prep.). It is a nonferroan dully-luminescent calcite that occurs primarily on allochemical surfaces. The second meteoric phase is a concentrically-banded, luminescent-nonluminescent, nonferroan calcite. This cement has low Fe and Mg concentrations, but variable Mn – which accounts for the thin luminescent microbanding (Driese et al., 1998, and in preparation). The first burial phase of carbonate cement is a dully-luminescent ferroan calcite that occludes available pore space – particularly central moldic pores. Figures 13a and b illustrate each of the three cements, both in CL and transmitted light.

Accessory late-diagenetic constituents are present as well. Zoned ankeritic siderite rhombs are found in the upper 10-20 cm of Unit 4. A microprobe analysis of the rhombs indicates high Ca, Mg, and Mn; for which reason the adjective ‘ankeritic’ is assigned (Driese et al., 1998 and in preparation). The rhombs are 0.05-0.1 mm in diameter, and consist of a non-luminescent sideritic core, followed by a brightly luminescent ferroan calcite overgrowth, which is in turn followed by another sideritic band. The last phase of cement, a brightly luminescent ferroan calcite cement, fills late cross-cutting fractures and occasional intragranular porosity. It has low concentrations of Mg, but high Fe and Mn concentrations (Driese et al., 1998 and in preparation).

C. Interpretation of Depositional Units

1. *Unit 1*

Unit 1, which comprises the highest part of the pre-upper Pennington Formation limestone, is a highly brecciated dolomicrite. It exhibits evidence of subaerial exposure, preferential dolomitization, and possible pedogenic processes, all of which obscure the original texture and lithology.

Evidence of exposure is seen in the extensive brecciation present throughout the

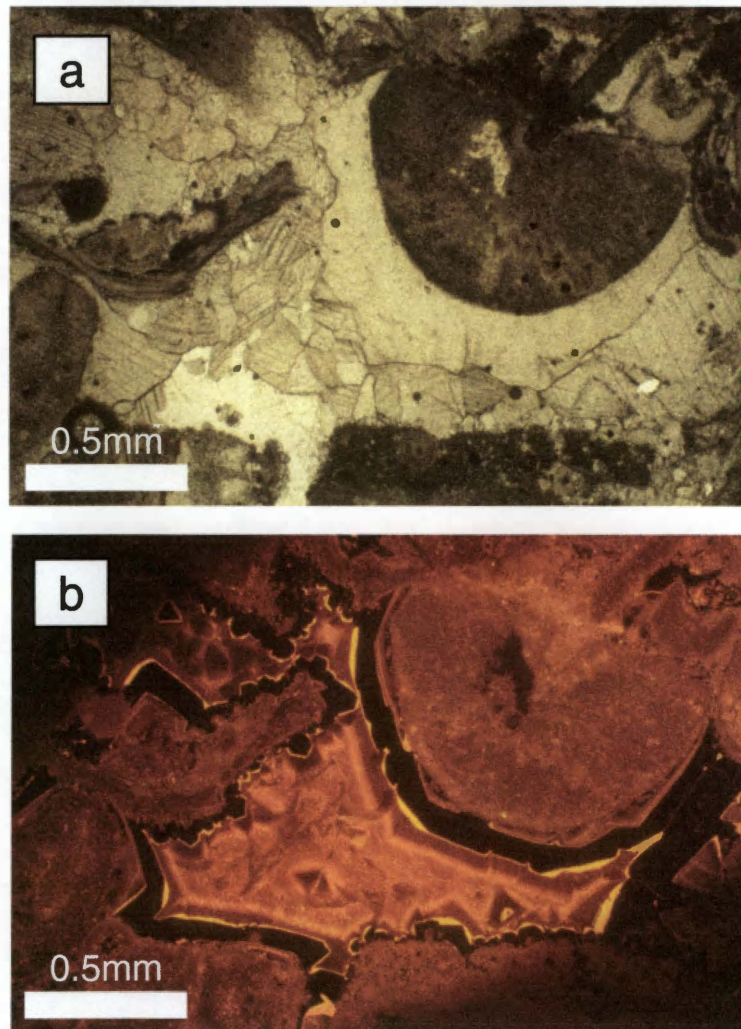


Figure 13 - Photomicrographs of upper Pennington limestone, taken in plane light and CL. Figure 13a - Photomicrograph taken in plane light, of an intergranular pore. Figure 13b - Photomicrograph of same pore in 13a, only in CL. Three different cement zones are visible: the first phase is of meteoric origin and is dully luminescent non-ferroan calcite; The second phase is also of meteoric origin, but is concentrically banded luminescent, non-luminescent non-ferroan calcite; the final burial phase is a dully luminescent ferroan calcite.

unit. Fracture types are varied, but appear to be dominated by long, vertical grikes spaced at regular intervals (Figure 9b). These fractures were probably initiated by drying, as with classical mudcracks, but quickly lost the traditional v-shape due to dissolution (Shinn, 1983). Brecciation is extensive (Figure 9c), and it is apparent that the unit experienced multiple generations of wetting and drying.

The presence of vague, and highly disrupted, laminated fenestrae supports this hypothesis. The laminations may be relict algal structures, which are common in supratidal flats. Algal mats aid in the brecciation by allowing cracks to propagate upward more readily into overlying sediments (Shinn, 1983).

Signs of algal occupation and extreme desiccation are certainly strong clues as to the depositional environment of Unit 1. Taken in conjunction with pervasive dolomitization and the presence of micritic intraclasts, a convincing argument can be made for deposition in tidal flats. Dolomite was probably generated penecontemporaneously with deposition on these supratidal flats, and spread downward into calcitic sediments as the unit became increasingly cracked from desiccation (Shinn and Ginsburg, 1964). Thompson (1970) noted, the more extensively mudcracked beds are, the more likely they are to be fully dolomitized.

In tidal flats, it is common for dolomitic crusts to form on the exposed carbonate (Shinn et al., 1965; Shinn 1983). This process of cementation and displacive-replacive introduction of calcium carbonate into the sediments occurs because of capillary action or tidal pumping, which draws water up to the surface. The water has an increased Mg/Ca ratio, due to precipitation of aragonite and possibly gypsum (Tucker and Wright, 1990).

During storm events, these brittle crusts are easily ripped up and broken into smaller pieces. The presence of small, dark intraclasts (Figure 9e) within the larger clasts of the

matrix indicate a tidal flat type of environment in which deposition is low, and exposed sediment or lithified rock is subject to the formation of a brittle crust (Shinn, 1983). Storm events, which are the main mechanism for sediment transport to the tidal flats (Hardie and Shinn, 1986), could easily break up these crusts and mix them in with the unlithified muddy deposits. The resulting intraclasts are generally referred to as 'black pebbles,' as their color is usually darker than surrounding matrix. These dark clasts are related to processes associated with subaerial exposure (Tucker and Wright, 1990), with origins for the darker color ranging from organic staining (Strasser and Davaud, 1983), to blackening during fires (Shinn and Lidz, 1988), or to pyritization (Wright, 1986).

The development of brecciation and dolomitization are quite extensive throughout Unit 1 and although these two characteristics are common in tidal flat deposits, other characteristics suggest long-term exposure and ensuing pedogenic processes. Such extensive brecciation, the presence of peloidal nodules surrounded by circumgranular spar, and the possibility of rhizoliths may be the necessary clues.

Although brecciation has been discussed in conjunction with original environment of deposition, a closer examination of the clasts indicates that the angular to rounded clasts exhibit more than one episode of brecciation, and maintain a moderately good fit in relation to each other. It seems obvious, therefore, that this unit has undergone *in-situ* multi-generational desiccation, fracturing, and dissolution (Harrison and Steinen, 1978). According to James (1972), this is common in the formation of calcrete (or dolocrete, in this case) crusts, which form at the surface of carbonate successions in semi-arid areas. The originally lithified carbonate rock is brecciated, partially dissolved, commonly recrystallized to microspar, and micritized.

With these processes in mind, the macrofeatures associated with dolocrete warrant discussion, including the black pebbles, nodules, and rhizoliths (Wright and Tucker, 1991). The black pebbles may also have an origin in later pedogenic processes. Though many of the smaller intraclasts are enveloped by matrix clasts, others are found disconnected from the depositional matrix. It may be that two generations of clasts, both formed in similar manners, are present, with the first formed from depositional processes and exposure, and the second from pedogenic alteration and exposure.

Rounded dolomitic peloidal nodules (Figure 9g), another characteristic of pedogenic processes and dolocrete formation, appear throughout the matrix of the major breccia-clasts, and are commonly surrounded by a dolomicritic circumgranular spar. The origin of these micritic allochems is debatable. Peloids within one unit can generally be polygenetic in origin. Peloidal grains in this unit could have formed from pedogenic processes, which transferred Mg and Ca through the matrix, and precipitated in specific nucleating sites forming nodules (Wright and Tucker, 1991). They could also be biogenic fecal pellets, micritized glaeboles (Wright, 1991), or sand-sized intraclasts (Tucker and Wright, 1990).

These observations raise the question: whether the peloidal allochems are simply portions of the matrix, weathering out in a rounded shape, or pedogenic nodules, or remnants of depositional peloids? They appear to be the same micritic material as the matrix, but material that reacted differently during desiccation. Circumgranular spar surrounding the allochems forms from the shrinkage of the peloid.

Although textural inversions are common in micritic calcrete parents – i.e., that the micritic parent material will eventually weather out as small, rounded peloidal clasts (Wright, 1991), this does not appear to be occurring in Unit 1. The peloids are contained well within

the matrix, and are generally not connected to dissolutional conduits. Based on similarity between the composition of matrix and peloid, it is most likely that the peloidal allochems are depositional. Early cementation caused them to react differently during desiccation, opening circumgranular cracks around the peloidal nodule. Perhaps, with a higher concentration of carbonate than the surrounding matrix, carbonate precipitation occurred preferentially in the voids around the peloidal nodule margins (Wright, 1991).

Another macrofeature often associated with calcrete (or dolocrete) sequences are root traces, or rhizomes. This unit shows no definitive root molds, however, their presence may have aided in the formation of vertical fissures throughout the dolocrete (Wright, 1991).

Although difficult to categorize, this unit certainly sets the stage for deposition of the Upper Pennington limestone. It indicates the variability of sea level during the late Mississippian, and foreshadows the major regression seen at the Mississippian – Pennsylvanian boundary. The initial deposition of the unit on a tidal flat, and then the extreme alteration by exposure and possible pedogenic processes, certainly highlight the changes seen with the advent of the Upper Pennington limestone.

2. *Unit 2*

Unit 2 is a skeletal packstone-wackestone at the base of the Upper Pennington Formation limestone, which is composed dominantly of small, abraded skeletal allochems and micrite (Figure 10b and 10g). It is a transitional unit, reflecting a rather abrupt environmental change from Unit 1, probably brought about by flooding of the Unit 1 exposure surface. This interpretation supports ideas proposed by Chestnut and Ettensohn (1985), who reported that a slight transgression occurred toward the end of the Pennington, allowing inundation of the well-developed tidal flats.

The high percentage of fauna and the biological diversity in this unit indicate input from an open-marine system, whereas in a restricted back barrier setting, faunas tend to become more restricted (Frazier, 1973; Tucker and Wright, 1990). Nonetheless, the presence of pellets, algal filaments (Figure 10e), foraminifera (Figure 10c, d), and calcispheres indicate a quiet, although probably only semi-restricted, back-reef environment (Bagby, 1989; Brown, 1987; Horowitz and Potter, 1971). Evidence for these two opposing environmental interpretations can be reconciled if Unit 2 was deposited as part of a flooding surface, which gradually converted to a restricted lagoonal environment.

The initial inundation imported a wide variety of new biota, while physically breaking existing allochems into smaller pieces. A barrier subsequently developed; the absence of ooids in the unit indicates that it was likely a biological buildup (Tucker and Wright, 1990). This allowed the production and deposition of micrite and the development of the lagoon to begin. In lagoonal environments, one commonly sees intense micritization of grains due to the presence of a large endolithic algal population.

Although Unit 2 is not as intensely micritized as overlying units, peloids with remnant foraminiferal structure and micritic envelopes surrounding larger allochems are common. The presence of these paleoenvironmental clues indicates that a shallow, low-energy environment was developing. The micritization also provides evidence about the rates of deposition as well. The development of micritic envelopes requires significant time. Although Kobluk and Risk (1977) stated that certain envelopes can form in as little as a year or two, it is more likely that, in general, this process is a good bit slower (Bathurst, 1966, 1971, 1975). The presence of a clastic clay fraction (found to be approximately 12% of the unit) may have aided in the process of micritization, by slowing carbonate production, and

therefore depositional rates.

3. Unit 3

Unit 3, a peloidal packstone-wackestone, contains spectacular examples of micritic envelopes (Figure 11d) and micritized grains in the guise of peloids. In some samples, the micritic envelopes are commonly as thick as 0.5 - 1 mm, and the grains are dominated by peloids, which commonly show remnant structure of foraminifera. Because micritization has been so particularly pervasive, endolithic algae are the likely cause (Kobluck and Risk, 1977; Tucker and Wright, 1990). The abundance of oncoids (Figure 11a, e) supports a cyanobacterial origin. These micritic allochems have relatively regular, dense laminations around skeletal grains. This type of oncooid is probably cyanobacterial in origin, developed by a process in which fine microbial mats trap and bind the sediment in concentric layers (Tucker and Wright, 1990). It is necessary for the oncooid grain to be overturned rather often, in order for the layers to be regularly laminated.

The presence of concentric oncooid grains indicates that this environment was not a stagnant backwater, but instead, had rather moderate circulation. However, it does not seem that lagoonal circulation was entirely open. Skeletal allochem percentages drop quite appreciably from Unit 2 to Unit 3, and the assemblages present are much more restricted. The most common skeletal allochems are echinoderms, gastropods and foraminifera, which can survive in a shallow, restricted environment with higher salinities and more variable water temperatures (Tucker and Wright, 1990; Cadee, 1998). The presence of calcispheres (Figure 10c) is also indicative of lagoonal conditions, because they are an indicator of restricted back-reef environments in the Paleozoic (Bagby, 1989; Brown, 1987; Horowitz and Potter, 1971).

The orthochemical composition of Unit 3 is problematic. The presence of peloids as allochems seems certain, but due to compaction and development of a grumeleuse texture (Figure 11b), it is generally difficult to discern between a grouping of peloidal allochems and a micritic matrix. An interesting addendum to this subject is found in a paper by Coniglio and James (1985), which suggests that in Early to Middle Paleozoic carbonates, grumeleuse structure, and associated peloids, may result from calcified algae – particularly *Girvanella* tubules.

Thus, in Unit 3 it appears that a shallow-water lagoon had fully developed. It seems to have been a moderately open system, which allowed for circulation of the waters, although a caveat must be added. With the lower amounts and lesser variety of skeletal allochems, it appears that a separate ecological community evolved, that was adapted for slightly higher than normal salinities and variable water temperatures.

4. Unit 4

Unit 4 is a skeletal packstone-grainstone, which has a high percentage of pellets and micritization, and shows evidence for a re-establishment of a more varied and prolific biota. Unit 4 also shows an increase in intergranular spar cementation; spar cements are commonly more abundant than micrite.

In the upper portions of unit 4, the biota is more varied, and includes certain fossils that are new to the upper Pennington limestone sequence. The dominant foraminiferal type changes from miliolid and fusilinid dominated-species to a biserial (Figure 12b) form, which is the dominant fossil in the unit. The biserial type of foraminifera is a thick-shelled taxon, which is quite different from the delicate, thin-shelled foraminifera seen in Units 2 and 3. According to Brasier (1980), foraminiferal type is not only dependent upon salinity and

temperature, but also upon substrate. With the advent of a possible porous grain-dominated, high-energy environment, a larger, thicker-shelled foraminifera would be expected. Although the other two foraminiferal types are still present, they are dominated by the larger biserial form.

The change in fauna indicates that the environment was becoming less restricted (Cadee, 1998), and the presence of increased porosity, sparry cements, and lesser amounts of micrite indicate a higher-energy, grain-dominated, shoaling environment (Tucker and Wright, 1990). Peloids are still common, often having internal "ghost" skeletal structure indicating extensive micritization (Figure 12c).

A new type of grain assemblage occurs in burrow-fillings. These well-sorted grains are rounded, with thin micritic laminations (incipient oolitic coatings?), and an apparent central grain (Figure 12f). The presence of these clean deposits of well-sorted allochems indicates one of two possible depositional environments: 1) an upward-shallowing of the lagoon continued to the point of shoal formation, or 2) the continued rise of sea-level, which causes the barrier to migrate landward by erosion in the surf zone and washover of sand into the lagoon.

It is common for a lagoon, particularly one with an outside sediment source, to fill up. If the lagoon were becoming less restricted, it would be undergoing changes in terms of sediment input, and in terms of depositional processes. A high-energy environment would have winnowed out fines, sorted the sediments, and offered enough turbulence to allow the grains to form concentric laminations, possibly due to an algal influence. Alternatively, if sea level were rising quickly, eroding the barrier, the lagoonal environment would experience an increase in wave energy and a change in sediment source and type. The presence of

immature ooids could be a relict from the demise of the barrier.

Although the top of the upper Pennington limestone indicates a sea-level rise in its facies, it also records the formation of an erosive and subaerial unconformity (discussed in more detail in a later section). A sea level drop may have sparked removal of overlying units – referring particularly to any oolitic sediments, which occur only at the very top of unit 4 in burrows.

Subaerial exposure is indicated by the accumulation of iron oxides and iron carbonates in the matrix (Figure 12h, i, j, k). In some cases, there is a total replacement of the carbonate by hematite, which forms a crust along the surface of the limestone. In these samples the allochems are completely replaced by the iron oxides, and the intragranular cement is dominated by the hematite. In other cases, rhombs of siderite-ankerite are seen scattered through the matrix.

D. Discussion of Depositional System

The Pennington Formation represents a time of transition between Early to Mid-Mississippian carbonate-dominated deposition and the Early Pennsylvanian influx of clastics from the east. Although this study only addresses the depositional and diagenetic history of a portion of the Pennington Formation, it illustrates the changes in sea level and in sedimentation occurring through the very Latest Mississippian (Chesterian).

This study is centered dominantly on the upper Pennington limestone, but to make a complete story, a unit beneath the limestone was included. Unit 1, a brecciated dolomitic mudstone, sets the stage for deposition of the upper limestone. Unit 1 represents the extensive development of a tidal flat, which occurred during a sea-level low-stand in early and early-middle Pennington time (Fig. 14-1).

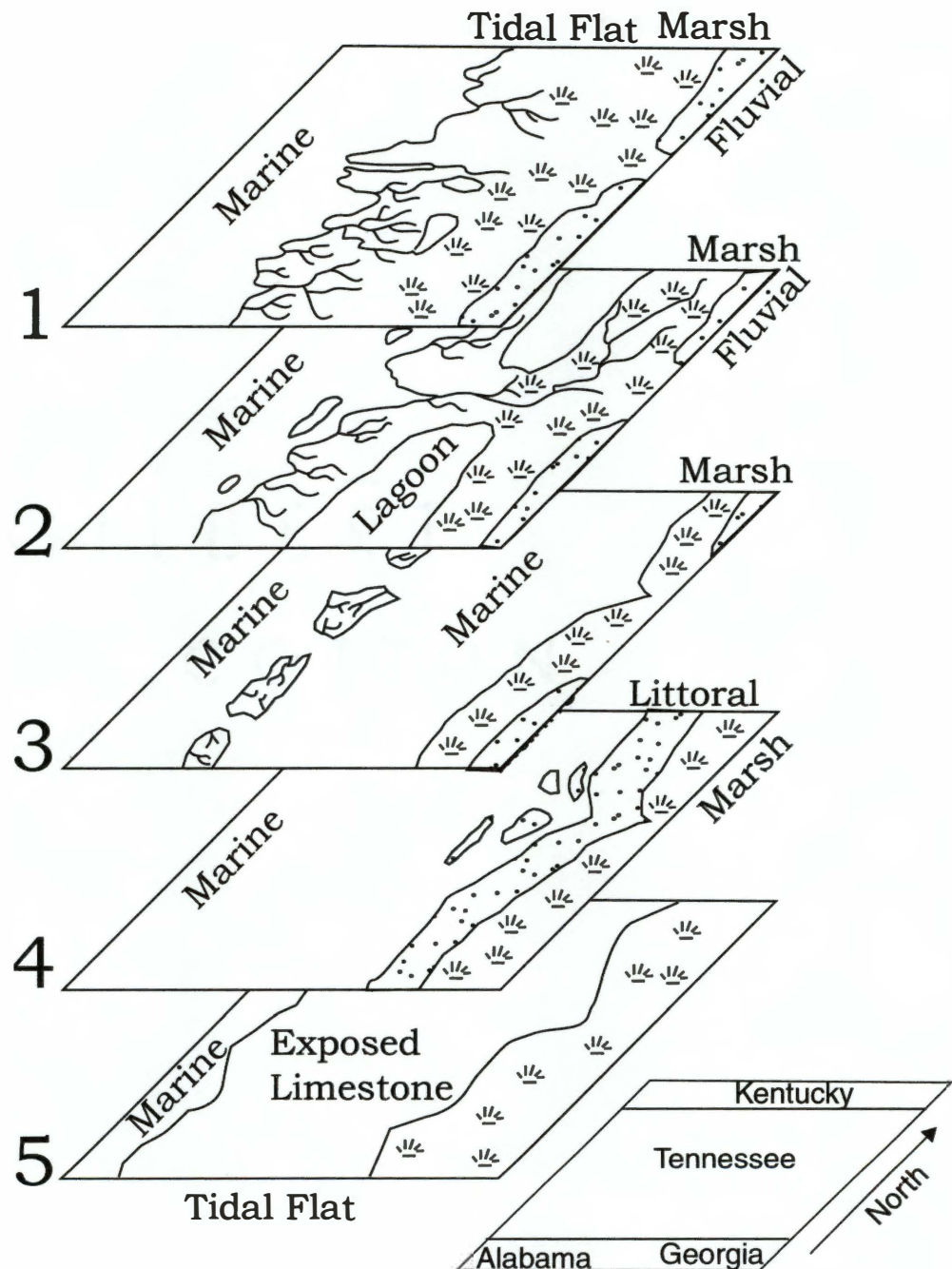


Figure 14: Hypothetical interpretation of environmental change during the deposition of the Pennington Formation. Illustrates change from early (1), early middle (2), late middle (3), late (4) Pennington time, and development of subaerial exposure surface found at the top of the upper Pennington limestone. Adapted from Frazier (1973).

It is important to point out that the body of water in question is a shallow epeiric sea, which covered an immense area of the craton. Although there is controversy as to whether epeiric seas are low-energy storm-dominated settings, with only a low, and restricted, tidal range (Tucker and Wright, 1990; Irwin, 1965), or whether they are tide-dominated bodies of water with a rather extensive tidal range (Tucker and Wright, 1990; Pratt and James, 1986), the Pennington was probably deposited in an environment of low tide and wave energy. This is based on the lack of scouring, flaser and lenticular bedding, bi-polar crossbedding, and reactivation surfaces, and the presence of horizontal lamination in the dominantly fine-grained rocks in the Pennington Formation (Fisher, 1978).

According to Frazier (1973) at this time of early Pennington deposition, the epeiric sea-level was at a lowstand, thereby allowing the underlying carbonates to develop on broad tidal flats (Figure 14-1). Additional carbonate sediment was derived from the marine environment, whereas substantial clastics were being supplied from the east. Sea-level rose from this point, throughout early middle and late middle Pennington time (Figure 14-2, 3, 4). This allowed the development of restricted lagoons and marshes, particularly in eastern and central portions of the Pennington Formation depositional area (Figure 14-2). To the west, particularly in early middle Pennington time, tidal flats were still present, although they were increasingly inundated. By late middle Pennington time, the tidal flats had been restricted to low tidal islands and barrier bars. With the protecting barriers and the rise in sea-level, lagoons were at their greatest extent during this stage (Figure 14-3). A continued rise in sea level eventually drowned the barriers, and allowed normal marine influences to resume deposition in the west (Figure 14-4). To the east, shoreward of the lagoons, extensive marshlands were forming.

At this point, the Leatherwood section appears to have been located along the locus of marine deposition. Moving through the units of the Upper Pennington limestone, there is evidence for a shallow lagoonal environment, which slowly shallows upward because of continued deposition in the lagoon itself. As it fills, environmental energy increases, winnowing out micrite, and leaving porous skeletal and peloidal deposits. It was at this point that an increasing amount of detrital material was being transported in from the east, causing the eastern marshlands to prograde over the marine carbonates. The final phase is that of continued regression, and exposure of newly deposited limestone (Figure 14-5). It is from this exposure surface that the hypothesized paleo-karst features, discussed in the next section, were formed.

Obviously, the sedimentation of the Upper Pennington limestone is heavily dependent on changes in relative sea-level. Sea level fluctuations from the Bangor, through the upper Pennington limestone are interpreted by Swann (1964). He inferred that the fluctuations in sea-level were dependent on climatic conditions in the source area, although tectonic uplift and subsidence could also have played a major role as well. Perhaps a combination of these factors led to the highly varied sedimentation in the Pennington Formation, leading to eventual subaerial exposure.

III. Paleokarst in Upper Pennington Formation Limestone

A. Introduction

For the sake of clarity, paleo-karst features in the Leatherwood Ford outcrop have been classified according to a three-scale system, which includes macroscale, mesoscale, and microscale. The names of each scale imply a size classification, with macro- indicating the largest features, meso- intermediate scale, and micro- the smallest scale. The original system was derived from previous work by Driese et al. (1998), but has been altered to fit a more detailed classification of the upper Pennington limestone paleo-karst features. This system is therefore subjective and is not meant to supplant other types of classification.

The macroscale is concerned with features occurring as outcrop-scale paleotopographic or paleogeomorphic variations. The mesoscale consists of smaller features, which occur in association with the macroscale features. They complement the larger features, and when put in temporal order, explain the formation of the macroscale features. These two scales have been difficult to subdivide, and are combined in both description and discussion. The microscale includes all petrographic-scale features caused by karstification that occur in the limestone itself. In most cases these features are observable in both outcrop and thin section. These features are relatively consistent throughout the outcrop, and will be treated as a single class.

The following descriptions of the outcrop are in order from the south (left) edge of the outcrop to the north (right). In most cases, the dominant dissolutional feature has been the focus of attention, but a description of associated pinnacles or the limestone framing the feature is included. Subdividing the paleo-karst features into separate entities has been difficult as in a karst landscape each feature is closely related to the other in terms of genesis

and continued development.

A caveat must be included before description of the features occurs. This outcrop, although primarily demonstrating paleokarst features associated with the Mississippian-Pennsylvanian unconformity, also includes karst features from Quaternary erosive action. These are particularly marked, as the outcrop has been directly affected by the downcutting of the Cumberland River. These features include vertical fissures, which can be as much as a 0.2 meters wide and 3.5m high, and freshly grooved limestone surfaces. The north edge of the outcrop has been extensively overprinted, leaving only a suggestion of the paleo-karst features that developed upon initial karstification.

Topographic relief measurements are based on a horizontal survey line, which was taken from the lowest point in paleo-doline 2. All measurements of vertical relief are compared directly with this line. The observed features are found well above this datum, but commonly their bases are obscured by the presence of a Quaternary alluvial cover. In one case, there is exposure below the datum, but is considered pre-upper Pennington limestone section (brecciated dolomicrite – Unit 1).

B. Paleokarst Feature Description

1. *Paleo-doline 1*

a. Macroscale (paleo-doline 1)

The first paleotopographic low occurs at the extreme south edge of the outcrop. The paleo-doline can be identified at two different sites, separated by 4.5 meters of alluvial cover and Quaternary collapse of overlying Pennsylvanian sandstone. The similarity of sites 1 and 2, which are 4.5 and 4.0 meters wide respectively, and their proximity to each other, suggests that they are actually one feature that is currently only intermittently exposed. The

sites are superficially similar, but have mesoscale differences, which indicate their development in different portions of the paleotopographic low. This is supported by the fact that they are situated at different vertical positions, based on the datum line. Site 1 is located 3.0 m above the datum, whereas site 2 is at an elevation of 3.7 m.

Because of poor exposures, *in situ* limestone associated with paleo-doline 1 is not observable. Although a limestone pinnacle separating the two sites is indicated on Figure 5, it actually occurs in front of the feature. Figure 15, a plan view of the paleo-doline, gives the appropriate placement for each feature in the horizontal plane.

b. Mesoscale (Paleo-doline 1)

Mesoscale features seen within the two sites in paleo-doline 1 include large brecciated fragments of limestone embedded in fine-grained matrices. As mentioned previously, Sites 1 and 2 are similar, but only superficially. Differences catalogued in the following description may reflect a different genesis as well as a different position for each site. The two sites will be described separately, although paleo-doline 1 is treated as one single feature.

i. *Matrix and Breccia Clasts*

Site 1, a depression protected by a sandstone overhang, is filled by a greenish yellow claystone that exhibits a hackly weathering fabric (Fig.16a). The greenish matrix consists of very fine clays and occasional silt-sized quartz grains. Iron oxides are rare. Thickness and lateral extent of the claystone is unknown due to the area's covered nature.

The claystone contains four visible well-rounded clasts of Upper Pennington Formation limestone, which range in size from 25 to 50cm in diameter. The clasts are separated from each other by the matrix, and show extreme reddening. Original fabric

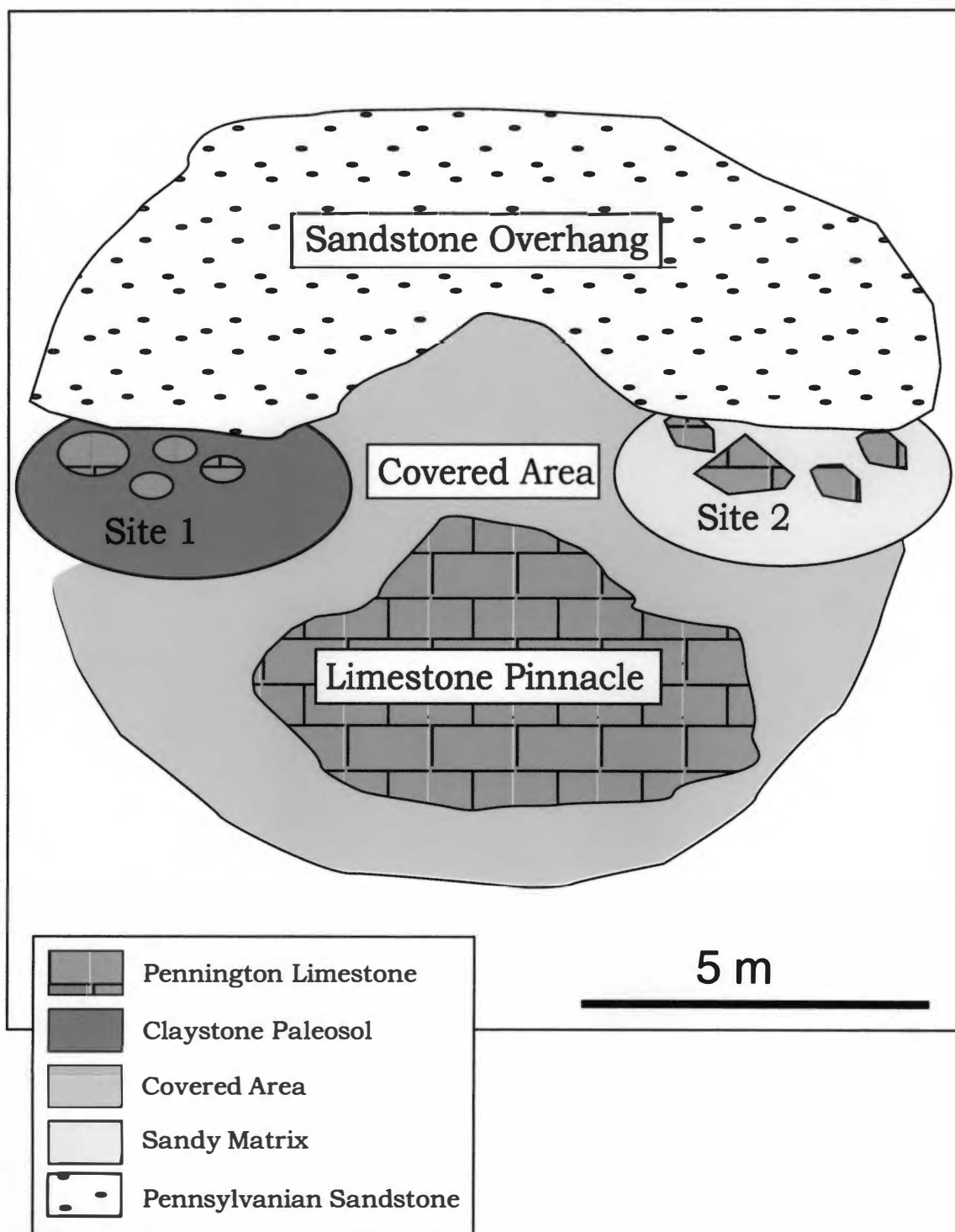


Figure 15 : Illustrative plan-view of paleo-doline 1, showing placement of pinnacle and sites 1 and 2. Each of the sites is approximately 4.5 meters wide.

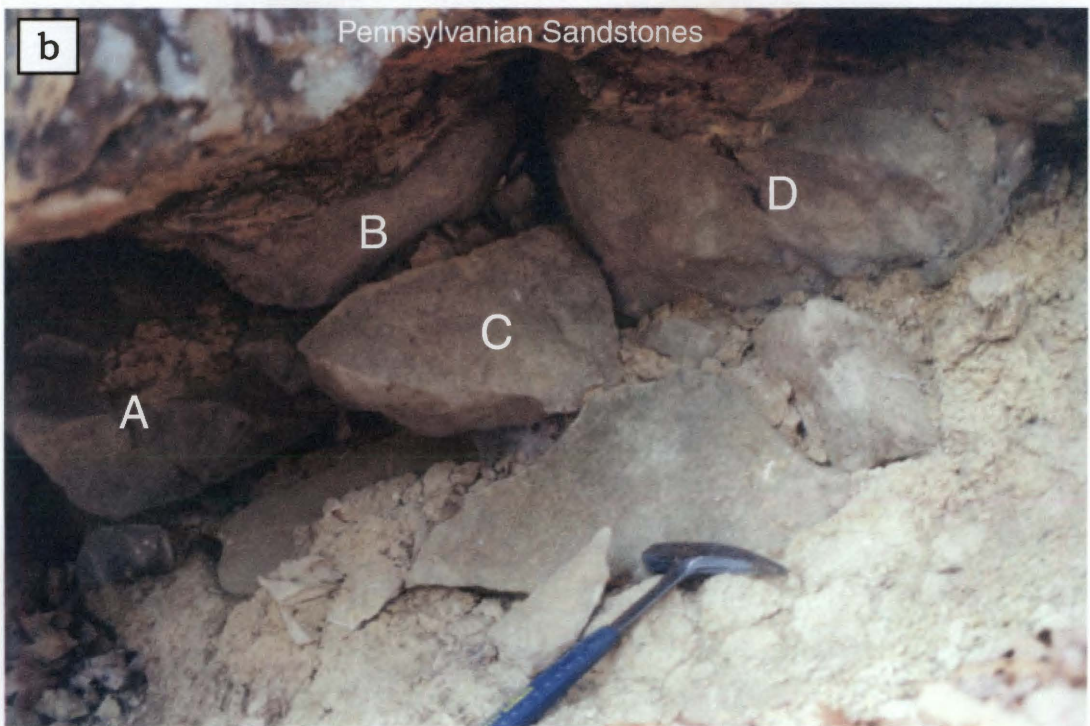
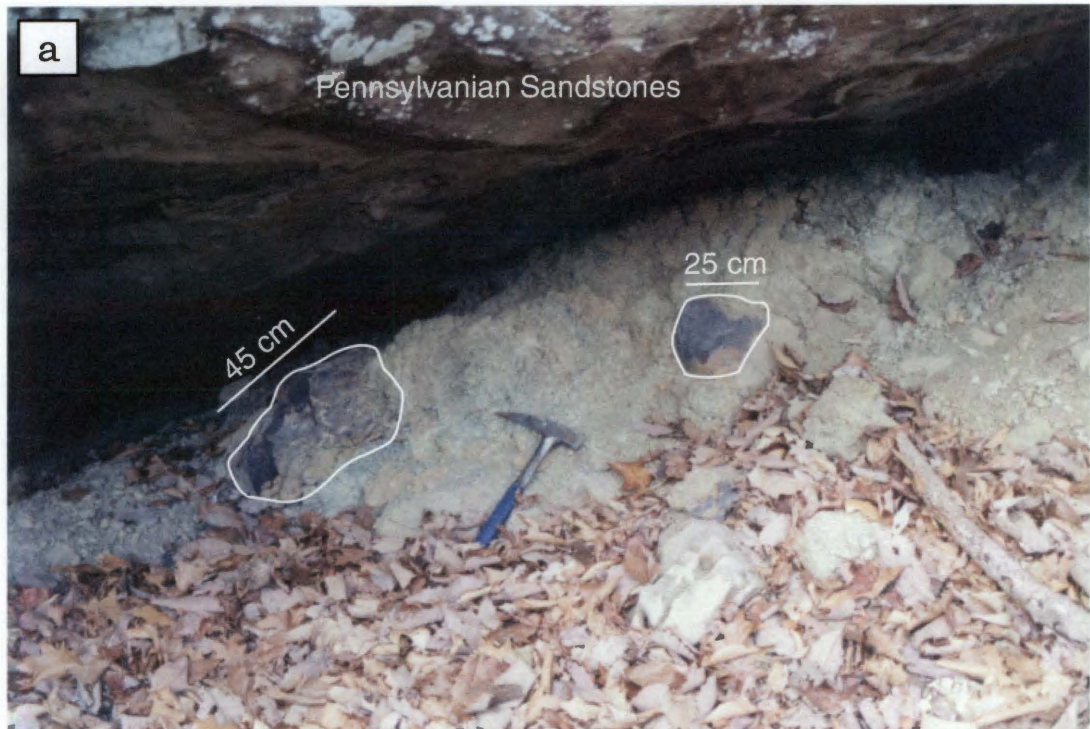


Figure 16 - Photographs of paleo-doline 1. Figure 16a - Paleodoline 1, Site 1: Rounded oxidized limestone clasts in a greenish-gray claystone paleosol matrix. Figure 16b - Paleodoline 1, Site 2: Angular limestone clasts in minor yellow sandy matrix. Diameter of clasts is : A - 75 cm, B - 60 cm, C - 45 cm, and D - 80cm.

and texture of the carbonate is obliterated due to iron oxide replacement of calcite.

Site 2, another depression protected by the overlying sandstone, also contains upper Pennington limestone clasts. The clasts occur in a sandy buff to yellow matrix (Fig. 16b), which does not exhibit any signs of pedogenic development. The matrix consists of fine quartz silt and sand grains, iron oxides, and a minimal amount of clays. Again, the thickness and extent of the sandy matrix is unknown due to cover.

Unlike site 1, the clasts in site 2 are extremely angular. Sizes are variable, but in general they are larger than those in site 1, and range from 25cm to the average sizes of 60 to 80 cm. The clasts have a random orientation, and are in direct contact with each other. A small amount of the sandy matrix fills interstices. There are as many as 15 to 20 clasts in this area, and only one or two show any signs of reddening or replacement by iron oxides. The majority of the clasts appear to be correlative to Unit 4 – a skeletal grainstone.

ii. Sandstone Deformation

In Site 1, overlying Pennsylvanian age sandstones show slight deformation. At the left edge of the feature, ball-and-pillow structures are found in the lowest layers. The rest of the Pennsylvanian sediments, though not extensively deformed, appear to gently dip back into the feature (Fig 17). Site 2 shows no obvious sandstone deformation.

2. Paleo-doline 2

a. Macroscale (paleo-doline 2)

The second paleokarst feature is found 35 meters to the north of paleo-doline 1. Paleo-doline 2 is the most spectacular and best-exposed paleotopographic low in this outcrop. It is a large depression that is approximately 40 meters in length, with a base that begins at the datum line. Based on surrounding limestone, the vertical relief is 4.0 m.



Figure 17 - Photograph of Paleo-doline 1, showing tilted sandstone layers filling in paleo-low. Oblique View of Site 1, from far left. Note overlying sandstone dipping backward into feature. Clast A, also seen in Figure 16a, is present in greenish-gray claystone. Fieldbook at lower left for scale.

Competent limestone surrounding the paleo-doline slopes gently toward the base of the feature. The south side, a wall of limestone approximately 20 m long, ranges from 4.0 to 4.5 m high in most areas, until it reaches the edge of the depression. There it slopes at approximately 45° , toward the base (Figure 18a). The north side of paleo-doline 2 is a conglomerate-covered pinnacle that grades into the paleo-doline with a slope of about 60° . It is discussed further, in association with a paleo-kamenitza.

Though both of the edges slope into the depression, imparting a bowl-shaped form, the appearance of a paleo-doline in outcrop can be rather misleading. As an observer sees only a two-dimensional outcrop, the feature may not maintain a consistent shape in three dimensions. The geometry of a paleo-karst feature is dependent on many variables. The most important variable in the upper Pennington limestone appears to be the limited thickness of the limestone itself. The upper Pennington limestone is only 4.5 meters thick at its greatest extent in the Leatherwood Ford outcrop. According to visual estimates in the field and a cross section based on rudimentary hand-leveled survey, the lowest visible point in the paleo-doline is only 0.2 to 0.4 meters above a highly resistant dolomicrite unit, which is pre-section upper Pennington limestone. Therefore, it appears that erosion forming the paleo-doline dissolved much, if not all, of the underlying upper Pennington limestone member.

b. Mesoscale (Paleo-doline 2)

The paleo-doline contains many diagnostic mesoscale features, including a reddish claystone paleosol, which fills in much of the available low space; a channel sandstone, which occupies the center of the paleo-topographic low; and a limestone pinnacle, present toward the north edge of the paleo-doline. Each of these, as well as other associated meso-

Figure 18 - Photographs taken within paleo-doline 2. Photos a, b, c, d, and e.



Figure 18 - Photographs taken within paleo-doline 2. Figure 18a - Left slope of paleo-doline 2. Circled area is mass of saprolitized limestone, square surrounds field book. A red claystone paleosol mantles the slope of the paleo-doline, and separates saprolite from competent limestone. Figure 18b - Paleo-doline 2, filled by a red and green paleo-vertisol that shows pedogenic features.



Figure 18 cont. - Photographs taken within paleo-doline 2. Figure 18c - Scattered limestone clasts occur at the base of paleo-doline 2. Figure 18d - A pinnacle arrangement of limestone clasts occurs in the paleosol matrix of paleo-doline 2. Figure 18e - An iron oxide crust occurs on weathered limestone in paleo-doline 2.

scale features, are described below.

i. Matrix and Limestone Features

Two different types of fine-grained deposits fill in the paleo-doline. The lower portions of the paleo-doline are filled by a hackly claystone that shows pedogenic features (Figure 18b). These include high clay content, occasional pedogenic slickensides, angular blocky peds, rare fine root traces, and sepic-plasmic microfabrics (Driese et al., 1998). The paleosol is red at the base, with elliptically shaped green mottles interspersed through the red matrix. Approaching the unconformity, the red color fades to a greenish-gray color, which dominates in the upper portions of the paleo-doline. Despite the contrast in color, there is no physical difference between the green mottles and the rest of the paleosol. Although the paleosol is the dominant fill for the paleo-doline, it is mantled by a fissile greenish-gray claystone that has no obvious pedogenic structures. The claystone is a thin unit that occurs as a mantle for the paleo-karst features throughout the entire outcrop. This includes, but is not unique to, the paleosol within the paleo-doline.

The red claystone paleosol contains limestone clasts derived from surrounding bedrock. All of the clasts are moderately rounded and occur in two different physical arrangements. The first type is a random scattered arrangement near the covered base of the paleo-doline (Figure 18c). The other type is a disconnected pinnacle type of arrangement, with vertically stacked cobbles of limestone, separated by paleosol material (Figure 18d).

Toward the north edge of the paleo-doline, an area of rotten limestone is found (Figure 18a). It maintains original placement and depositional structure, but is very soft, and appears to have been extensively leached. It is interpreted as saprolitized limestone weathered during the formation of the unconformity.

Limestone surrounding the dissolutional feature maintains competence, but has also been affected by the karstification process. As noted in Figure 18a, the edging limestone forms a gentle shelf that gradually dips down into the feature. The limestone in contact with the red claystone paleosol has an iron oxide crust, which extends at least 3-6 cm down into underlying limestone (Figures 18e). The boundary between the reddened and the unaltered limestone is commonly very sharp.

ii. Associated Sandstones

A sandstone channel occurs in the center of the paleo-doline. It consists of a dominant channel form and a layer of horizontally bedded sandstone, which is beneath and to the north of the channel (Figure 19a). The channel system begins about 0.2 meters above the lowest visible point of the depression, and extends vertically so as to intertongues with the base of the overlying Pennsylvanian sandstone units.

The dominant channel is 3.0 m high and approximately 1.0 m wide at the base, becoming 3.0 m wide at the top. Geometrically, the channel has a v-shape. Bedding within the channel complex is obscured, but occasional sets of upright cross-bedding occur in the upper right-hand section.

The most interesting feature about the channel concerns its relationship with Pennsylvanian sandstones that overlie the feature. Thin sandstone layers, approximately 0.25 m thick, show deformation on either side of the dominant channel. The layers bend like a hinge on either side of the underlying channel, and then wrap around the edges. The south side shows nearly 1.5 m of displaced sandstone, whereas the north side shows 0.75 m (Figure 19b). Although the layers are deformed in a manner suggesting large displacement, they still maintain original depositional lamination that is oriented vertically. Laterally continuous

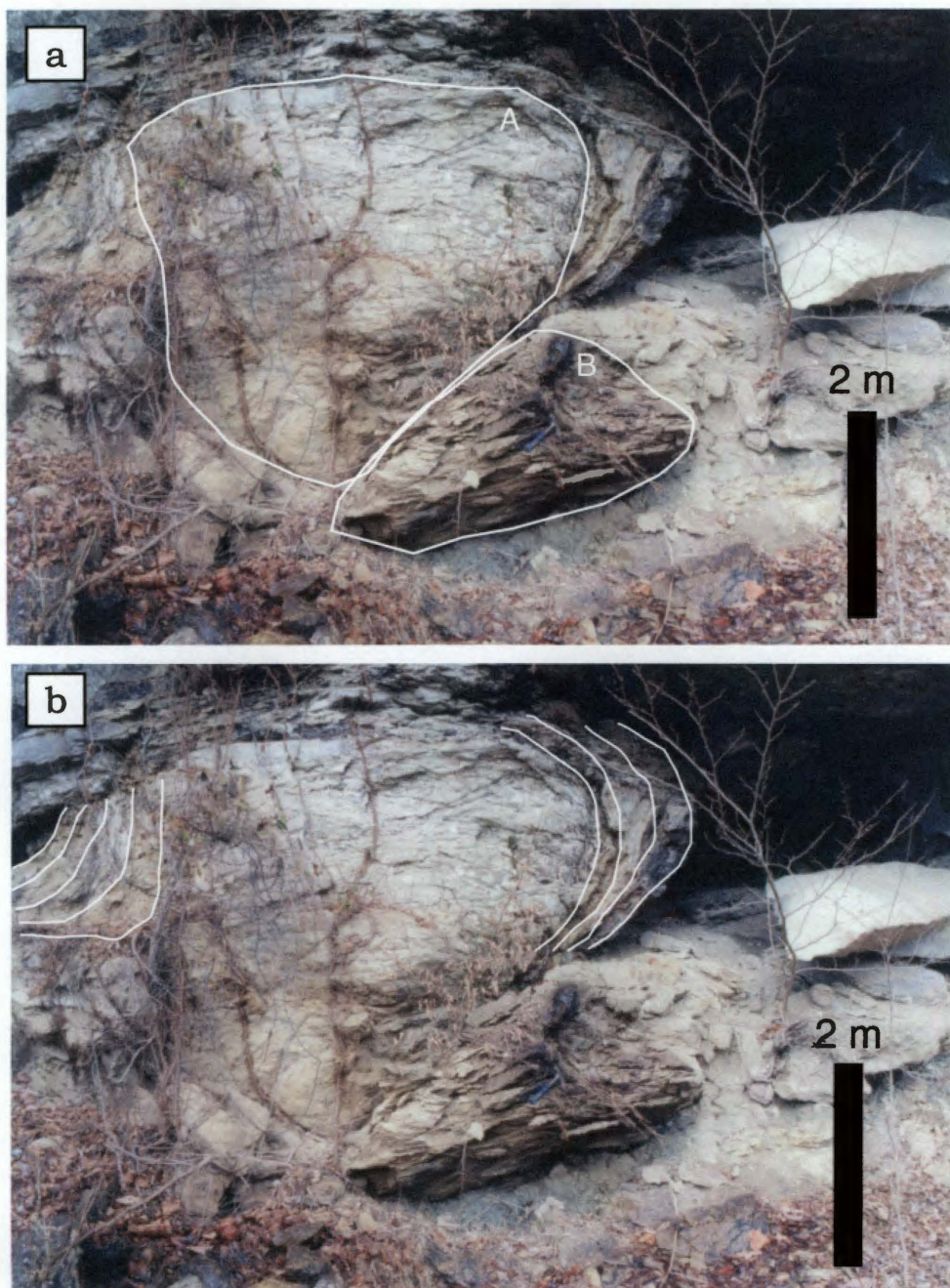


Figure 19a - Paleo-doline 2: Channel sandstone (A) occurring in the center of paleo-topographic depression. Note smaller disconnected sandstone body (B) beneath and to the right of main channel. Figure 19b - Paleo-doline 2: Graphic illustration of deformed sandstone. Compare to Figure 19a.

sandstone layers that overlie the channel complex are undeformed. Above the deformed layers of Pennsylvanian sandstones are hundreds of meters of locally flat lying and undisturbed Pennsylvanian sandstones. Only when other major paleo-karst features are present do the overlying sandstones show any type of deformation, and, as is the case here, the disturbance disappears within approximately 2 meters. Any attempt to laterally trace or correlate the channel-wrapping sandstones along the roof of the Pennsylvanian sandstone overhang is impossible, due to extensive Quaternary episodes of collapse and erosional removal.

The small sandstone layer that occurs below and to the north of the dominant channel sandstone is unremarkable, except in its placement. Although bedding is difficult to discern, it appears horizontally laminated, but slightly deformed. The small sandstone layer is separated from the dominant channel sandstone by a thin layer of greenish-gray claystone.

iii. Limestone Pinnacle

To the north of the sandstone channels, and within the paleo-topographic low, is a limestone pinnacle. It is probably only 3 meters high, but because it is surrounded and covered by the paleosol, the maximum size and placement of the limestone pinnacle feature is unknown. The very top of the pinnacle is exposed within the paleo-doline. It has a rounded and smoothed surface, which shows the presence of the iron oxide weathering rind that stops abruptly within 3-6 cm of the rock-soil interface.

3. Paleo-Kamenitza and Surrounding Pinnacles

a. Macroscale (Paleo-kamenitza)

The immediate north edge of paleo-doline 2 is bounded by a limestone pinnacle that defines the edge of the next paleo-karst depression. Although this next feature is not of the

same scale as the paleo-doline, it is also a dissolutional depression. In this case, it is a shallow depression, with a flat floor that is referred to as a paleo-kamenitza (Figure 20a). It is about 4.0 m in width, but has only about 50 cm of relief, and is located on a paleo-topographic high in the Pennington Formation limestone, 4.3 meters above the datum line. The paleo-kamenitza contains thinly bedded deposits of the green claystone, which mantle other paleo-karst features as well.

The north side of the paleo-kamenitza changes from a pinnacle approximately 2 m above the base of the paleo-kamenitza, with a 60° slope, to the flat surface of the dissolutional feature. The south edge is a pinnacle approximately 0.5 m above the paleo-kamenitza that has a much gentler slope. This reduced slope is due to the presence of residual conglomerate that trails off of the south pinnacle. Not only does the conglomerate mantle the south slope and edge of the kamenitza, it also fills an unusually shaped karren feature that occurs at the interface between pinnacle and paleo-kamenitza.

b. Mesoscale Features

i. Pinnacle 1 and Karren Feature

The limestone pinnacle comprises a paleo-topographic high that is about 4.8 m above the datum line (Figure 20b). Although the pinnacle is at the south edge of the paleo-kamenitza, it also forms the defining north edge of paleo-doline 2. Whereas the top of the pinnacle is bare, all sides are draped by a consolidated residual conglomerate (Figures 20c, d, and e). The conglomerate consists of mostly rounded limestone clasts up to 50 cm in diameter. Interstices between clasts are filled by a mixture of greenish-gray claystone, and chert and carbonate lithic-dominated sandstone.

This breccia/conglomerate not only mantles the edges of the pinnacle, but it also fills

Figure 20 - Photographs of paleo-kamenitza and associated features. Photos a, b, c, d, e, and f.



Figure 20 - Photographs of paleo-kamenitza and associated features. Figure 20a - Flat floored feature (paleo-kamenitza) is filled by a mixture of greenish gray claystone and a mantling breccia (breccia is circled.) Note karren feature (A) and pinnacle (B) to the left. Figure 20b - West side of the pinnacle to the west of the kamenitza. Note solution runnels (circled), 1 -2 cm deep indentations in the rock.

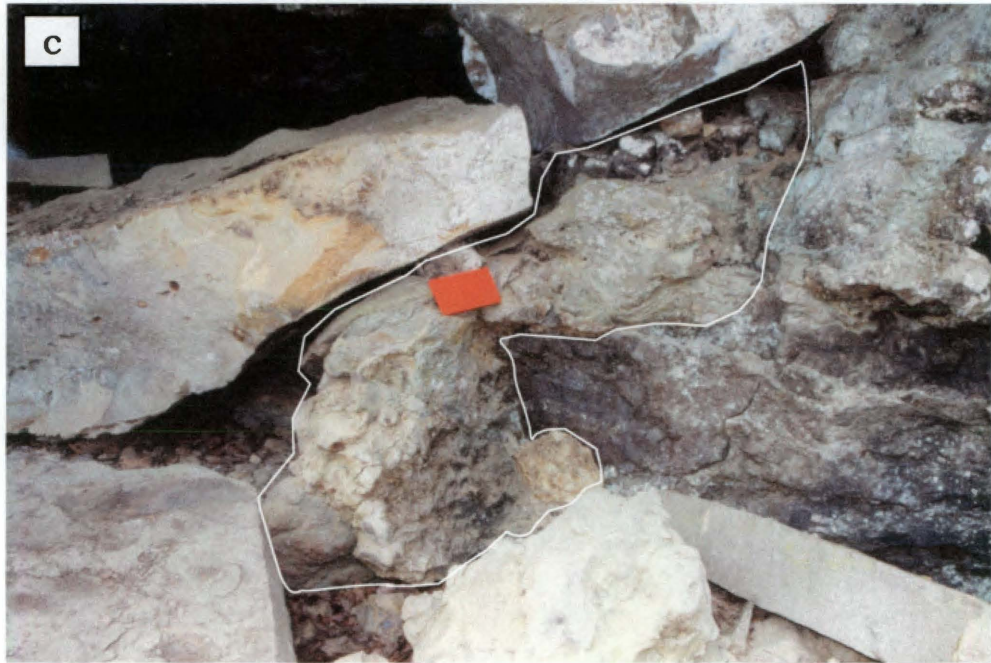


Figure 20 cont. - Photographs of paleo-kamenitza and associated features. Figure 20c - Breccia - Conglomerate, mantling west side of pinnacle depicted in Figure 20b. The mixture consists of greenish-gray claystone, limestone clasts, sandstone, and chert. Breccia body is outlined. Figure 20d - Breccia- Conglomerate spilling off the north side of the pinnacle shown in Figure 20b. In this instance, much of the matrix has been eroded away, leaving only the limestone clasts.

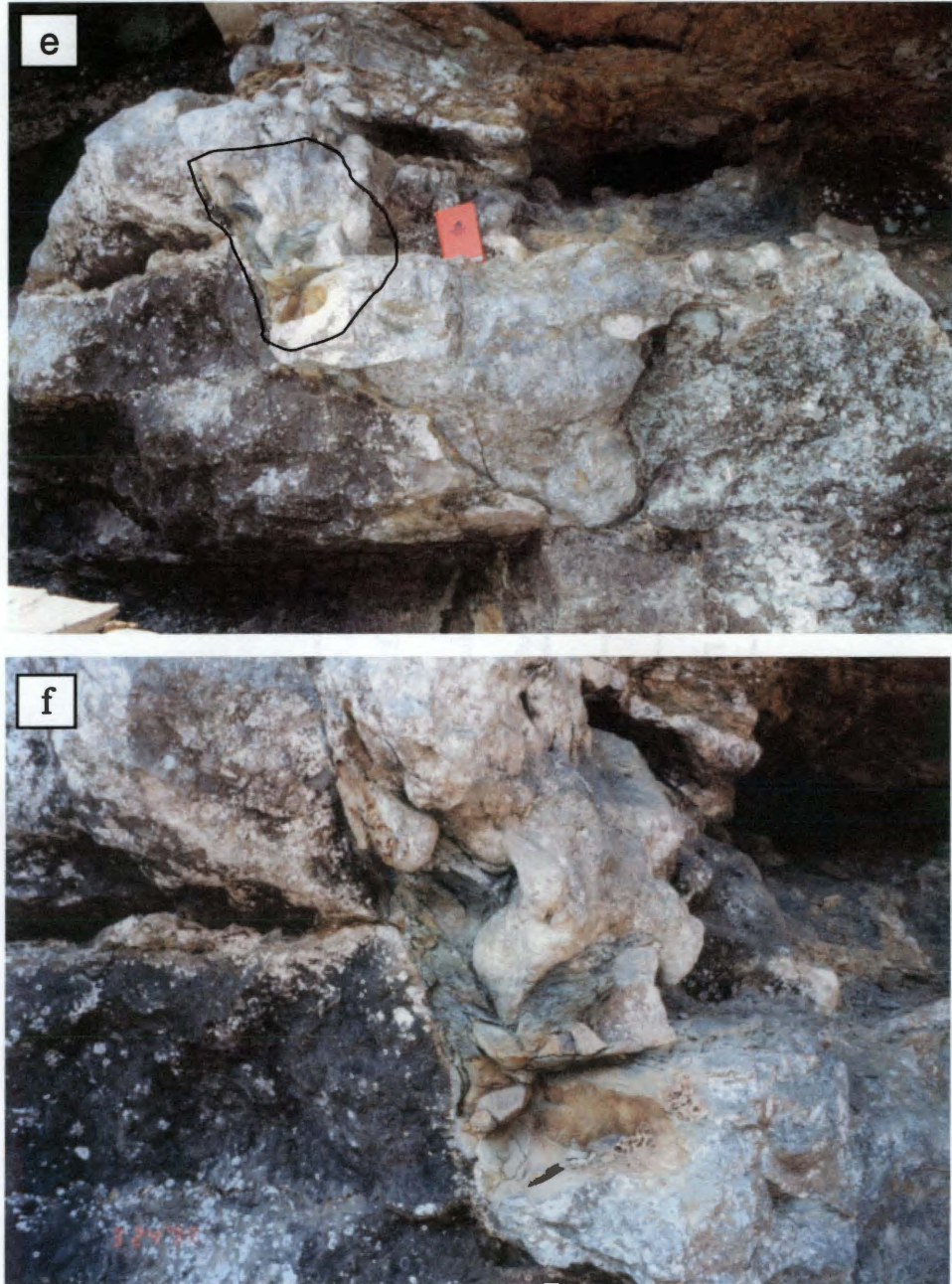


Figure 20 cont. - Photographs of paleo-kamenitza and associated features. Figure 20e - Funnel shaped paleo-karren feature found at the intersection of the paleo-kamenitza and the pinnacle to the left. Paleo-karren is filled with a breccia-conglomerate, composed of limestone clasts, green claystone, sandstone, and chert. The feature is approximately 0.75m high. Figure 20f - Closeup of circled area at west edge of paleo-karren feature, seen in Figure 20e. Notice the green claystone matrix filling interstices between limestone clasts.

in another paleo-karst feature that occurs near the junction between the paleo-kamenitza and the limestone pinnacle. This feature, called a paleo-karren, has an irregular shape that resembles a wavy V (Figure 20f). It is 0.6 m high and only a few tens of centimeters wide at the base, and gradually widens to a full meter at the top. The paleo-karren is very sharp-sided, and is entirely filled by the residual conglomerate.

One other mesoscale feature occurs on the pinnacle that is entirely separate from the conglomerate. A set of solution runnels, which are centimeter-sized grooves incised into the bare limestone, occur on the sloped top of limestone pinnacle 1 (Figure 20b).

ii. Limestone Pinnacle 2

Limestone pinnacle 2 is the paleo-topographically highest point in the Leatherwood Ford outcrop (Figure 21a), approximately 6.5 meters from the datum line. Not only does pinnacle 2 comprise the thickest section of upper Pennington limestone, it also is the only place where the pre-section brecciated dolomicrite (Unit 1) is exposed (Figure 21b).

This pinnacle is capped by a concentration of moderately rounded limestone clasts, which are incorporated into a conglomerate that is quite similar to the conglomeratic body occurring in the paleo-kamenitza. The matrix consists of greenish-gray claystone, chert and carbonate lithic-dominated sandstones. Clasts range from 35 - 60 cm in diameter.

4. Shallow Paleo-Dolines 3, 4, and 5

a. Macroscale

Limestone pinnacle 2 mentioned earlier constitutes the north edge of a series of paleo-dolines, referred to here as 3, 4, and 5. These small depressions, ranging from 3 to 5 meters each in width, are quite shallow, with original depths of probably less than 2 meters. Although the base of the upper Pennington limestone is covered, each of the depressions are

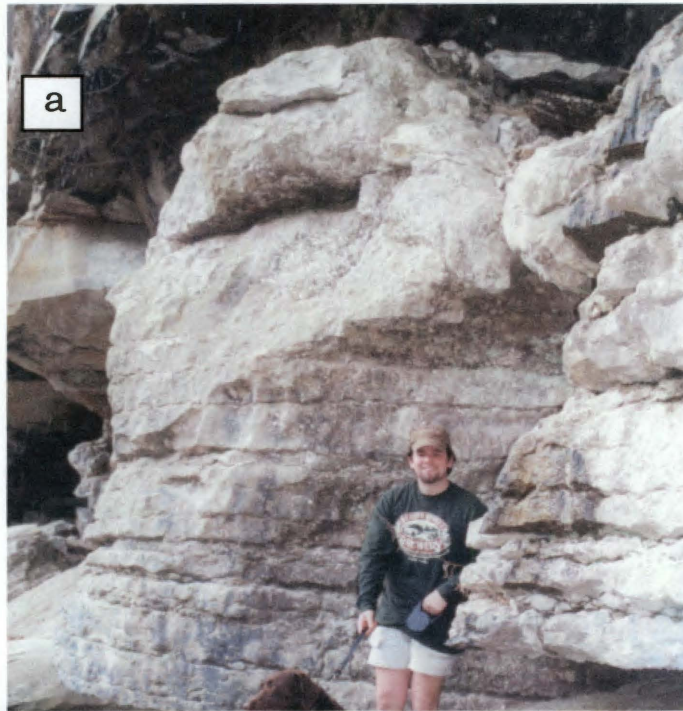


Figure 21a - Pinnacle that separates paleo-kamenitza from paleo-doline 3. This is the thickest upper Pennington limestone section at the Leatherwood Ford outcrop. Figure 21b - Pre-upper Pennington limestone, is Unit 1 - a brecciated dolomicrite that occurs beneath pinnacle shown in Figure 21a.

3 to 4 m above the datum line. The series of paleo-dolines ends abruptly with a sharp elevation increase in the limestone, thereby giving rise to a knife-sharp surface that is in direct contact with overlying Pennsylvanian sandstones. This contact marks the end of the outcrop section.

One problem encountered in this area not present in other portions of the outcrop is the presence of modern karstic dissolution. Some limestones have developed sharp karren along bare surfaces, indicating a possible conduit for Quaternary groundwater flow.

b. Mesoscale Features

One paleo-topographic low, paleo-doline 3, is 3.5 meters wide and has a smooth, flat base. It is surrounded by the 6.5 m limestone pinnacle to the south, and a wall, 0.5 meters wide and 5.0 meters above the datum line, of weathered limestone to the north.

Paleo-doline 3 contains a sandstone channel that is about 1.5 meters wide and less than 0.6 meters deep (Figure 22a). The channel has an oval-shaped geometry, except for a limb that extends laterally from the midsection of the channel sandstone. The thin arm of sandstone laterally extends 0.5 m, and appears to have been deposited beneath an overhang on the limestone pinnacle on the north side of the depression.

A pinnacle separates paleo-dolines 3 and 4 (Figure 22b), and traces of the limestone conglomerate mantle the sides of the pinnacle and drape down the south side of paleo-doline 4 (Figure 22c). This depression is 2.4 m wide and the base of the depression is 4.5 m above the datum line. This depression is not a smooth-bottomed surface, but instead shows a grooved and pitted surface. The conglomerate is not present in the center of paleo-doline 4, but reappears on the north side, where it drapes the pinnacle separating paleo-dolines 4

Figure 22 - Photographs of paleo-dolines 3, 4, and 5, and associated features including sandstone channel and pinnacles. Photos a, b, c, and d.

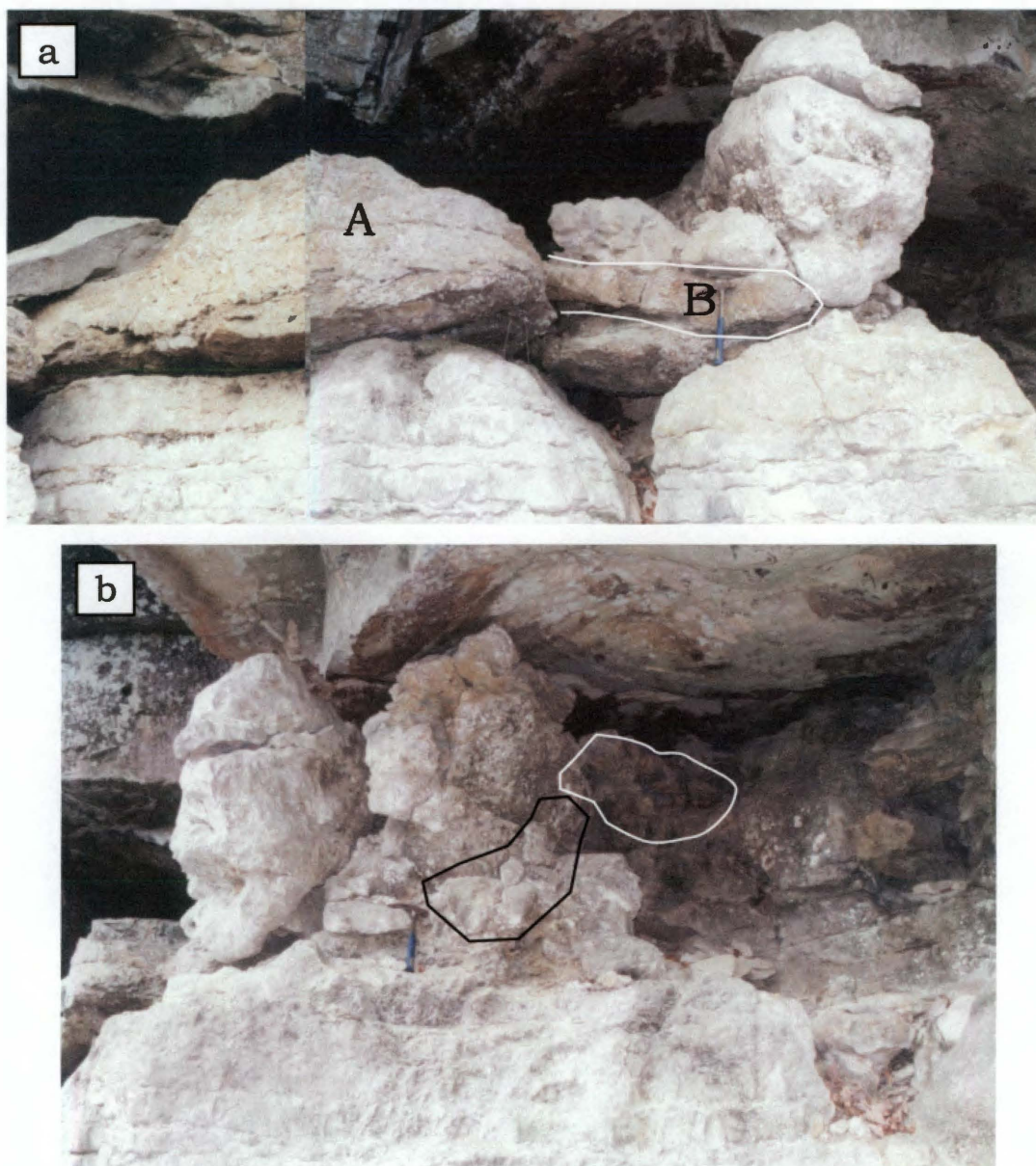


Figure 22 - Photographs of paleo-dolines 3, 4, and 5, and associated features. Figure 22a - Sandstone channel (A) occurring in paleo-doline 3. Note an extension of sandstone (B), which appears to have been deposited beneath the pinnacle to the right. Figure 22b - Limestone pinnacles separating paleo-dolines 3 and 4. Circled areas indicate conglomerate-breccia mantling the east pinnacle.



Figure 22 cont. - Photographs of paleo-dolines 3, 4, and 5, and associated features. Figure 22c - The base of paleo-doline 4 has a rounded, but pockmarked appearance. Circled area surrounds a particularly good example of small grooves and pits, which were possibly caused by root growth. Figure 22d - This was once a wall of limestone that separated paleo-dolines 4 and 5. When the wall was breeched, a hole developed that was filled with mantling breccia -conglomerate. Hammer is resting on the fill.

and 5.

The limestone paleo-high that subdivides paleo-doline 4 and 5 comprises a pair of pinnacles. The pinnacles are aligned in a parallel line, which suggests the former presence of another limestone wall divider that was later breached. Limestone conglomerate occurs on the edges of paleo-doline 5 and also in the space between the two pinnacles (Figure 22d). This shallow depression, as was the case with the other two associated paleo-dolines, has been altered by Quaternary karstic dissolution. This has changed the geometry of the feature to the degree that the initial shape is unknown.

This feature marks the end of the exposed Leatherwood Ford outcrop. Paleo-doline 5 ends with the abrupt rise of a pinnacle to the north, which is 6.0 m above the datum line. At this point the surface of the limestone, which has been so topographically and geomorphically varied throughout the outcrop, becomes planar and is buried beneath the overlying Pennsylvanian sandstones.

5. Microscale – General

The microscale includes all petrographic-scale features caused by karstification that occur in the limestone. In most cases features are observable in outcrop and thin section.

Reddened limestone is common throughout the outcrop (Figure 23a). In general, it is present in small amounts, concentrated along open fractures or grikes. The amount of iron oxide decreases further from the fracture/dissolutional openings.

Reddened material is also present along the upper surfaces of exposed limestone. The iron oxides partially replace, as well as coat, allochem grain surfaces (Figure 23a). They are also commonly present as intergranular cement. An extreme example of this is seen in limestones associated with the overlying claystone paleosol. In these samples, the iron

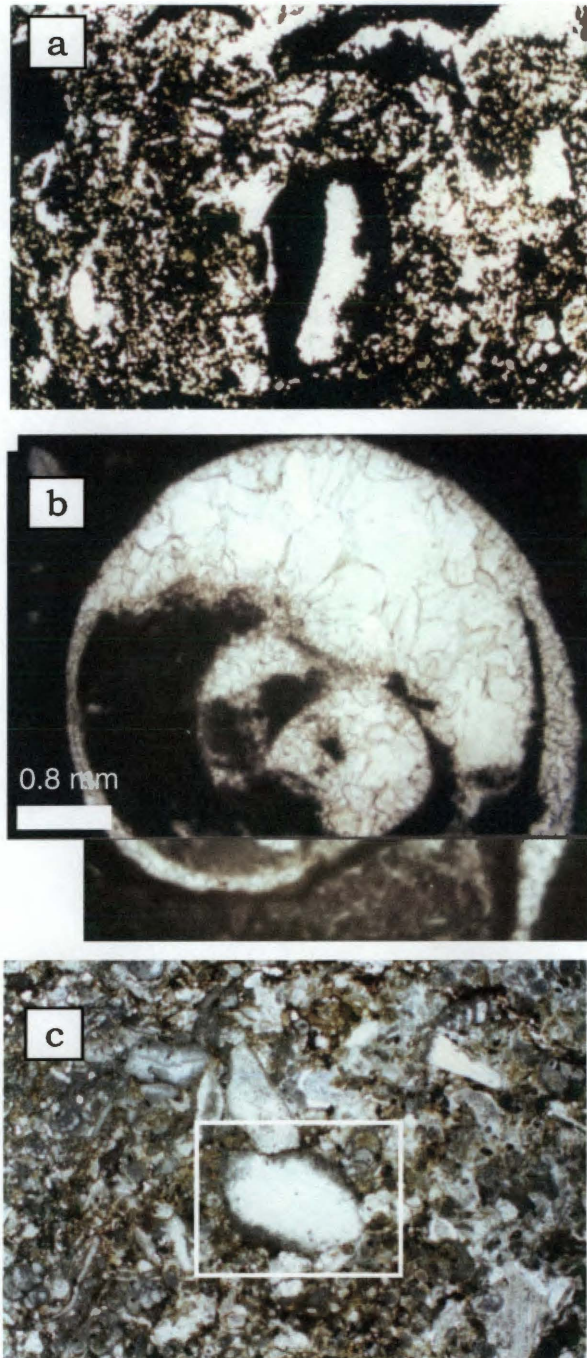


Figure 23 - Photomicrographs taken in plane light, illustrating subaerial karstification on the microscale. Figure 23a - Iron oxides are present as grain coatings, replacive and intergranular cement. Figure 23b - Moldic pores are common throughout the outcrop. This is a photomicrograph of a gastropod, which has been filled in by calcite cements. The fringing crystals are first generation meteoric cements. Figure 23c - The box illustrates an echinoderm grain that has been micritized.

oxides have formed a crust, replacing or displacing all of the available calcite. The crust extends downward from the unconformity, usually for 4 - 6 cm, where it stops abruptly.

Different types of dissolution-related porosity occur both in outcrop and thin section. Moldic pores of larger allochems, including brachiopods, gastropods, ostracodes, and occasional echinoderm grains, are generally occluded with calcite spar cement (Figure 23b). Oversize intergranular pores are also filled with calcite spar cement. Downward-tapering vertical fissures, also called grikes, occur at the upper surface of the limestone. The grikes are up to 1 cm wide, and 30 to 50 cm long. They are generally filled with calcite cement, clay, and iron oxide.

One last result of karstification is micritization of allochems occurring within 5 to 10 cm of the upper surface of the limestone (Figure 23c). The grains have been altered from their original state to a muddy fine-grained matrix mimicking original grain shape.

6. Cement Phases

Diagenetic cement phase description is found at the end of the limestone section.

C. Paleokarst Feature Formation and Interpretation

Karst development is dependent on the exposure of carbonate rock to aggressive (acidic or carbonate-undersaturated) water. This can occur in many different ways, often with more than one superficial mechanism contributing to karst feature development. The two most obviously different modes of formation are those of subaerial exposure and intrastratal karst, that is, karst developing at the earth's surface or beneath lithified rock, respectively. This thesis will consider karst developing under a soil or alluvial mantle, covered karst, a natural component of subaerial exposure.

The paleokarst features described in the previous section are the basis for the

following hypothesis of subaerial exposure and karstification of the upper Pennington Formation limestone. This discussion section interprets a likely mode of formation for the entire paleo-karst surface, based on a loosely constrained relative timing of events. Because many of the steps occur penecontemporaneously, it is difficult to write a simple narrative of events. The relative timing of formation for each phase of the paleo-karst plane is included in Figure 24, which shows relative visual placement for each of the features.

A paleokarst surface represents the history of an evolving, interconnected landscape. Although the past sections presented descriptions of many different, and seemingly disconnected, karst features, the crux of this thesis is to place the paleo-karst features in a temporal order, explain their associated mode of formation, and prove subaerial exposure as the mechanism for their development. The genesis and continued development of each feature is intertwined with the development of the entire paleokarst surface. Due to the differences in timing of formation and in preservation potential, each feature reveals insights as to the development of the karst plane as a whole.

1. PHASE 1 – Background and Initial Development

The Pennington Formation represents changing depositional conditions because it is a mixed siliciclastic-carbonate sequence. Although the Chesterian represents a time of overall regression, the Pennington Formation records repeated small-scale fluctuations of sea level rise and fall. During a small-scale transgression, the upper Pennington Formation limestone member was deposited (Figure 14). As sea-level continued to drop, the limestone was subaerially exposed, beginning the history of subaerial exposure and karstification recorded in features found in the upper Pennington Formation limestone.

Dissolution of the upper Pennington Formation limestone began, and continued

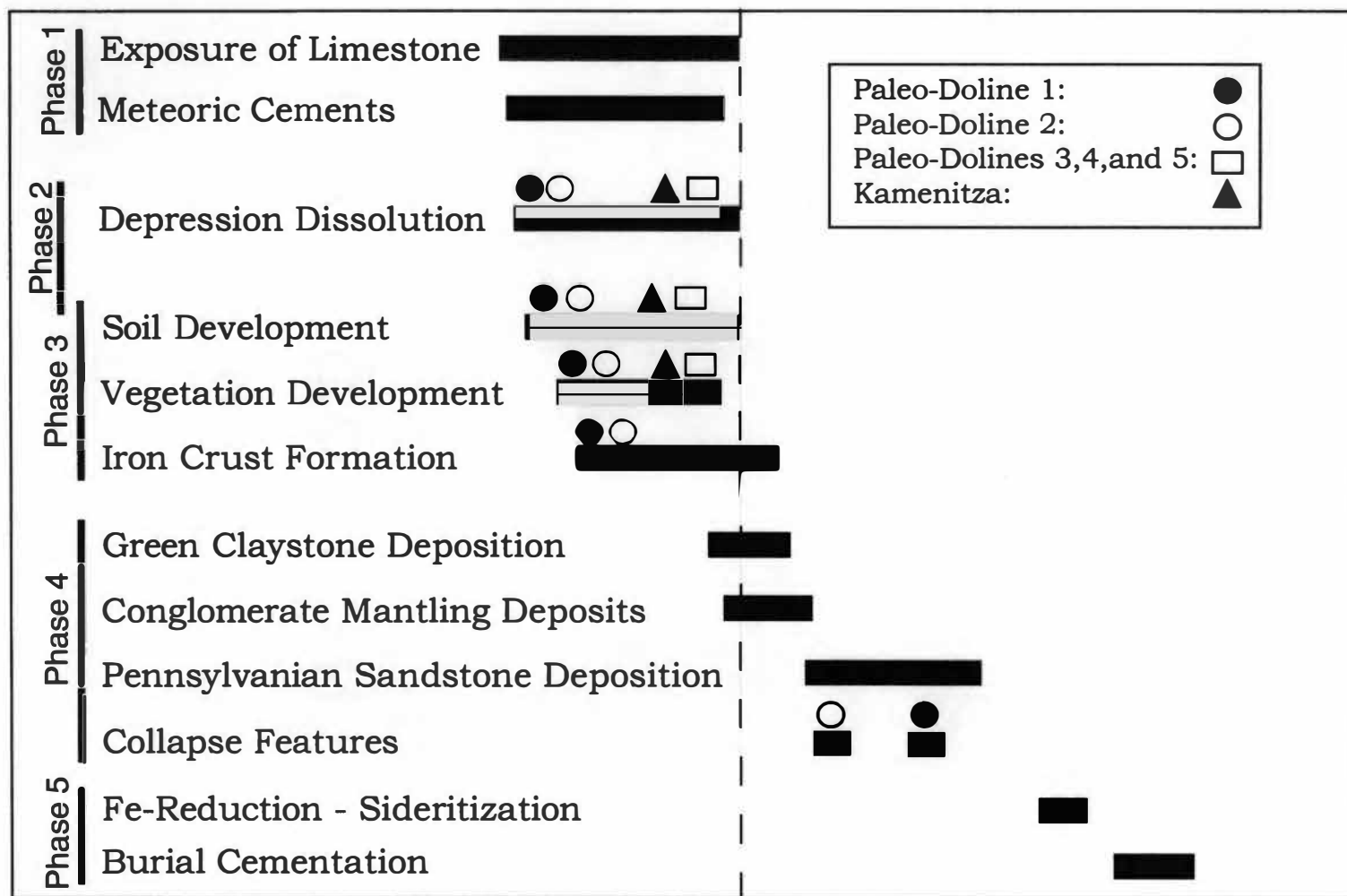


Figure 24: A relative time diagram of feature formation, Pennsylvanian sedimentation, and late diagenesis. Each of the features are placed according to their development relative to each other. Refer to symbols. Centrally located dashed line indicates the change from exposure (late Miss - early Penn?) to sandstone sedimentation (early Penn).

throughout paleokarst formation, on a small scale. Meteoric water, upon reaching the surface of the carbonate, dissolved metastable carbonate constituents. This resulted in the formation of moldic pores (Figure 23), intragranular pores, micritized grains, and non-fabric-selective, vertically oriented, dissolution fissures (grikes). Although the pores are seen throughout the upper Pennington limestone, most of the larger pores are seen in the upper meter of section. As waters became oversaturated with respect to CaCO_3 , early meteoric carbonate cements precipitated in the open pores.

The hypothesis that meteoric water was both the mechanism for carbonate removal, and the initial precipitator of mold-filling calcite cements, is supported by work done by Driese et al. (1998). This study investigated stable isotope data taken from whole rock, cement, and allochemical analyses in the upper Pennington limestone. Figure 25 is a plot of isotopic values from whole rock analysis of the upper Pennington Formation limestone. Relatively low $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, as compared to normal isotopic values for Mississippian marine calcite, in limestone nearest the paleokarst surface may indicate limestone stabilization in the presence of meteoric water. The values vary throughout the limestone, with the most depleted isotopic values for both C and O nearest the paleokarst surface. Less alteration by meteoric waters is inferred in the lower portions of the outcrop, as limestone nearer the base has $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values closer to those of Mississippian marine calcite, although still not marine values.

According to Driese et al. (1998), the isotopic values from the upper Pennington limestone reflect two processes consistent with a subaerial exposure interpretation: (1) contribution of isotopically light soil-gas CO_2 near the exposure surface, resulting in low $\delta^{13}\text{C}$ values in the altered carbonate; and (2) provision of isotopically light oxygen by

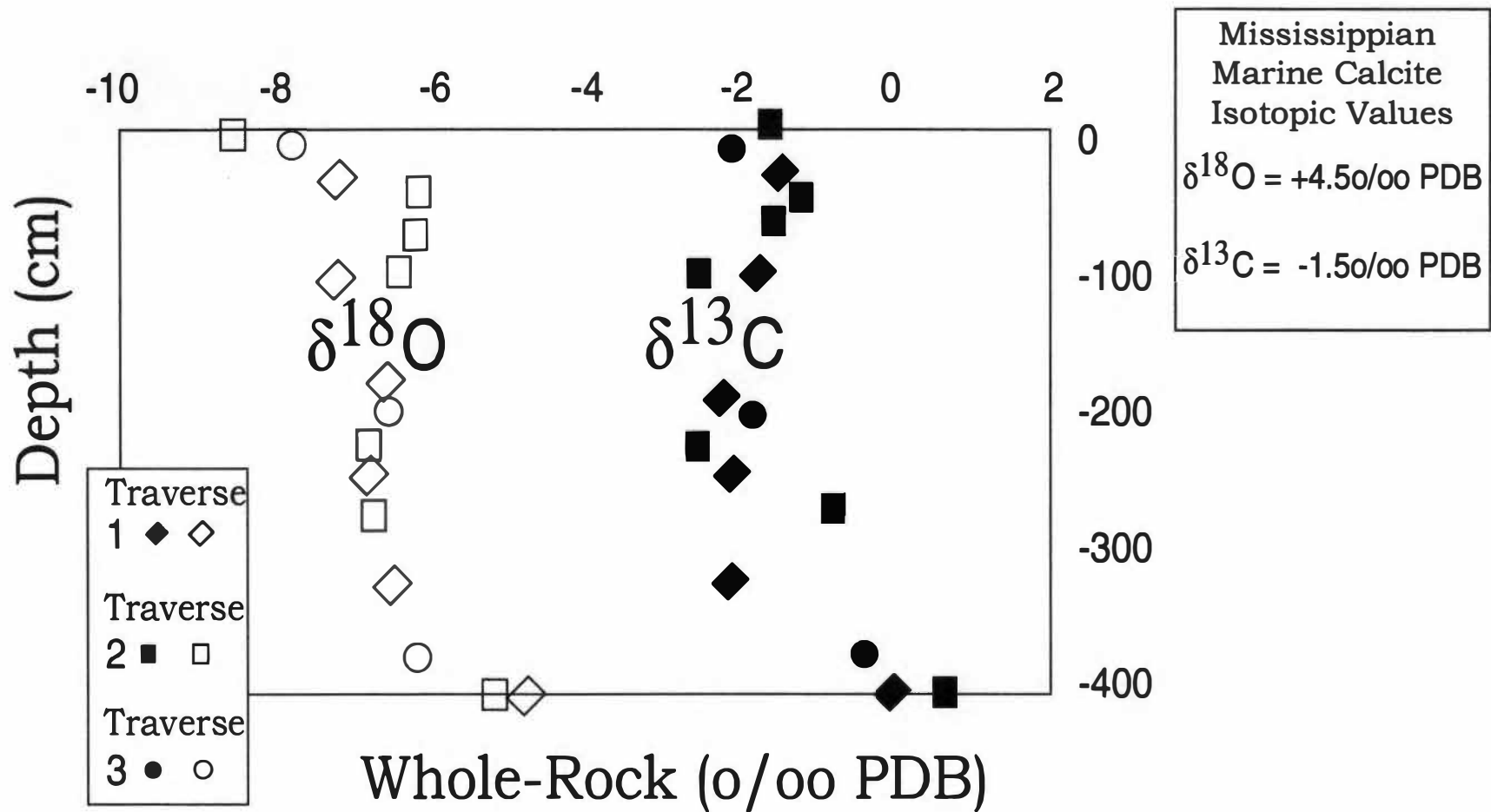


Figure 25 - Isotopic data from whole rock sampling traverses of upper Pennington Formation limestone. Adapted from Driese et al. (unpub.). Isotopic values for Mississippian Marine calcite are from Meyers and Lohmann, (1985) and Popp et al. (1986).

meteoric water, resulting in the depleted oxygen isotope values found nearest the paleokarst surface. Though these trends indicate alteration by meteoric water, they also offer insights as to the nature of the exposure surface. A study by Allen and Matthews (1982) indicates that $\delta^{18}\text{O}$ values of limestone at an exposure surface would become increasingly enriched as evaporation removes lighter isotopes. The depleted values seen in the upper Pennington limestone contradict this study, suggesting insignificant amounts of evaporation at the surface. Additionally, an overlying claystone (paleosol) mantle may have acted as a barrier to evaporation, maintaining the meteoric $\delta^{18}\text{O}$ value. The claystone paleosol also relates to the presence of the negative $\delta^{13}\text{C}$ values. The contribution of lighter ^{13}C to the paleosol by vegetation would result in an increasingly negative $\delta^{13}\text{C}$ isotopic value, due to the fact that plants incorporate isotopically light $\delta^{13}\text{C}$ more readily than the heavier isotope.

Although this explanation is plausible, an additional hypothesis, could be entertained (C. Mora, pers. comm., 2000). There is a possibility that the isotopic signatures for $\delta^{18}\text{O}$ have been overprinted by diagenetic fluid flow. The fact that the $\delta^{18}\text{O}$ value is so negative is problematic in light of the Leatherwood Ford's paleo-latitude and paleo-altitude, thus the possibility that later diagenetic fluids affected the $\delta^{18}\text{O}$ value. Additionally, there is the likelihood that the data is averaged, due to the use of whole rock analyses, which show an average signal for the entire rock. The problem implicit in this is that the whole rock study includes cements from early and late diagenesis as well as other constituents, which might cause signal distortion.

2. PHASE 2 – *Paleo-karst Feature Development*

The development of karst features in limestone is dependent on many different variables. One of the most important is the manner in which the rock itself reacts to

dissolution. This can be the deciding factor in paleokarst feature type, size, and shape. As the carbonate changes with dissolution, other factors come into the equation. These include carbonate interaction with soil and/or vegetation.

The manner in which upper Pennington Formation paleokarst features formed is discussed below in two sections. The paleo-doline, which is the most common feature seen in subaerially exposed limestone, is discussed first. As most of the depressions seen in the upper Pennington limestone fall into this category, it is of greatest importance in understanding the formation of the exposed surface. The second portion of this section discusses the only other major type of paleokarst depression found in the upper Pennington limestone, a flat-bottomed kamenitza, which is less common and has a different genesis.

a. Paleo-doline Development

Dolines are closed hollows of small to moderate dimensions, which are generally bowl-shaped, with a circular or elliptical plan. The diameter is usually much greater than depth, and they range in size from 10 - 1,000 m wide and 2 - 100 m deep (Sweeting, 1973).

There are a number of reasons why this paleo-landform was prevalent in Chesterian Tennessee; these include climate, limestone type, and possibly the limited thickness of the Pennington limestone itself. Dolines do not tend to form in arid or semi-arid landscapes due to the rapidity of both the intense showers and the run-off. Under these circumstances, surface waters do not have the time to percolate and penetrate into the limestone. Due to the prevalence of the doline form, it seems safe to assume a moderately wet climate by late Pennington time. The type of limestone must also be considered. Limestone that is impermeable between cracks or joints is much more likely to give rise to a doline than porous limestone that absorbs water more uniformly at the surface. The upper Pennington

limestone member is armored by a dense sparry calcite-cemented grainstone, which appears to have been the perfect medium for doline formation.

The climate and the type of limestone are only the initial factors that lead to the ultimate geometry of the feature. Another factor that seems to have played an integral role in the formation of paleo-dolines within the Leatherwood Ford outcrop is the limited thickness of the limestone itself. The upper Pennington limestone in this outcrop is only approximately 4.5 m thick, thus limiting dissolution to this thickness. It is important to note that the unit beneath the upper Pennington limestone is a well-cemented, highly resistant brecciated dolomicrite. It may prove that this resistant layer beneath the upper Pennington limestone stunted vertical dissolution, while encouraging lateral growth. Aggressive water would dissolve the limestone more quickly and with greater ease than the underlying dolomitic unit, thereby giving rise to a laterally-extensive depression.

Doline dissolution begins when limestone exposed to the meteoric environment begins wholesale dissolution. As dissolution continues, though, patterns of removal become established based on joints and fissures in the rock. These natural points of weakness appear to be the only preference in the sites of major paleo-doline features within the Leatherwood Ford outcrop, as there is little lateral facies variation in the upper Pennington limestone across the 150-200 meter outcrop (Figure 6).

Continued dissolution along dominant fissures tends to form a rounded depression, called a doline. Although dolines can form in many ways, the most common, and the type present in the Leatherwood Ford closed depressions, is called a solutional doline - a bowl-shaped depression (Figures 16a, 18a and b, and 22b and c) that forms without obvious disturbance or dislocation of the limestone. Due to pervasive dissolution, fissures widen,

deepen and join laterally, causing a settling and lowering of the surface as illustrated in Figure 26 (Sweeting, 1973).

Natural accumulation of residual clays and alluvial materials in the openings aid in further dissolution of the limestone, and eventually form a cover on the exposed surface. The fine-grained residual mantle initially collects in topographic lows where pedogenesis can form a soil. If protected, the ancient soil can be found at the associated unconformity, as a paleosol, which can be an important identifying trait of erosional surfaces (Wright, 1994). Generally the paleosols are composed of both residual clays and transported alluvium, as is the case of the red and green claystone paleosol in the upper Pennington Formation, present in paleo-dolines 1 and 2 (Figures 16a and 18b). The interaction between paleosol and underlying bedrock is discussed more fully in a following section.

The presence of a residual paleosol filling a paleo-doline is indicative of a solutional origin, but other features can also support this interpretation. Rounded limestone clasts, cleaved from bedrock and incorporated into 'soil' cover, are also a characteristic of dissolutional dolines. Rounded clasts of upper Pennington limestone are seen in both paleo-dolines 1 and 2, and were probably shaped by both physical and chemical means (Figure 16a). Mechanical weathering at or near the surface could physically abrade the surface of the cobble by knocking off sharp edges. Chemically, the clasts can undergo dissolution and rounding on all sides, as the meteoric waters move through surrounding soil. One of the last features noted in a dissolutional doline is the development of saprolitized limestone (Figure 18c). Only paleo-doline 2 contains noticeable amounts of saprolitized limestone, which is indicative of pervasive dissolution. The rotten limestone maintains depositional form, but due to extensive leaching has been transformed into saprolite.

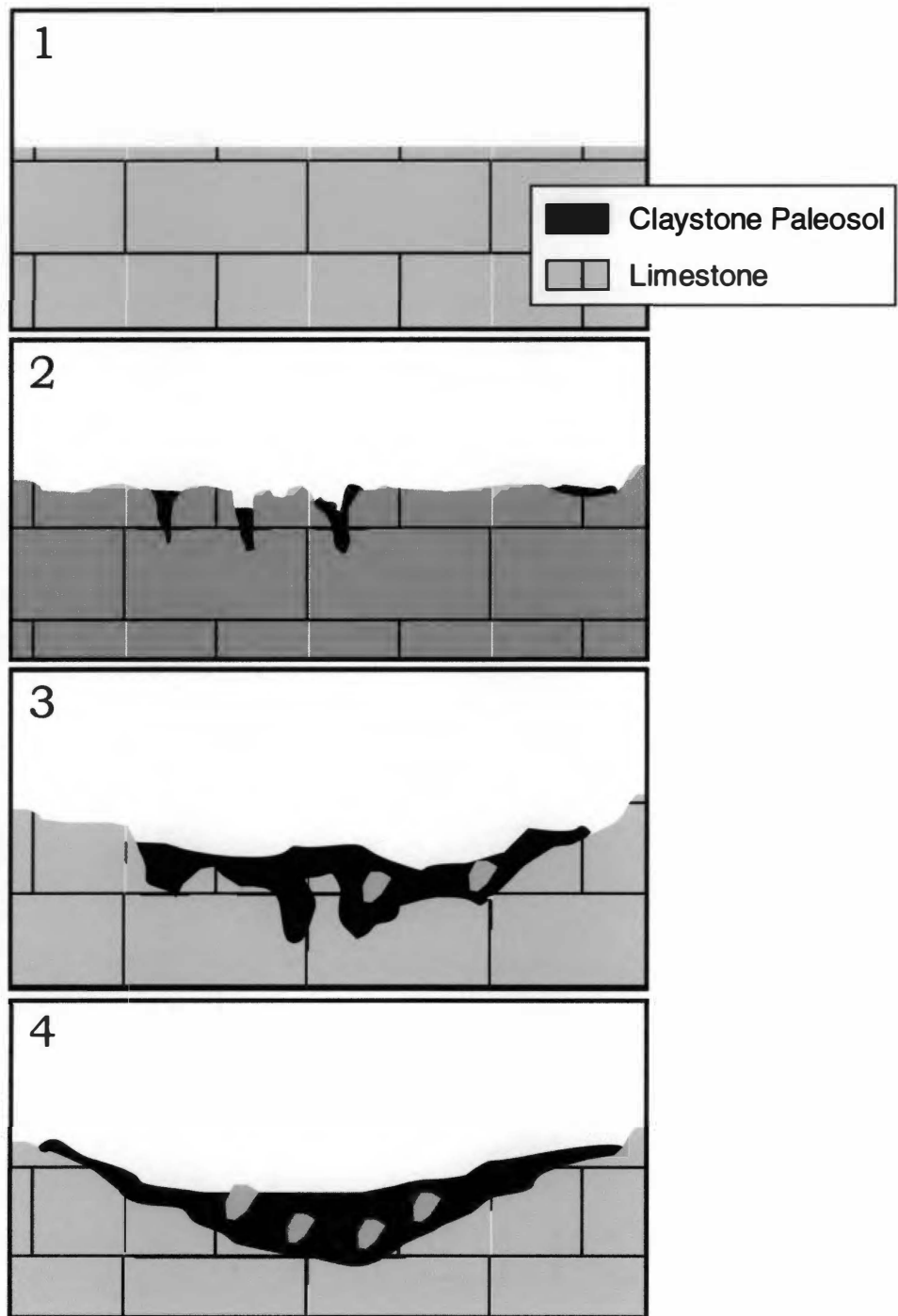


Figure 26 - A generalized solution doline, illustrating the development of vertical grikes in Phase 2, soil cover, and pinnacles in Phase 3, and a bowl shaped form including spalled and residual limestone clasts in a soil matrix in Phase 4.

Similar types of in-situ dissolution and associated karst formation are seen in "classical" karst found throughout Slovenia, in the former Yugoslavia. This area is pockmarked by dolines, and is one of the earliest areas of karst research. Though initial studies in this area postulated collapse origins for bowl-shaped depressions, later studies proved doline formation through dissolution. Supporting evidence included many of the features discussed above, e.g.: lack of clast displacement through collapse, rounded limestone cobbles, and obvious *in situ* weathering of limestone to saprolite (Sweeting, 1973).

Although the process of doline dissolution will often produce the idealized bowl-shaped depression, it can also produce a free-form feature. This is particularly true when two or more fissures are at work creating one feature, or, on a grander scale, when two or more fully formed depressions coalesce. Recognition of compound features is generally based on the presence of a limestone pinnacle in the base of the compound paleo-doline (Figure 27). Examples of coalescence occur in paleo-doline 2, and paleo-dolines 3, 4, and 5.

In paleo-doline 2, it appears that two rather large depressions coalesced. This hypothesis is based on the size and the competence of an associated pinnacle, which may have been a wall separating two depressions. The pinnacle itself is at least 2 meters high, and separates the deeper south side of the doline with a more shallow area to the north. Because of a paleosol mantle, other characteristics indicative of a merged feature are hidden.

The Quaternary removal of mantling material in paleo-dolines 3, 4, and 5, shows the results of coalescence more fully. The erosion has exposed what appear to be three small paleo-dolines, separated by competent limestone walls. In fact, this is merely the view seen in a two dimensional outcrop. When examined further, it becomes apparent that the walls are breached by holes, interconnecting the paleo-dolines. Soil and mantling breccia are

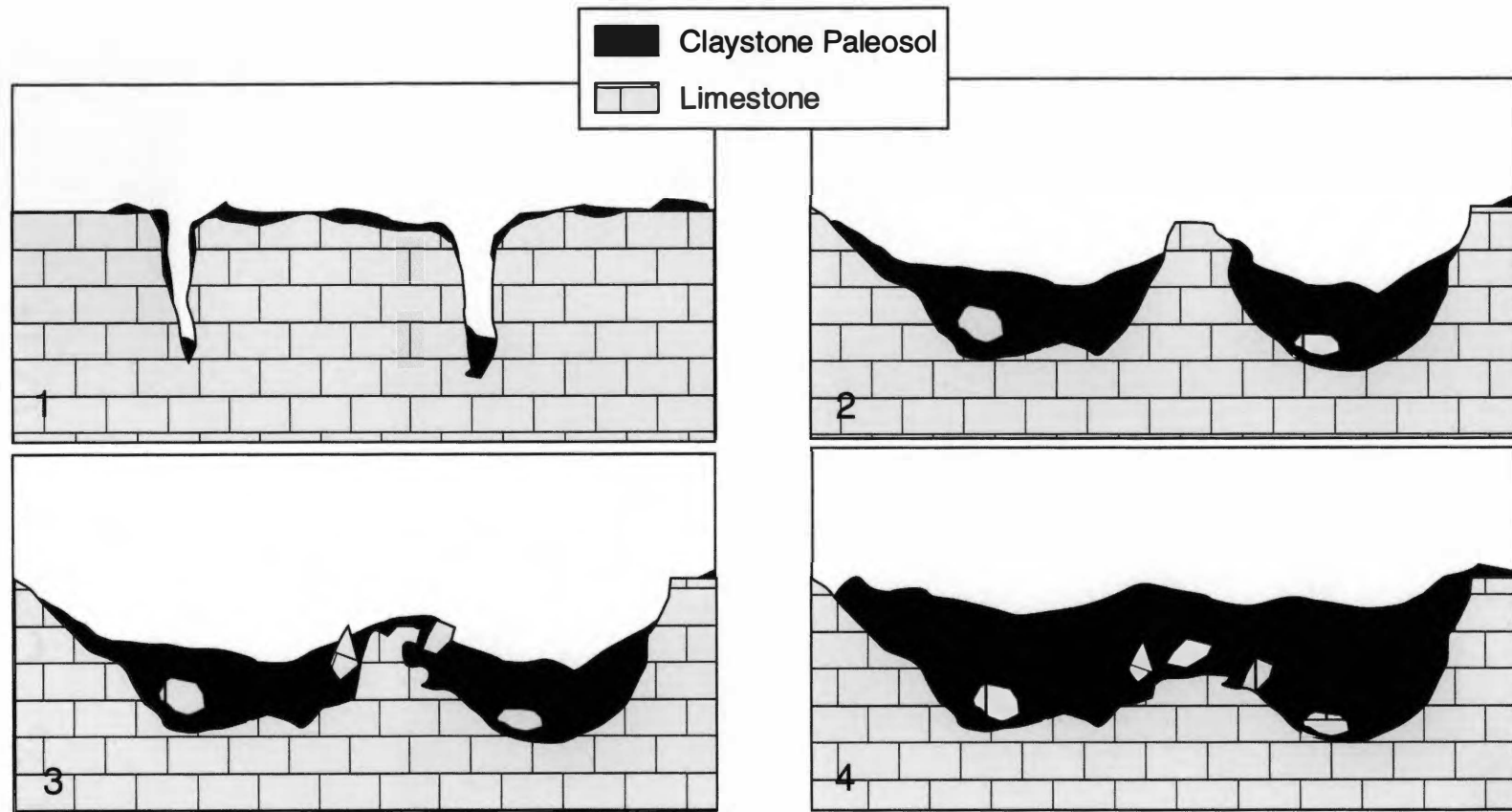


Figure 27 - A graphic interpretation of the development of a coalesced doline. Phase 1 shows the initial development of two separate grikes. Continued dissolution results in two separate dolines, seen in Phase 2. The pinnacle, which separates the two depressions is slowly dissolved and eroded, resulting in a break-down, seen in both Phases 3 and 4. In the final diagram, the two depressions function as one single doline.

shared between each of the depressions, illustrating co-dependent feature formation (Figures 22b, c, and d).

b. Kamenitza Development

Although dolines are the most common paleo-karst feature seen in this exposure, the presence of a kamenitza indicates another type of process. In this instance, the surface of the rock appears to have been homogeneous, with no obvious preferred dissolution pathways. In addition, the rock surface was initially flat (Figure 20a). The combination of these characteristics results in an area where water pools and stagnates. Dissolution is uniform, causing a 'lowering' of the rock floor that maintains a flat, smooth surface as illustrated in Figure 28.

Meteoric water begins initial carbonate removal, but the addition of organic matter increases acidity of the water in the solution pan. In wet, vegetated climates the basins can enlarge quite rapidly, as humus and organic debris collect in the base. The presence of the collected litter can cause the pH of the water to be anywhere from 7.6 to 8.0, especially at the base. Kamenitzas are thought to grow rather quickly, due to the presence of such acidic waters. Studies from northern England have shown that solution pans 3-5 cm deep can form in less than ten years (Sweeting, 1966).

3. PHASE 3 – *Soil and Vegetation Interaction with Exposed Limestone*

One problem with interpreting the timing of paleokarst features is that they often occur penecontemporaneously. As discussed in the previous section, karst feature development begins with the first exposure of limestone, before a soil mantle is fully developed. But in a karst plain, soil quickly develops, collecting initially in topographic lows and eventually mantling the entire exposure. With soil comes vegetation – particularly in the

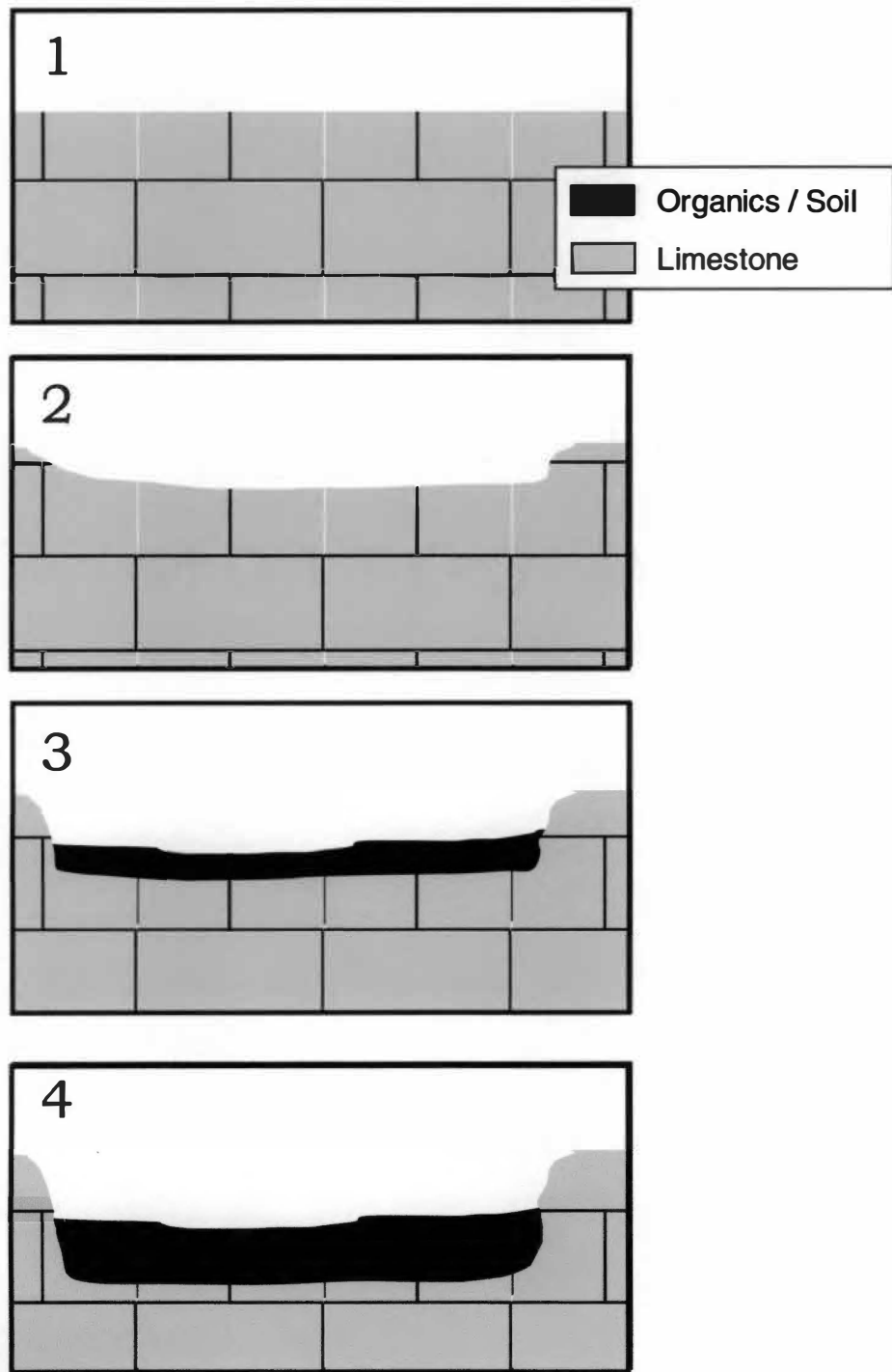


Figure 28 - A generalized solution kamenitza. This feature illustrates the development of a flat floored depression that has maintained uniform dissolution across the horizontal rock surface. Note the collection of organic matter in the base.

Mississippian, where there is abundant evidence for substantial land plants. So discussing karst formation without discussing implications of a soil cover and accompanying vegetation would not tell the complete story.

a. Soil Interaction

As mentioned in the previous section, dolines are aided in growth by the addition of residual and alluvial material. The fine grains work their way into small openings, acting as a scour, in conjunction with surface waters. Initially, only topographic lows fill, but continued collection of fine-grained material can eventually mantle the entire limestone surface.

Karst features that form under a 'soil' mantle have a smooth mammilated carbonate base (Walkden 1998), which is comparable to modern covered karst terrains (Sweeting, 1972). The south edge slope of paleo-doline 2, although overprinted by Quaternary sculpted karren, typifies the smooth and gently rounded features that form beneath the soil mantle (Figures 18a and 22c).

The smoothed and mammilated south edge of paleo-doline 2 is only one characteristic of possible paleokarst development beneath a soil cover. Another feature supporting this interpretation is the presence of a small, disconnected pinnacle near the base of the paleo-doline. The column, a vertical arrangement of disconnected limestone cobbles, is common in alluvial dolines – dolines that form beneath a considerable ground cover (Sweeting 1973) (Figure 29). Pinnacles buried beneath the soil cover are vulnerable to extensive dissolution on all sides. Horizontal bedding planes are natural fissures, which are easily enlarged, causing the separation of the cobbles and formation of this oddly shaped disjointed column (Figure 18d).

The cobbles in this pinnacle, as well as other cobbles seen scattered throughout the

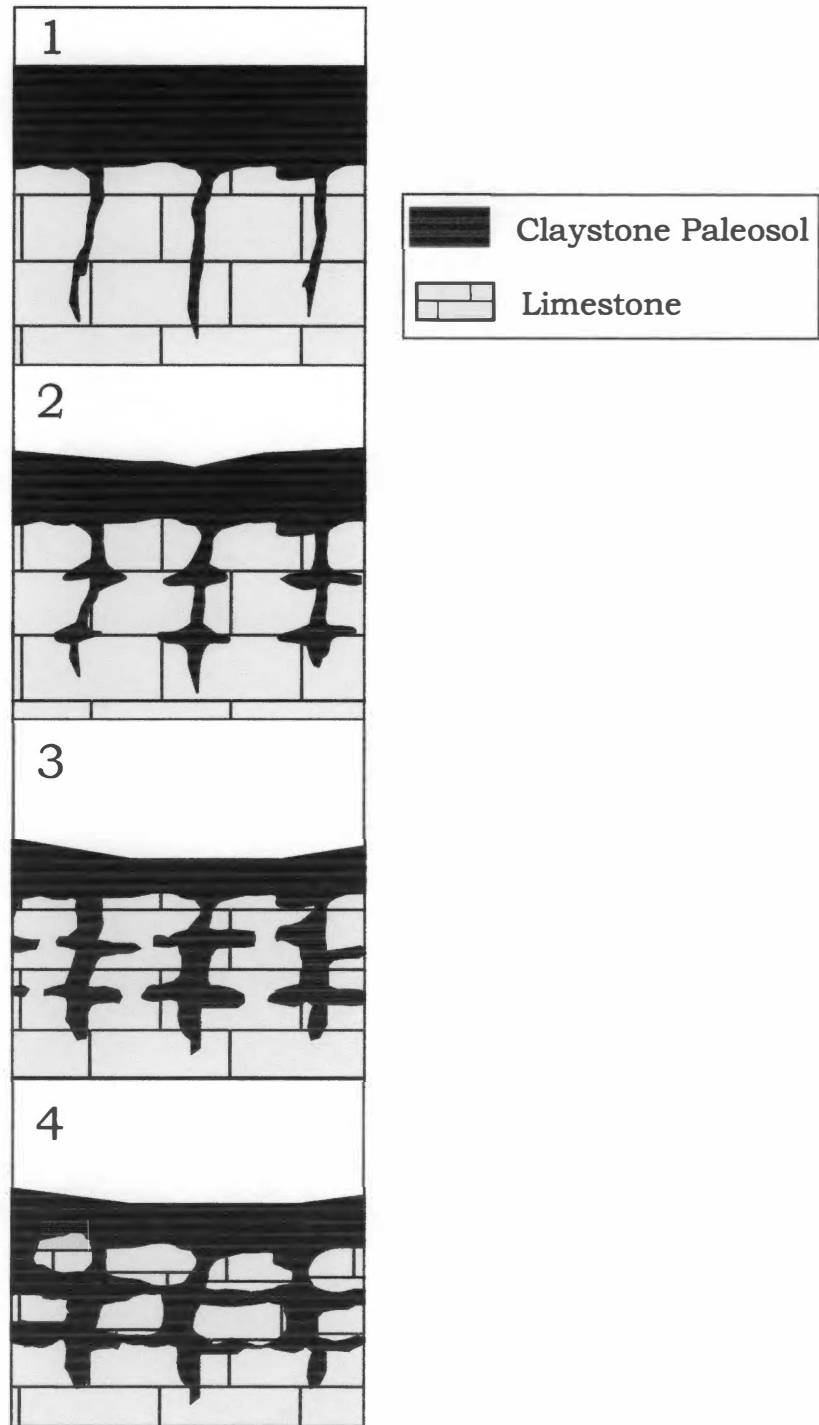


Figure 29 - Graphic interpretation of the development of an alluvial doline. The limestone is surrounded by soil, thus allowing water to attack the limestone on all sides, particularly at it's weakest point - bedding planes. Thus the outcome is a disconnected pinnacle arrangement. Adapted from Sweeting (1977).

paleosols in paleo-dolines 1 and 2 are moderately rounded. This could be due to mechanical or chemical means, but due to the *in situ* nature of the disconnected pinnacle, chemical means seem more likely. The soil provides the necessary porous medium through which meteoric waters can move and dissolve the carbonate clasts on all sides.

The soil obviously interacts with the limestone as a variable in paleokarst formation. It can physically affect how karst processes will shape the limestone, but we have yet to examine the chemical aspects. In particular, this is in reference to the iron oxide replacement seen in clasts from paleo-dolines 1 and 2, the surrounding limestone, and the pinnacles found near the base of the paleo-dolines.

The formation of the crust appears to be dependent on the presence of the paleosol, as the crust only occurs in areas that were initially, and are still, overlain by the iron-rich paleosol (Figure 18e). Crust development began as water moved through iron-rich soil. The water, meteoric and slightly acidic, mobilized iron as organic iron complexes. Upon reaching the soil – rock interface, the pH of the system changed rapidly. Calcium became mobile by replacing iron bounded in organic ligands, and iron oxides and hydroxides were deposited (Bardossy et al., 1989). Because the crust only occurs in the upper 4-6 cm of the limestone, it seems likely that the system was quickly exhausted, dropping all available iron at or near the soil – rock interface. This chemical process obliterates original texture and fabric of the limestone. When examined in the microscale, the only remaining carbonate is seen as rare echinoderm grains, or calcite spar-filled pores.

Other areas show interaction between the limestone and an exposed oxidizing environment, but lack the pervasive replacement seen in the crusts associated with the paleosol. These superficial features include iron staining, which is seen following fractures

or the limestone exposure surface.

b. Vegetation Interaction

With soil, comes vegetation; and in this outcrop, it seems certain that Mississippian plants played a major role in the formation of specific karst features. The most striking examples are found in the northern half of the section, in features associated with the last three small paleo-dolines and the paleo-kamenitza.

Paleo-dolines 3, 4, and 5 are all of a dissolutional origin, but differ from their larger counterparts (paleo-dolines 1 and 2) in the mechanism of formation. This area is difficult to study due to Quaternary erosive and overprinting processes. The removal of overlying soil is helpful in studying the entire feature, but in many cases surrounding limestone has been scoured into sharp rillenkarren. The base of paleo-doline 4 is the only area that maintains original Mississippian-Pennsylvanian paleo-karst features (Figure 22c). It is there that additional clues to the formation of these last three paleo-dolines are found.

The smooth, yet pitted and undulating, surface is indicative of uneven rates of dissolution, with grooved areas showing quicker removal of the limestone. The grooves are thought to be directly related to the interaction of an active root system with the underlying limestone. The roots enlarge small fractures or joints and increase acidity of the meteoric waters through carbon dioxide respiration (Vanstone, 1998). Dissolution beneath a soil cover produces a mammilated surface (Walkden, 1974), while smooth grooves and pits are incurred through root penetration. Figure 30 shows a modern tree growing on limestone, illustrating interaction between root systems and soluble carbonate in tropical environments.

Although small plants and their invasive root systems superficially affected the base of paleo-doline 4, the feature itself did not form simply from vegetative interaction with the



Figure 30 - Modern tree roots create grooves and pits in the limestone as the tree grows. This type of karren development is also seen in paleo-doline 4. This modern tree is growing in a tropical environment, where the limestone is exposed by extensive erosion.

limestone. A feature forming from interaction with vegetation alone would be much smaller, and very well defined. A possible example of this would be the meter wide pit found near the south edge of the paleo-kamenitza (Figures 20e and 20f). The pit is the only feature of its type, and is shaped like an irregular funnel with sharp, but smooth and undulating, sides.

A study by Vanstone (1998) suggests that this type of pit is initiated through the stem-flow drainage of trees. Although the features can resemble cylindrical root karst, the size, which ranges from 0.15-0.55 m in diameter and 0.2-2.4 m in depth, makes this an unlikely possibility. The largest cylindrical root karst pit with a central root zone exhibits a maximum diameter of 2 cm.

Therefore, it seems very likely that the process described by Vanstone (1998) is the likely cause for the unusual funnel-shaped feature. Funneling of rainwater, intercepted at the crown of the tree and passed out through the roots, concentrates drainage in a specific area. This gives rise to a feature that begins as a cylindrical pit in the limestone (Figure 31).

Dissolution continues, aided by water that is increasingly acidic, reflecting the leaching of tree tissue, causing the shape of the pit to change. Figure 32 illustrates the evolution of the pit from a cylindrical pit, to a funnel shape, and onward to the final, most stable, karst feature, which is a bowl. The feature seen in the paleo-kamenitza shows an immature or incomplete morphology, reflecting, perhaps, the end of erosion in this particular area due to the onset of intense Pennsylvanian sedimentation.

4. *PHASE 4 – Early Pennsylvanian Sedimentation*

The beginning of the Pennsylvanian changed the face of the subaerially exposed karst plane. The area, which was likely covered by a mantling paleosol, had a superficially flat topography, with only the highest pinnacles near the right edge of the outcrop exposed.

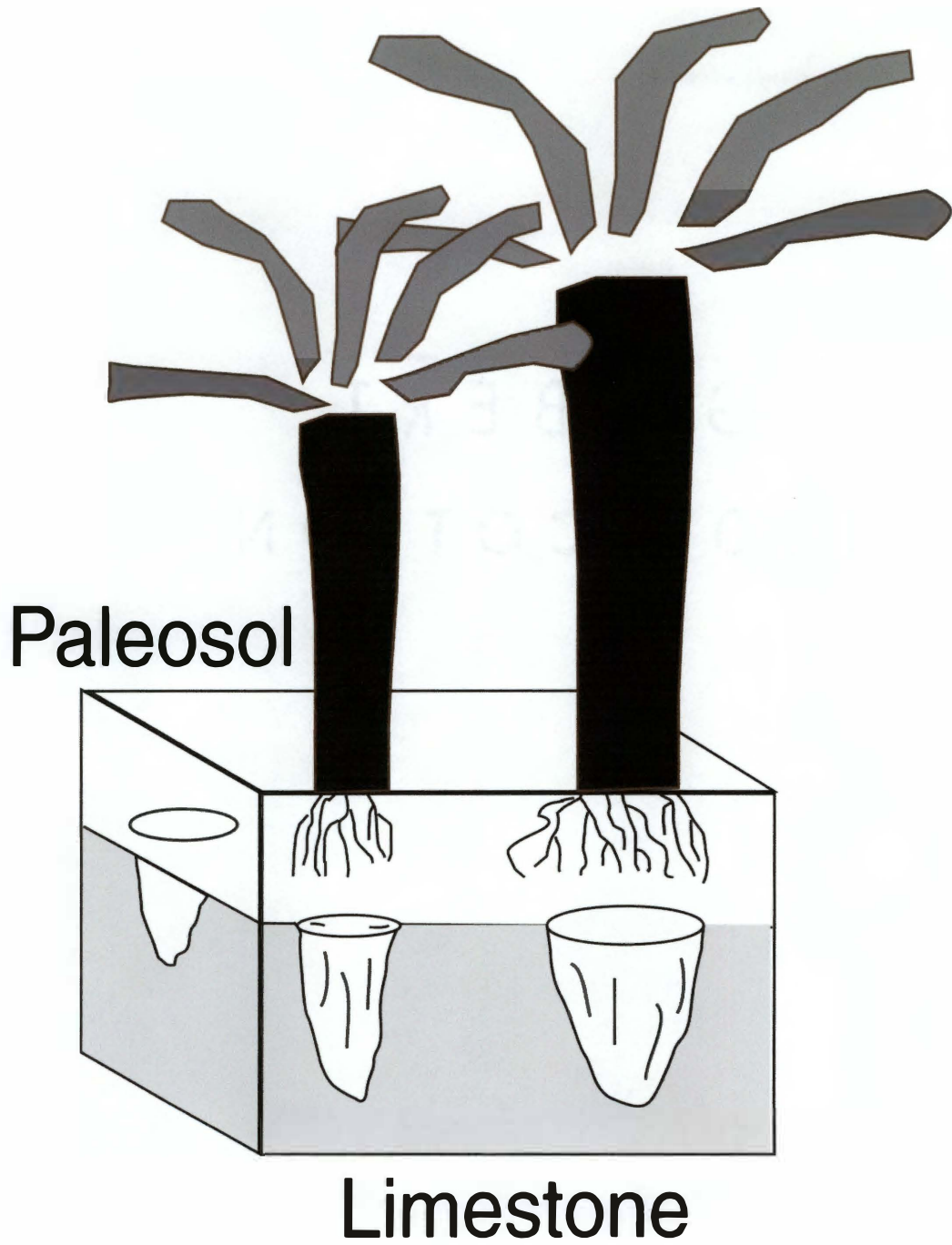


Figure 31 - Illustration of the Stem Flow model (from Vanstone, 1998.) Trees concentrate drainage at specific sites on carbonate, allowing for extensive pit development.

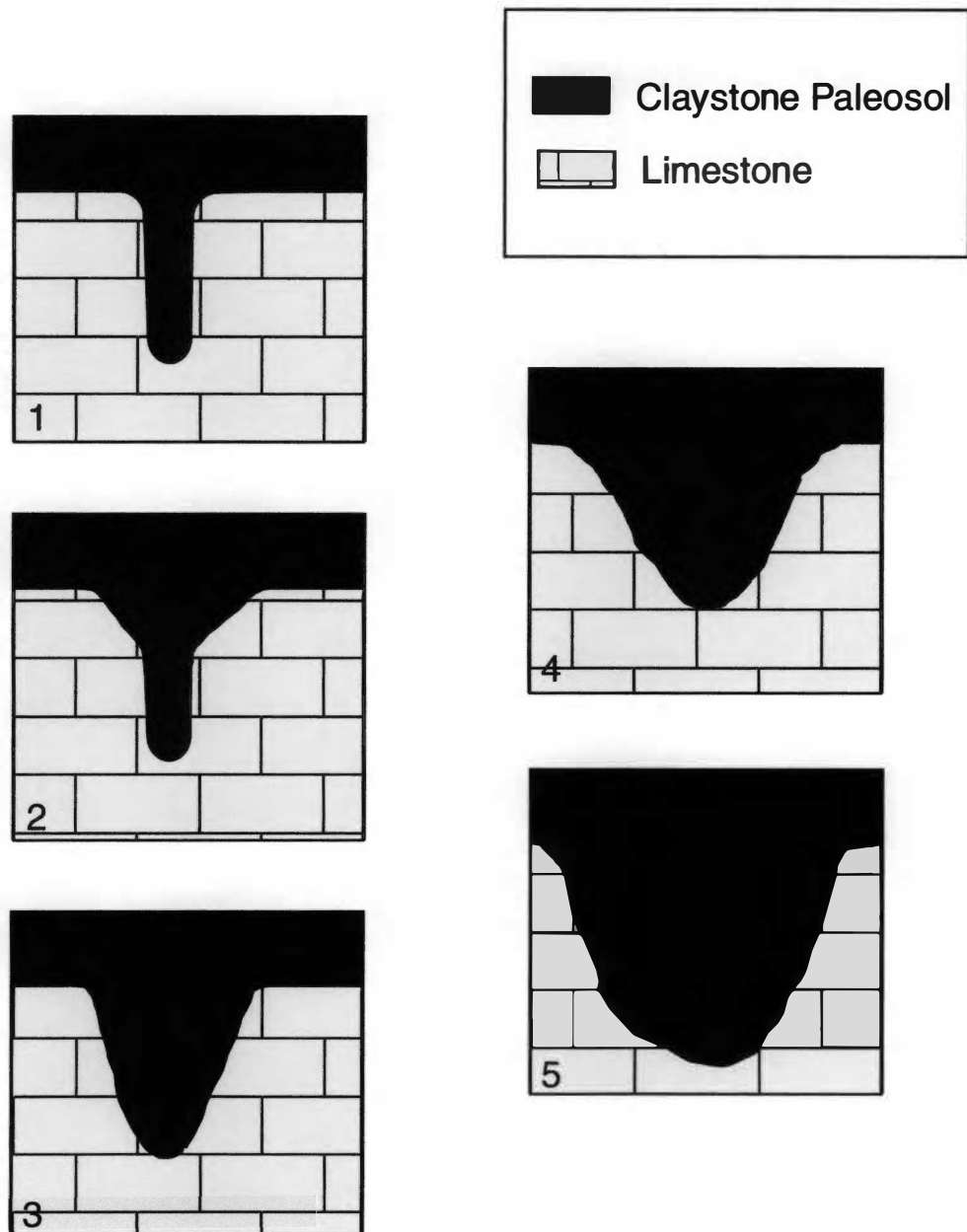


Figure 32 - Model for paleokarst pit evolution, adapted from Vanstone, 1998. The forms represent a genetic sequence that begins with the cylindrical form (1). This evolves into a funnel shape (2), which grows more conical (3, 4), until the final bowl-shaped form is reached (5).

A precursor to active Pennsylvanian sandstone sedimentation began importing sands from the new tectonic regime (Alleghenian Orogeny) to the east. This process began as runoff carrying light loads of sediment washed across the landscape. As water and sediment load increased, channelized flow developed. Streams were ultimately captured by the paleo-topographic depressions, which were covered by deep mantling soils. The variations in surface topography produced greater depth of flow, resulting in increased erosive forces in low spots (Ritter et al., 1995). Streams became entrenched as sediment loads increased.

With the advent of streams, mechanical erosion increased. Perhaps the early sheet-flow acted as a scouring agent, clearing excess soil, and overwhelming local vegetation. When the flow eventually channelized, the surface of the landscape was left denuded in areas of higher limestone, particularly pinnacles near the northern edge of the outcrop.

a. Development of Mantling Breccia - Conglomerate

The initial mechanical transport of earliest Pennsylvanian clastics appears to have played a major role in the formation of the paleo-karstic breccia-conglomerate seen on many of the pinnacles in the northern half of the outcrop. Clasts were spalled from the limestone pinnacles and, in some cases, underwent a moderate rounding process that was both mechanical and chemical. This mélange of limestone clasts, greenish-gray claystone, and fine sandstone spilled off and surrounded the topographically elevated pinnacles, to fill in local karren, like the type found at the edge of the paleo-kamenitza (Figures 33, 20a, b, c, and d).

Mantling deposits are common at unconformities, and occur in irregular patches. They are generally found filling topographic lows, grikes, or any other available depression (Choquette and James, 1988). In this sense, the patches of breccia are troubling in their placement. They occur next to pinnacles, and spill off of the sides, but are commonly

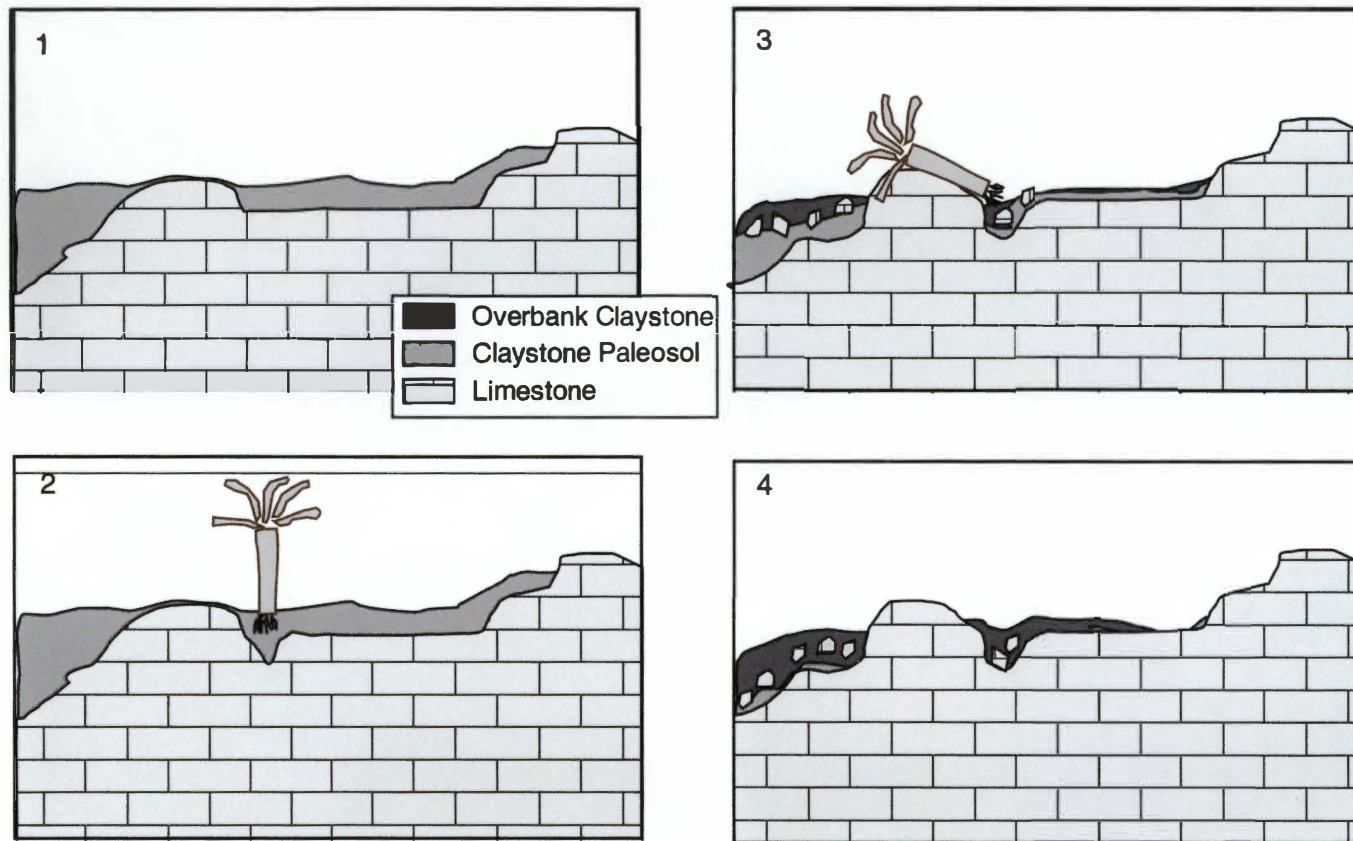


Figure 33 - A graphic illustration that models the emplacement of breccia near the pinnacle on the southern side of the Kamenitza. In phase 1, the area is covered by a relatively uniform mantle of paleosol. In phase 2, the presence of a tree causes the formation of a funnel shaped karren feature. In phase 3, active erosion and influx of overbank deposits (green claystone) kills the tree and causes spalling of clasts from the pinnacle. In phase 4, the erosion is complete, and the breccia bodies are fully formed, filling in available topographic lows.

concentrated on promontories next to the paleo-topographically lower paleo-dolines. The question remains: why did the breccia not fill in the lower areas more fully? The answer is related to the amount of soil fill in the area. Each of the depressions was filled to different extents by soil material, or by the overbank deposits of greenish-gray claystone. This limited breccia – conglomerate placement.

Breccia - conglomerate in paleo-dolines 3, 4, and 5 occurs in a wide spectrum of arrangements. One of the largest accumulations occurs filling a hole in a breached wall, between paleo-dolines 4 and 5. Assorted sediment from the adjacent pinnacles filled in the only available low spot – the other low points being covered by soil. The same is true of breccia spilling off of the pinnacle that separates paleo-dolines 3 and 4. The breccia mantles only the area next to the pinnacle and the edge of the paleo-doline slope. Again, soil plays an active role in the placement of this surficial detritus (Figure 22b, c, and d).

The last patch of breccia, spilling off of a pinnacle to the north of the kamenitza, fills almost the entire south half of the flat-bottomed solution basin. In this instance, the lack of a deep soil profile in this area allowed the breccia to fill in both the karren, formed by tree stem flow, and much of the paleo-kamenitza pit area.

b. Collapse Features

Karst landscapes as a rule are unstable, changing environments that can alter quickly. From the beginning of Pennsylvanian sedimentation, the karst plane, found at the top of the Pennington Formation, began settling into a more stable form. This involved collapse of limestone due to either innate mechanical instability, or material failure due to overburden. It also includes the possibility of a disturbance stress, which caused deformation of overlying sandstones.

In paleo-doline 1, site 1 (Figure 16b), evidence of collapse is seen in the presence of large angular limestone blocks, which are overlain by Pennsylvanian sandstones. The blocks are in direct contact with each other, and show signs of rapid displacement and quick burial. Figure 34 is a graphical illustration of how this juxtaposition may have occurred.

Although the initial doline (paleo-doline 1) formed in a manner suggesting open dissolution, it appears that this process was incomplete. Instead of forming the ideal bowl-shaped feature, seen in Figure 26, it is likely that an overhang developed, projecting over the north edge of the feature. This unusual projection probably occurred because the uppermost unit was a well-cemented grainstone, resistant to dissolution. A natural fissure or grike initiated development of the feature, allowing aggressive waters to attack the more susceptible limestone in underlying units. In this manner, a depression protected by a limestone overhang developed. The overhang became unstable as new stresses, such as erosion and weathering, and the development of an overburden, in the form of Pennsylvanian sand, occurred, making collapse imminent. The collapse broke the limestone overhang into large angular blocks, which settled on the lower floor of paleo-doline 1.

Due to the lack of deformation in overlying sandstones, it appears that the collapse in this area must have occurred just as active Pennsylvanian sandstone sedimentation began. The clasts are found in a matrix that consists of clay, quartz silt and sand, which is indicative of input from the earliest pulses of Pennsylvanian sedimentation. As sandstone sedimentation continued, thick flat-lying sandstones were deposited, tightly encapsulating the limestone clasts and matrix.

In this area, it is easy to hypothesize a reason for collapse. The actual displacement is apparent, allowing for reasonable conjecture. In paleo-doline 2, deformation of overlying

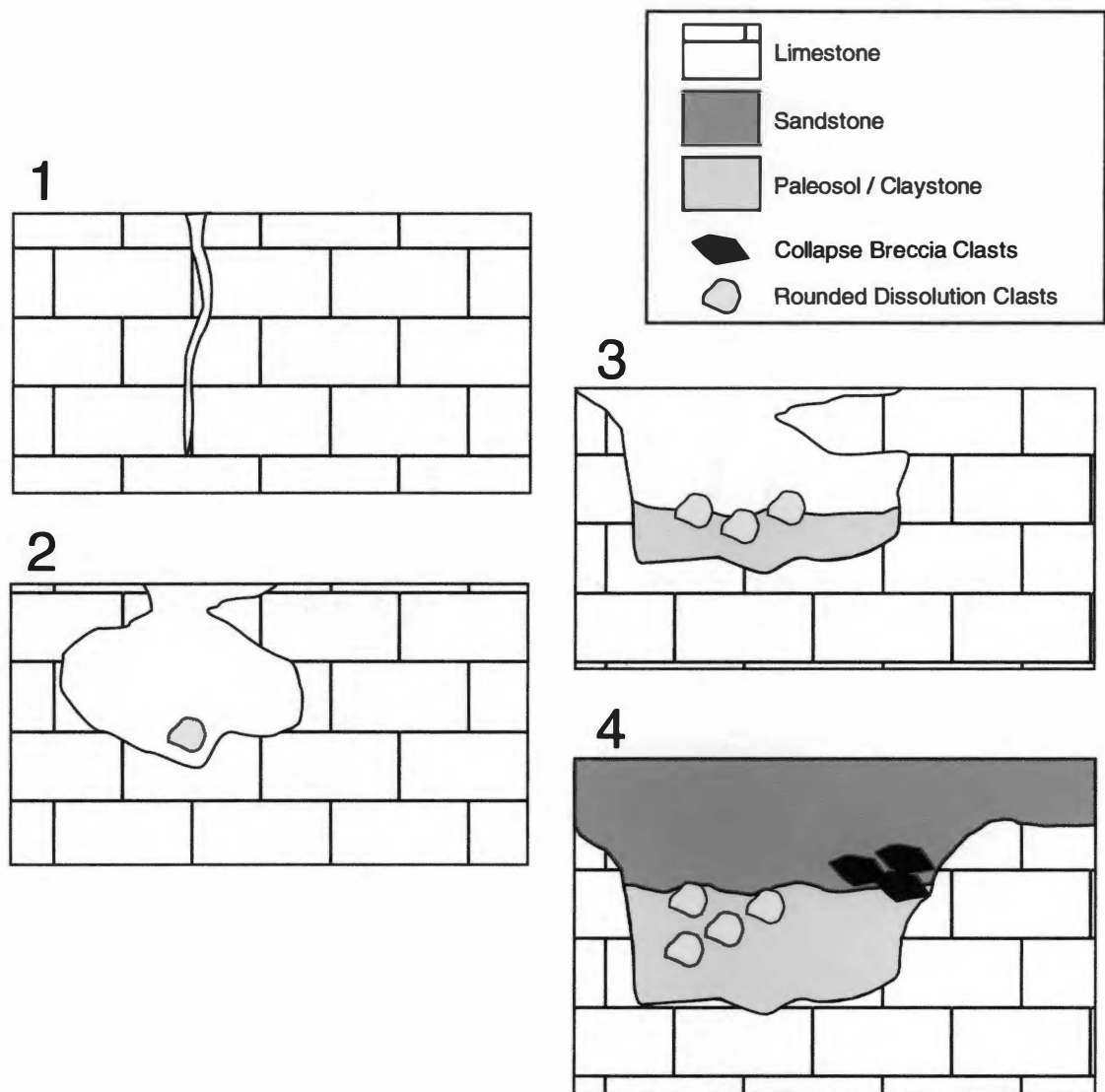


Figure 34 - Speculative graphic illustration of history of collapse in paleodoline 1. In phase 1 the exposed pavement is attacked by dissolution, particularly at joints and fractures. In phase 2 a large cavity forms. It is protected by a well cemented grainstone at the top of the section. Enlargement of the cavity continues in phase 3, along with the development of a clay rich paleosol which contains spalled limestone clasts. Early Pennsylvanian deposition in phase 4, causes the collapse of the jutting arm of limestone. This collapse occurs early with only a minimum of deformation of the Pennsylvanian sands, and produces angular clasts shown here in black.

sandstone is the only clue as to a paleo-collapse or some other deformational occurrence.

The signs of displacement are seen in the thin layers of sandstone, which wrap around the large sandstone channel in the center of the paleo-doline. On both sides of the channel, the sandstone layers have been deformed, and are nearly perpendicular to the original flat-lying depositional trend. This sandstone cannot be traced along the floor of the massive sandstone cliff, due to displacement by Quaternary erosion, collapse, and removal (Figure 19a and b).

Displacement can also be inferred from the placement of a large block of sandstone, at the base of the north side of the main channel. One of the problems dealt with in the deformation of overlying sand layers, was the question of associated displacement of paleosol or assorted sediments within the paleo-doline itself. In order for the sandstone to tightly wrap around the channel, surrounding sediments would have to be removed or deformed. The block of sandstone at the north base of the channel may provide an answer to this problem. If a collapse occurred in the subsurface, the paleo-doline fill must have shifted. It may have even funneled into the subsurface. The sandstone block is probably contemporaneous with the sandstones that wrap around the channel. Perhaps upon collapse, the sandstone block dislodged and moved with the claystone to the base of the channel. This seems plausible in that it is separated from the main channel by greenish-gray claystone, which could have acted as a glide, allowing the block to slide into the base of the paleo-doline.

That something happened to cause displacement and deformation in Lower Pennsylvanian sandstones is obvious, but how it occurred is more problematic. The base of the paleo-doline shows no evidence of a catastrophic collapse; specifically, angular limestone

clasts, which are associated with pore collapse, are absent. It therefore seems that the collapse must be deep within underlying rocks.

The upper Pennington is underlain by a variety of different rock types within the Pennington Formation, which include thin-bedded dolostone, limestone, sandstone, and shale. As the development of a sizeable pore in these materials seems quite unlikely, one must look to possibilities in the older rocks underneath the Pennington Formation. It is there that the Middle Mississippian carbonates, which are thick-bedded, pure and vulnerable to dissolution, are found.

Karst development in a subaerial environment does not take place only on the surface. Although the surface experiences the most intense dissolution, particularly in respect to surface meteoric waters, groundwater also plays a role. Changes in sea-level, resulting in the exposure of a limestone pavement, would also affect groundwater. Limestone deep within the stratigraphic column would be vulnerable to changes in the water table, particularly if the marine waters, saturated in calcium carbonate, dropped, and allowed the incursion of fresh, meteoric, groundwater. The interaction of meteoric and marine waters could result in a mixing zone. The mixing area, where fresh and ocean waters meet, tends to be a place where dissolution can easily take place, due to the release of CO_2 as the waters equilibrate (Sweeting, 1973). It is therefore plausible that the area affected by this mixing zone was the middle Mississippian carbonates. This would result in the formation of intrastratal macropores. The collapse of these pores could have affected the overlying rock column, resulting in the collapse of Pennsylvanian sandstones overlying the Pennington paleokarst surface (Figure 35).

The possibility that the upper Pennington was a low lying karst plain may also

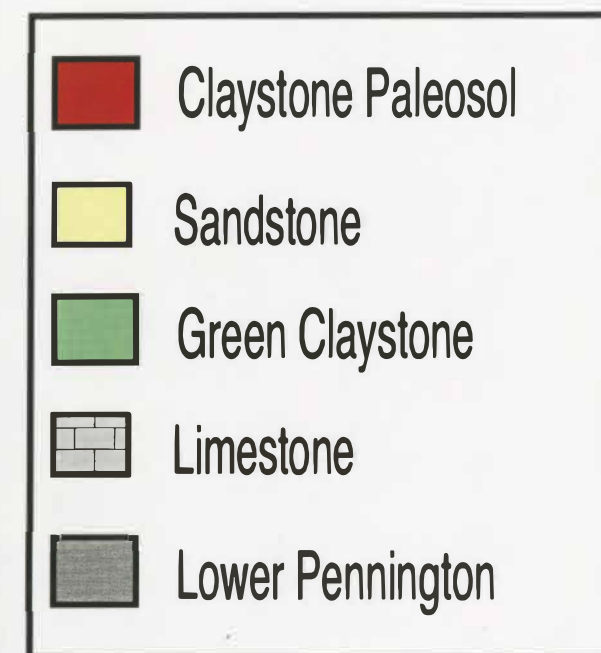
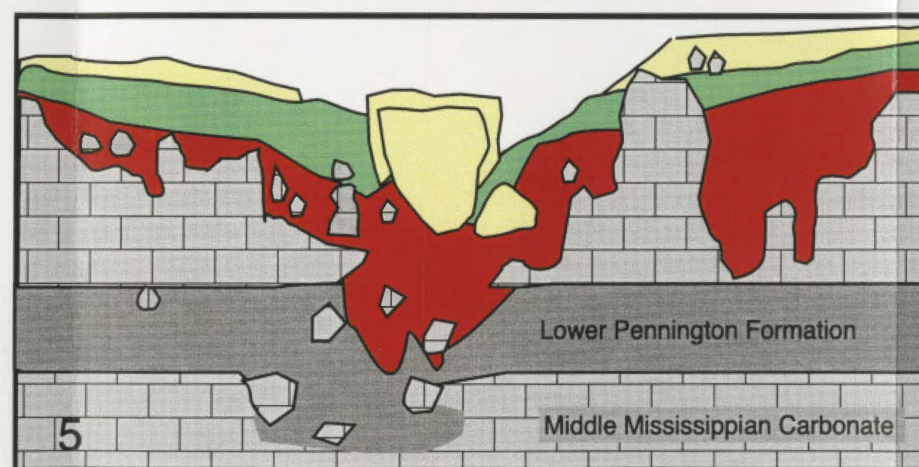
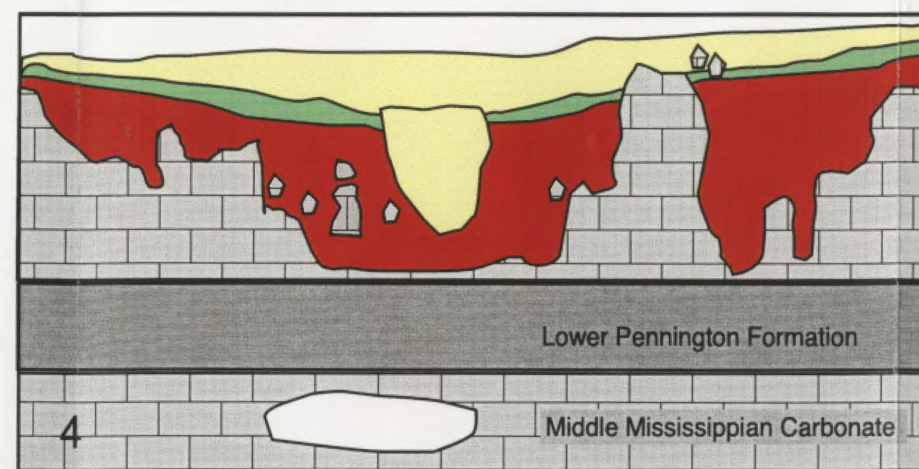
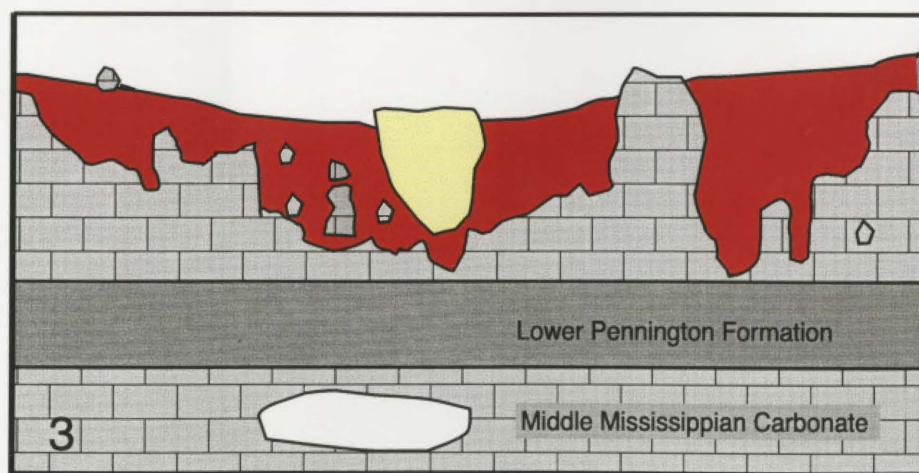
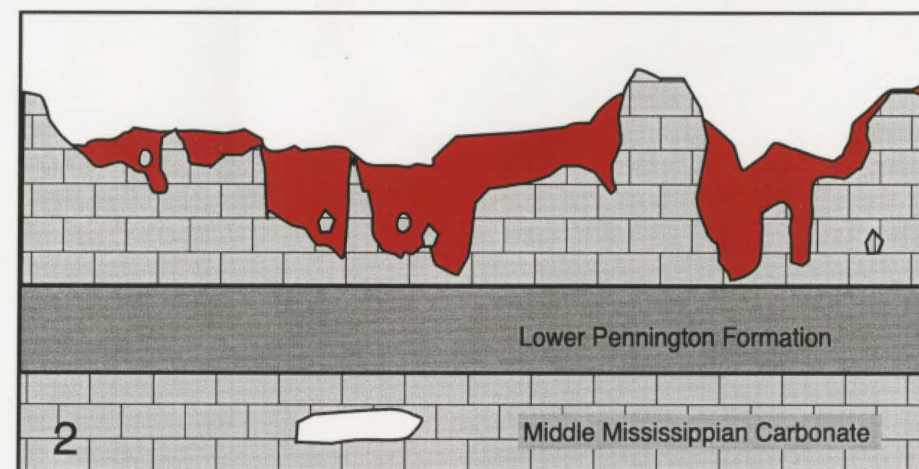
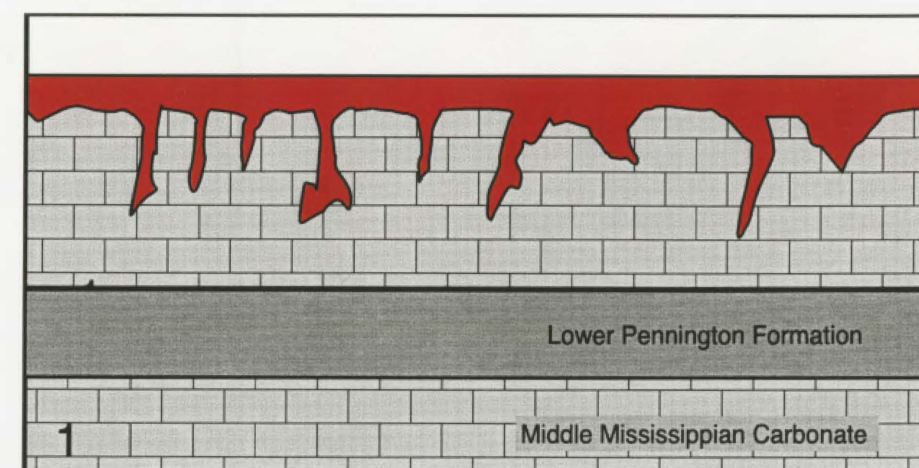


Figure 35 - A graphic illustration of the development of paleo-doline 2, and the associated collapse of overlying Pennsylvanian sands. Phase 1 and 2: Dissolution and development of grikes, which coalesced to form a large depression. Also notice the beginning of a pore in the subsurface. Phase 3: Entrenchment of a sandstone channel into the paleo-low; Size of the pore in the subsurface increasing. Phase 4: Deposition of overbank deposits in the form of greenish claystone, and the earliest Pennsylvanian sandstone deposition. Phase 5: collapse of the pore in the subsurface, which caused the facies of the Pennington, including Upper Pennington limestone, paleosol, claystone, and Pennsylvanian sands to shift. In this manner, the sandstone layers collapsed and surrounded the channel. Additionally, a small plug of sandstone was carried from the roof, to the base of the right side of the channel.

explain how the deformed sandstone maintained bedding, even while deforming to such steep angles. If the area was flooded, with a high water table, the clay within the sandstone could help it maintain its form. It is also possible that there was some early cementation, with meteoric carbonate cements. Unfortunately, Quaternary dissolution has removed any calcite cement present.

Other possible explanations for the presence of the vertical sandstones found rimming the channel complex, include the collapse of evaporite molds in the lower Pennington and upper Bangor, the development of openings between the channel complex and the claystone paleosols that were filled by the Pennsylvanian sandstones, or the foundering of the sandstone layers into the surrounding clay paleosols.

The first explanation does not differ substantially from the above hypothesis, except in postulating caverns at depth (in the Mississippian Bangor limestone). Although there is abundant evidence for modern caverns and collapse within the Bangor limestone, no major studies have examined possible paleokarst caverns and collapse in the unit. Frazier (1975) does mention the presence of evaporites (celestite) and evaporite molds, in the upper Bangor and lower Pennington. The presence of evaporites and evaporite molds was noted along the North Highland Rim of east-central Tennessee, and runs directly beneath the Leatherwood Ford outcrop. Possible coalescence of a layer of these evaporite molds could result in a collapse (Lorenz and Neal, 1999) that would affect overlying sediments.

Another hypothesis is that the synsedimentary deformation represents an unusual "clastic dike" that filled in, as early Pennsylvanian sandstones were deposited. Although more speculative, it is possible that openings on either side of the channel occurred due to some sort of vertical displacement (earthquake?) or even desiccation of the surrounding

clays. These openings could have been filled by overlying Pennsylvanian sandstones. According to Peterson (1968), it is possible to fill openings from any direction, with a gradual fill or injection of water-charged sediment. It is also possible that if a disturbing stress occurred (in the form of an earthquake) it would liquefy the sand, thereby allowing flow to occur (Frazier, 1989). One of the questions in this scenario is how the limbs of the wrapped sandstone layers maintain vertical lamination. According to Frazier (1989), sandstone dikes in the Eutaw Formation on the eastern Gulf Coast Plain maintain lamination that parallels dike walls. This phenomenon is likely due to flow banding.

The presence of these deformed sandstone layers could also have occurred due to a contemporaneous mass movement on the free surface. This spontaneous movement starts in the soft sediment due to increasing weight of the sediment and is lubricated by clay, which can flow readily. An example of this is seen in the Berea sandstone of central Ohio (Cooper, 1943). The Leatherwood Ford outcrop has a clay paleosol surrounding the channel complex, and if an opening appeared between the channel and the surrounding paleo-doline fill, the sand could flow into the openings using the clays as a lubricant and a constraint.

The last hypothesis concerns the foundering of the sand layers, into the underlying clays. Over time, the weight of the sand could cause the layers to sink through the clay until they folded themselves around the channel sandstone (which could act as an immobile boundary.)

5. Phase 5 – Reduction and Burial Diagenesis

The last phase of geologic processes in this outcrop (ignoring Quaternary erosion) includes the movement of reducing fluids along the unconformity and the emplacement of burial constituents. The associated processes caused the deposition of zoned ankeritic

siderite and ferroan calcite burial cements (Figures 12e and 12 g).

The presence of siderite is somewhat problematic, due to its placement both above and below the unconformity. It is entirely possible that the siderite was emplaced before Pennsylvanian sedimentation, due to the flooding of the karst plane and localized reduction in the wetland soils and sediments. Under similar conditions, it has been noted that sphaero-siderite is common in paleosol horizons (Ludvigson et al., 1998). If, in fact this did occur, the flooded karst was characterized by euxinic conditions. Organic matter, in a closed basin, would quickly deplete much of the oxygen within the system, allowing for reducing conditions to develop. Low Eh solutions would become favorable for precipitation of siderite (Bardossy et al., 1989). The wetlands may have continued into the time of active Pennsylvanian deposition, thus causing siderite to cross the unconformable boundary.

Another possibility is the movement of reducing fluids along the unconformity during burial. This could happen often, resulting in the zoned ankeritic siderite, which has a non-luminescent core, followed by brightly luminescent ferroan (burial) calcite, which is in turn followed by a non-luminescent siderite overgrowth (Driese et al., in prep.) This could indicate initial wetland deposition, with later pulses of reducing fluids migrating along the unconformity during burial. This could also explain the presence of siderite both above and below the unconformity.

Reduction is also noted in color changes within the paleosol. Reducing fluids moving along the unconformity incorporated soluble Fe and Mn, causing a significant loss of these constituents in the upper portion of the paleosol (Driese et al, in prep.). Microbial reduction of Fe and Mn could have occurred in the paleosol due to the presence of high amounts of organic carbon buried in the overlying sediments.

The burial constituents consist of dull to non-luminescent ferroan calcite cements (Figures 13a and b), which fill both intergranular, intragranular, and grike porosity, and bright luminescent ferroan calcite, which fills late fractures and veins. Interestingly, the unconformity played a major role in the enrichment of these cements, as the cements nearest the unconformity are greatly enriched in Fe and Mn (Driese et al., in prep.). Moving down-section, the Fe and Mn concentrations in burial cements decrease, indicating differences in the fluid chemistry within a few meters of the unconformity.

D. Discussion of Paleokarst

When discussing karst topography, one often neglects the importance of the initial topography of the underlying bedrock. In this instance, it may be very important in explaining differences in both the form and the timing of the karst features. In Figure 24 the relative timing of each paleokarst feature was presented. In the following discussion, absolute time constraints are also considered.

When the upper Pennington Formation limestone was initially exposed, it is probable that the northern edge of the outcrop was several meters higher than the area to the south. Unit 4 is a grainstone, which may in fact represent a shoaling environment. Although the whole area contains different volumes of unit 4, the thickest accumulation occurs at the northern edge of the outcrop.

When initially exposed, the paleo-topography of the limestone caused preferential karstification in the lower area. Meteoric waters moved from the interpreted paleo-topographically higher areas to lower areas. This may explain observed differences seen in the distinct forms of the paleo-dolines, and in the timing of their developments.

It is therefore plausible to hypothesize that paleo-dolines 1 and 2 began forming

earlier than the paleokarst features seen at the northern edge of the outcrop. The presence of reddened clasts and iron oxide crusts occurring in paleo-dolines 1 and 2 represent a significant amount of subaerial weathering time. The limestone, which has been replaced by iron oxide, was overlain by an iron-rich red paleosol, which had formed in both of the depressions. Interactions between water, soil, and eventually, the limestone, over time would produce the well-developed crusts.

Although the lower area received much of the initial runoff, the upper area was also evolving as well. Due to runoff, it probably took a significant amount of time for a soil horizon to begin on the upland portions, but as the dolines were filled and vegetation spread, the karst plain began to level off. The soils began to collect in upper areas and were held in place by root systems of vegetation.

Soils and vegetation play an important role in karst formation, as they can increase acidity of meteoric waters and speed up dissolution. It is probable then, that the formation in the upland areas of major landforms of any real depth did not begin until this had occurred. The kamenitza is a prime example of the changing regime. These flat bottomed features often form in exposed horizontal limestone. They pool water, and continue to grow as they collect water. It is interesting to note that these types of features are rather uncommon in a climate such as we assume for the late Mississippian – wet and tropical, with much vegetation (Chaloner and McElwain, 1997). If the area had been covered with soil quickly, the solution pan would be overprinted with signs of dissolution by vegetation – a grooved and undulating base, as opposed to the smooth flat floor in evidence. The paleo-kamenitza must have formed then rather quickly – without the presence of an extensive soil cover. When soil and associated vegetation began to collect in the area, a new feature

developed at the southern edge. This feature, caused by stem flow of a plant (tree), indicates the presence of soil and the increased dissolution rate of underlying limestone.

Paleo-doline 4 may also support this interpretation. Although possibly affected by Quaternary dissolution, this depression does not have the smooth flat floor associated with the gradual processes of doline dissolution. Instead the floor is pitted and grooved, with rounded edges. This is another indicator of the presence of soil cover and plants. Whereas the Quaternary grooves in paleo-doline 5 are sharp and angular, indicating limestone exposed directly to water, this surface indicates the buffer of a soil cover, and the dissolution of water directed by roots.

So, the uplands did eventually develop karst landforms, but not until the development of soil and the establishment of vegetation. This brings forth a question: If iron oxide crusts, associated with the overlying soils, formed in paleo-dolines 1 and 2, why did they not form in the features found at the northern edge of the outcrop? This appears to be a case of timing. Not only did the first two paleo-dolines form earlier, but they were also mantled by the iron-rich paleosol for a longer period of time. Although the surfaces of the features in the uplands do show signs of reddening and iron-staining, they did not have the time necessary for such extensive replacement.

In any discussion of the development of karst surfaces, one must consider the basic solution of limestone. This process can be influenced by many factors that include density of limestone, purity of limestone, type of limestone, and climate. An equation by Corbel, included in Sweeting's text, Karst Landforms (1973), estimates the amount of limestone lost by solution in modern karst regions. One calculation that is offered is Mississippian/Pennsylvanian limestones in the British Isles are currently being dissolved at a rate of

40mm/1000 years. In Columbia, South America, unspecified limestones are being dissolved at a rate of 10mm/1000 years. It is also stated that a doline in Yorkshire, of less than 50m in diameter and 15m deep, took less than 14,000 years to develop (Sweeting, 1973). These estimates can change based on temperature and rainfall fluctuations. In the case of Cenozoic karst in the Yucatan Peninsula, cenotes, a type of sinkhole that extends to great depths, could grow in a matter of a few thousand years (Isphording, 1974a, 1974b). Based on the doline features seen in the Leatherwood Ford outcrop, it seems likely that subaerial exposure, although extensive, did not need to last more than 10-20,000 years. This allowed time for the development of deep doline 2, the largest feature in the outcrop.

Some of the smaller features seen toward the right (north) side of the outcrop could have formed in less time. The kamenitza, for example, could have formed in as little as 10-50 years, due to the extremely acidic conditions within the solution pan (Sweeting, 1973). The decken-karren seen at the south edge of the kamenitza would have formed during the lifetime of the tree, so the estimates for development could be approximately 35 - 100 years (Vanstone, 1998).

Final assignment for an absolute timing of the karst plane is based on the paleosol development on the plane. The paleosol can be considered relatively immature, based on the lack of horizonation and weakly-developed slickensides. According to Vanstone (1998), the immaturity of the paleosol is indicative of a relatively short period of exposure and development of paleo-karst features, on the order of a few ten of thousands of years. Based on the other evidence seen in the Leatherwood Ford outcrop, a short time period of subaerial exposure and karst development, perhaps less than 10-20,000 years, seems to fit the evidence.

IV. Summary and Conclusions

The basis of this thesis was to test the hypothesis of subaerial exposure as the mechanism for the formation of paleokarst features found at the top of the upper Pennington limestone. In order to test this, it was necessary to examine the depositional history of the section, to classify the three scales of paleokarst features found within the section, and to place each of these features within a relative temporal order. By achieving each of these goals, a strong case could be made for the hypothesis that subaerial exposure was the dominant instrument of early diagenesis in the upper Pennington limestone. The following are the conclusions reached from this study:

1. The depositional history, based on three units subdivided within the upper Pennington limestone and one pre-section unit, illustrates sea level fluctuations that were associated with a full-scale regression that occurred at the end of the Mississippian or the beginning of the Pennsylvanian. It is this regression that is responsible for the exposure of the upper Pennington limestone.

2. The aforementioned regression brought about short-term exposure, which likely lasted for 10-20,000 years. This was the mechanism for the development of three scales of paleokarst features within the upper Pennington limestone.

3. The hypothesis for subaerial exposure is supported by observations of different scales of paleokarst features. The macroscale features include paleo-dolines, a paleo-kamenitza, and paleo-topographic limestone pinnacles, each of which can be proved to have

formed in a subaerial environment. The evidence found in macroscale features is also supported by mesoscale and microscale features. These include evidence for interaction between the upper Pennington limestone and soil, vegetation, and subaerial deposition.

4. By placing these features into a temporal order, a plausible history of exposure and erosion on the Pennington limestone plain develops. This account envelops the beginnings of exposure with the widespread regression at the end of the Mississippian or the beginning of the Pennsylvanian and continues through exposure to the eventual cover and burial of the karst plain.

References Cited

Algeo, T.J., Rich, M., 1992, Bangor Limestone; depositional environments and cyclicity on a Late Mississippian carbonate shelf: *Southeastern Geology*, v.32, no.3, p. 143-162.

Allan, J.R., Matthews, R.K., 1982, Isotope signatures associated with early meteoric diagenesis: *Sedimentology*, v.29, no.6, p. 797-817.

Bagby, B.A., 1989, Paleoenvironmental and Diagenetic Analysis of the St. Louis Limestone: Unpublished MS Thesis, Indiana University, Bloomington, Indiana.

Bardossy, G., Fuchs, Y., and Glazek, J., 1989, Iron ore deposits in paleokarst, in Paleokarst, (eds. Bosak, Ford, Glazek, Horacek): Elsevier, Amsterdam.

Bathurst, R.G.C., 1966, Boring algae, micrite envelopes and lithification of molluscan biosparites: *Geological Journal*, v.5, pt.1, p. 15-32.

Bathurst, R.G.C., 1975, *Carbonate Sediments and their Diagenesis* (2nd ed): *Developments in Sedimentology* 12, Elsevier, New York.

Bergenback, R.E., Horne, J.C., and Inden, R.F., 1972, Depositional environments of Mississippian carbonate rocks at Monteagle, Tennessee, in *Carboniferous depositional environments in the Cumberland Plateau of southern Tennessee and northern Alabama* (eds. Ferm, Milici, and Eason): *GSA Pre-meeting field trip Guidebook*, p. 14-18.

Brasier, M.D., 1980, Microfossils: George Allen and Unwin Publishers, London.

Brown, M.A., 1987, Depositional and Diagenetic history of a Middle Mississippian shoal and related facies: Unpublished MS Thesis, Indiana University, Bloomington, Indiana.

Budd, D.A., and Saller, A.H., 1994, Unconformities and porosity development in carbonate strata; ideas from a Hedberg conference. *AAPG Bulletin*. v.78, no.6, p. 857-872.

Burke, A.R., Bird, P.F., 1966, A new mechanism for the formation of vertical shafts in Carboniferous limestone: *Nature*, v.210, p. 831-832.

Cadee, G.C., 1998, Influence of benthic fauna and microflora in Intertidal fauna and vegetation Ch.8, in *Intertidal Deposits: River Mouths, Tidal Flats, and Coastal Lagoons*, (ed. Eisma): CRC Press, Boca Raton, p. 383-402.

Campbell, M.R., 1893, *Geology of Big Stone Gap coal field of Virginia and Kentucky*: U.S. Geologic Survey Bulletin., v.111.

Caudill, M.R., Mora, C.I., Tobin, K.J., and Driese, S.G., 1992, Preliminary interpretations of Paleosols associated with Late Mississippian marginal marine deposits, Pennington Formation, Monterey, TN, in *Paleosols, paleoweathering surfaces, and sequence boundaries*, (eds. Driese, Mora, Walker): *Studies in Geology* (Knoxville), v.21, p. 57-77.

Caudill, M.R., Driese, S.G., and Mora, C.I., 1996, Preservation of a paleo-vertisol and an estimate of Late Mississippian paleoprecipitation: *Journal of Sedimentary Research*, Vol. 66, No.1, p.58-70.

Chaloner, W.G., and McElwain, J., 1997, The fossil plant record and global climatic change, in: *Euramerican Carboniferous paleobotany and coal geology; proceedings of the 1st Walter A. Bell memorial symposium*, (eds. Lyons, and Zodrow): *Review of Palaeobotany and Palynology*, v.95, p. 73-82 .

Chestnut, D.R., Jr., Eddensohn, F.R., 1994, Life mode of *Pterotocrinus* in the lower Pennington (Lower Carboniferous) of east-central Kentucky: *Abstracts with Programs - Geological Society of America*, v.16, no.3, p. 128.

Colton, G.W., 1970, The Appalachian Basin, its depositional sequences and their relationships, in *Studies of Appalachian geology*, (ed. Fisher): Interscience Publishers, New York, p. 5-47.

Coniglio, M., and James, N.P., 1985, Calcified algae as sediment contributors to Early Paleozoic limestones: Evidence from deep-water sediments of the Cow Head Group, Western Newfoundland: *Journal of Sedimentary Petrology*, v.55, no.5, p. 746-754.

Deaver, B.G., and Smith, J.A., 1999, *Hiking the Big South Fork*: University of Tennessee Press, Knoxville, 272p.

Dennison, J.M., and Wheeler, W.H., 1975, Stratigraphy of Precambrian through Cretaceous strata of probably fluvial in origin in southeastern United States and their potential as uranium host rocks: *Southeastern Geology Special Publication*, no.5.

Dickson, J.A.D., 1966, Carbonate identification and genesis as revealed by staining: *Journal of Sedimentary Petrology*, v.36, no.2, p. 491-505.

Driese, S.G., Caudill, M.R., Srinivasan, K., 1998, Late Mississippian to Early Pennsylvanian paleokarst in east-central Tennessee; field, petrographic, and stable isotope evidence: *Southeastern Geology*, v.37, no.4, p. 1998.

Driese, S.G., Tobin, K., and Caudill, M.R., in prep, Influence of Late Mississippian paleokarst processes on fluid flow during burial diagenesis.

Englund, K.J., 1964, In the Cumberland Mountains of southeastern Kentucky, stratigraphy of the Lee Formation: *USGS Professional Paper 501-B*, p. B30-B38.

Englund, K.J., and Delaney, A.O., 1966, Intertonguing relations of the Lee Formation in southwestern Virginia: *USGS Paper 550-D*, p. D47-D52.

Eddensohn, F.R., 1994, Tectonic control on formation and cyclicity of major

appalachian unconformities and associated stratigraphic sequences: Tectonic and Eustatic Controls on Sedimentary Cycles, SEPM Concepts in Sedimentology and Paleontology #4, p. 217-242.

Ettensohn, F.R., and Chestnut, D.R., 1989, Nature and probable origin of the Mississippian-Pennsylvanian unconformity in the Eastern United States: *Compte Rendu, Onzieme Congres International de Stratigraphy et de Geologie du Carbonifere*, Beijing, v.4, p. 145-159.

Ettensohn, F.R., and Chestnut, D.R., 1985a, Depositional environments and stratigraphy of the Pennington Formation (Upper Visean-Namurian A), East-Central and Eastern Kentucky, U.S.A.: *Compte Rendu, Dixieme Congres International de Stratigraphy et de Geologie du Carbonifere*, Madrid, v.3, p. 269-283.

Ettensohn, F.R., and Chestnut, D.R., 1985b, Echinoderm paleoecology and paleoenvironments from the Glen Dean/ Bangor and lower Pennington (Chesterian), south-central Kentucky: *Compte Rendu - Congres International de Stratigraphie et de Geologie du Carbonifere*, v.9 no.5, p. 349-360.

Ettensohn, F.R., and Peppers R.A., 1979, Palynology and stratigraphy of Pennington shales and coals (Chesterian) at selected sites in northeastern Kentucky: *Journal of Paleontology*, v.53, p. 453-474.

Ferm, J.C., 1974, Carboniferous environmental models in eastern United States and their significance, in *Carboniferous of the Southeastern US*, (ed. Briggs), GSA Special Paper 148, p. 79-95.

Ferm, J.C., Horne, J.C., Swinchatt, J.P., and Whaley, P.W., 1971, Carboniferous depositional environments in northeastern Kentucky: Geological Society of Kentucky, Guidebook Spring Field Conference, KGS, Lexington.

Fisher, M.P., 1978, Sedimentology and stratigraphy of the Pennington Formation, Upper Mississippian in south-central Kentucky: Unpublished Masters Thesis, University of the University of Cincinnati, Cincinnati, Ohio.

Frazier, W., 1973, Carbonate petrology of the Mississippian Pennington Formation, central Tennessee: Unpublished Ph.D. Dissertation, UNC-Chapel Hill, North Carolina.

Frazier, W.J., 1975, Celestite in the Mississippian Pennington Formation, central Tennessee: *Southeastern Geology* 16; 4, p 241-248.

Harrison, R.S., and Steinen, R.P., 1978, Subaerial crusts, caliche profiles, and breccia horizons: comparison of some Holocene and Mississippian exposure surfaces, Barbados and Kentucky: *Geological Society of America Bulletin*, v.89, p. 385-396.

Horne, J.C., Ferm, J.C., and Swinchatt, J.P., 1974, Depositional model for the

Mississippian-Pennsylvanian boundary in northeastern Kentucky, in Carboniferous of southeastern United States (ed. Briggs): GSA Special Paper 148, p. 97-114.

Horowitz, A.S., and Potter, P.E., 1971, Introductory petrography of fossils: Springer-Verlag, New York.

Hurd S.A., and Stapor, F.W., 1997, Facies, stratigraphy, and provenance of the Warren Point Sandstone (Pennsylvanian) Cumberland Plateau, central Tennessee: *Southeastern Geology*, v.36, no.4, p. 187-201.

Irwin M.L., 1965, General theory of epeiric clear water sedimentation: *AAPG Bulletin*, v.49, p. 445-459.

Isphording, W.C., 1974a, Tectonic and geomorphic evolution of the Yucatan Peninsula: *GSA Abstracts with Programs* 6;4, p. 368.

Isphording, W.C., 1974b, A model for limestone weathering and soil development in tropical climates: *GSA Abstracts with Programs* 6;7, p. 805.

James, N.P., 1972, Holocene and Pleistocene calcareous crust (caliche) profiles: Criteria for subaerial exposure: *Journal of Sedimentary Petrology*, v.42, no.4, p. 817-836.

James, N.P., and Choquette, P.W., 1988, *Paleokarst*: Springer-Verlag, New York.

Keith, A., 1896, Description of the Briceville quadrangle, Tennessee: *USGS Geologic Atlas*, Folio 33, 12p.

Kobluck, D.R., and Risk, M.J., 1977, Calcification of exposed filaments of endolithic algae, micrite envelope formation and sediment production: *Journal of Sedimentary Petrology*, v.47, no.2, p. 517-528.

Lorenz, J.C., and Neal, J.T., 1999, The effects of evaporite-dissolution fronts on overlying fractured reservoirs: *AAPG Bulletin* 83; 7, p 1185.

Ludvigson, G.A., Gonzalez, L.A., Metzger, R.A., Witzke, B.J., Brenner, R.L., Murillo, A.P., White, T.S., 1998, Meteoric sphaerosiderite lines and their use for paleohydrology and paleoclimatology: *Geology*, v.26, no.11, p. 1039-1042.

Meyers, W.J., and Lohmann, K.C., 1985, Isotope geochemistry of regionally extensive cement zones and marine components in Mississippian limestones, New Mexico, in *Carbonate Cements: SEPM, Special Publication #36*, (Eds; Schneidermann, N., Harris, P.M.) p.223-239.

Milici, R.C., 1979, Stratigraphy and depositional environments of the Upper Mississippian and Lower Pennsylvanian rocks in the southern Cumberland Plateau of Tennessee, in *Carboniferous depositional environments in the Appalachian region*, (eds,

Ferm, Horne, Weisenfluh, Staub): p. 404-421.

Milici, R.C., 1974, Stratigraphy and depositional environments of Upper Mississippian and Lower Pennsylvanian rocks in the southern Cumberland plateau of Tennessee, in Carboniferous of southeastern United States (ed. Briggs): GSA Special Paper 148, p. 115-133.

OTS Heavy Oil Science Center Internet Source (1998):
<http://www.lloydminterheavyoil.com>

Popp, B.B., Takigiku, R., Hayes, J.M., Louda, J.W., and Baker, E.W., 1986, Brachiopods as indicators of original isotopic conditions in some Paleozoic limestone: GSA Bulletin, v.97, p. 1262-1269.

Pratt, B.R., James, N.P., 1986, The St George Group (Lower Ordovician) of western Newfoundland; tidal flat island model for carbonate sedimentation in shallow epicritic seas: Sedimentology, v.33, no.3, p. 313-343.

Pryor, W.A., and Sable, E.G., 1974, Carboniferous of the Eastern Interior Basin, in Carboniferous of southeastern United States (ed. Briggs): GSA Special Paper 148, p. 281-313.

Saller, A.H., 1994, Models for predicting subaerial exposure and porosity in carbonates: Annual Meeting Abstracts –AAPG and SEPM, p. 249.

Saunders, W.B., and Ramsbottom, W.H.C., 1986, The mid-Carboniferous eustatic event: Geology, v.14, p.208-212.

Shinn, E.A., and Lidz, B.H., 1988, Blackened limestone pebbles: Fire at subaerial unconformities, in Paleokarst, (eds. James, Choquette): Springer-Verlag, New York, p. 117-131.

Shinn, E.A., 1983, Tidal flat environment, in Carbonate depositional environments, (eds. Scholle, Bebout, Moore): AAPG Memoir 33, p. 171-210.

Shinn, E.A., Ginsburg, R.N., and Lloyd, R.M., 1965, Recent supratidal dolomite from Andros Island, Bahamas, in Dolomitization and limestone diagenesis – a symposium, (eds. Pray and Murray): SEPM, Special Publication 13.

Shinn, E.A., Ginsburg, R.N., and Lloyd, R.M., 1969, Anatomy of a modern carbonate tidal flat, Andros Island, Bahamas: Journal of Sedimentary Petrology, v.39, p. 1202-1228.

Shinn, E.A., Ginsburg, R.N., Lloyd, R.M., 1965, Recent supratidal dolomite from Andros Island, Bahamas, In: Dolomitization and limestone diagenesis-a symposium: SEPM Special Publication, p. 112-123.

Strasser, A., Davaud, E., 1983, Black pebbles of the Purbeckian (Swiss and French Jura); lithology, geochemistry and origin: *Eclogae Geologicae Helvetiae*, v.76 no.3, p. 551-580.

Swann, D.H., 1964, Late Mississippian rhythmic sediments of Mississippi Valley: *AAPG Bulletin*, v.48, no.5, p. 637-658.

Sweeting, M.M., 1978, Some observations on New Zealand limestone areas, in *Landform evolutions in Australasia*, (eds. Davies and Williams) Austr. Nat. Univ. Press. Canberra, Australia, p. 250-258.

Sweeting, M. M., 1973, *Karst landforms*: Columbia University Press, New York.

Sweeting, M.M., 1972, The Karst of Great Britain, in *Karst: Important Karst Areas of the Northern Hemisphere*, (eds. Herak and Stringfield): Elsevier, Amsterdam.

Sweeting, M.M., 1966, The weathering of limestones, with particular reference to the Carboniferous limestones of northern England, in *Essays in Geomorphology*, (ed. Drury): Heinemann, London, p.177-210.

Terry R., and Chilingar, G., 1955, Summary of "Concerning some additional aids in studying sedimentary formations", M. Shvetsov: *Journal of Sedimentary Petrology*, v.25, p. 229-234.

Thompson, A.M., 1970, Tidal flat deposition and early dolomitization in Upper Ordovician Rocks of southern Appalachian valley and ridge: *Journal of Sedimentary Petrology*, v.40, no.4, p. 1271-1286.

Tucker, M.E., and Wright, V.P., 1990, *Carbonate Sedimentology*: Blackwell Scientific Publications, Oxford.

Vanstone, S.D., 1998, Late Dinantian palaeokarst of England and Wales: Implications for exposure surface development: *Sedimentology*, v.45, p. 19-37.

Walkden, G.M., and Davies, J., 1983, Polyphase erosion of subaerial omission surfaces in the Late Dinantian of Anglesey, North Wales: *Sedimentology*, v.30, p. 861-878.

Walkden, G.M., 1974, Paleokarstic surfaces in Upper Visean (Carboniferous) limestones of the Derbyshire Block, England: *Journal of Sedimentary Petrology*, v.44, no.4, p. 1232-1247.

Williams, H., Hatcher, R.D., Jr., 1982, Suspect terranes and accretionary history of the Appalachian Orogen: *Geology*, v.10 no.10, p. 530-536.

Wright, V.P., 1994, Paleosols in shallow marine carbonate sequences: *Earth Science*

Reviews, v.35, p. 367-395.

Wright, V.P., 1986, The polyphase karstification of the Carboniferous limestones in South Wales, in New directions in karst, (eds. Paterson and Sweeting): Proceedings of Anglo-French Karst Symposium, Geoabstracts, Norwich, p. 569-590.

Wright, V.P., 1982, The recognition and interpretation of paleokarsts: Two examples from the Lower Carboniferous of South Wales: *Journal of Sedimentary Petrology*, v.52, no.1, p. 83-94.

Wright, V.P., and Tucker, M.E., 1991, *Calcretes*: Blackwell Scientific Publishing, Oxford, 352p.

Appendices

Appendix 1

Five measured stratigraphic sections were used to make lithologic interpretations in this thesis. These sections, and their lateral and vertical relationships are shown in Figure 6. For their relation overall to the Leatherwood Ford outcrop, refer to Figure 5.

Following are the descriptions of the five measured sections. Stratigraphic sections were described in ascending stratigraphic order from the base of the measurable section. Descriptions are based primarily on field data, but have been augmented by thin section and hand sample data when appropriate. Rock names are from Dunham (1965).

Note that a complete stratigraphic section occurs only in transect 6, whereas others are only partial sections due to outcrop cover or paleo-karst processes.

Transect 2 Field Descriptions

Unit 3:	Thickness:	0.85meters
	Cum. thick.:	0.85 meters
	Classification:	Peloidal Wackestone to Packstone
	Color:	Yellowish gray (5Y 8/1) to Light olive gray (5Y 6/1)
	Description:	Diagnostic oncolitic allochems, other obvious allochems in hand sample include gastropods and brachiopods. Well-developed micritic envelopes (0.125 - 0.5mm thick) surround many of the allochems. Burrows (1mm) noted. Spar filled voids include moldic (3 – 5mm) and intergranular pores (1 – 3mm). Shelter pores common. Upper contact gradational.
	Sample:	2.1, 2.2, 2.3
Unit 4:	Thickness:	1.65 meters
	Cum. thick.:	2.50 meters
	Classification:	Skeletal Packstone to Grainstone
	Color:	Light olive gray (5Y 6/1) with variations dependant on iron oxide staining: Grayish orange (10 YR 7/4) to Yellowish gray (5Y 7/2) to Grayish red (5R 4/2)
	Description:	High amounts of fossils include brachiopods, crinoids, and ostracodes. Intraclasts with skeletal allochems found throughout unit. Occasional 0.25mm clay seams noted. Spar filled moldic (2 – 4mm), shelter, intergranular and intragranular (0.1mm) pores. Iron oxide staining increasingly common, hematite and ankeritic siderite blebs found in matrix. Unconformable surface marks the upper contact of this unit.
	Samples:	2.4, 2.5, 2.6

Transect 4 Field Descriptions

Unit 2:	Thickness:	0.40 meters
	Cum. thick.:	0.40 meters
	Classification:	Skeletal Wackestone to Packstone
	Color:	Brownish black (5YR 2/1) to Grayish black (N2)
	Description:	Extensive vertical fissures, small-scale horizontal clay seams (0.25 – 0.5mm thick) common, mottled texture due to presence of burrows (1 – 2mm), iron staining rare - but when present follows fractures. Skeletal allochems seen in hand-sample include ostracode, echinoderm, and brachiopod; Spar filled moldic porosity. Upper contact gradational.
	Samples:	4.1
Unit 3:	Thickness:	1.20 meters
	Cum. thick.:	1.60 meters
	Classification:	Peloidal Wackestone to Packstone
	Color:	Yellowish gray (5Y 8/1) to Light olive gray (5Y 6/1)
	Description:	Diagnostic oncolitic allochems, other obvious allochems in hand sample include gastropods and brachiopods. Well-developed micritic envelopes (0.125 - 0.5mm thick) surround many of the allochems. Burrows (1mm) noted. Spar filled voids include moldic (3 – 5mm) and intergranular pores (1 – 3mm). Shelter pores common. Upper contact gradational.
	Samples:	4.2, 4.3, 4.4, 4.5
Unit 4:	Thickness:	1.20 meters
	Cum. thick.:	2.80 meters
	Classification:	Skeletal Packstone to Grainstone
	Color:	Light olive gray (5Y 6/1) with variations dependant on iron oxide staining: Grayish orange (10 YR 7/4) to Yellowish gray (5Y 7/2) to Grayish red (5R 4/2)
	Description:	High amounts of fossils include brachiopods, crinoids, and ostracodes. Intraclasts with skeletal allochems found throughout unit. Occasional 0.25mm clay seams noted. Spar filled moldic (2 – 4mm), shelter, intergranular and intragranular (0.1mm) pores. Iron oxide staining increasingly common, hematite and ankeritic siderite blebs found in matrix. Unconformable surface marks the upper contact of this unit.
	Samples:	4.7, 4.9, 4.10, 4.12, 4.13

Transect 5 Field Descriptions

Unit 3:	Thickness:	0.70 meters
	Cum. thick.:	0.70 meters
	Classification:	Peloidal Wackestone to Packstone
	Color:	Yellowish gray (5Y 8/1) to Light olive gray (5Y 6/1)
	Description:	Diagnostic oncolitic allochems, other obvious allochems in hand sample include gastropods and brachiopods. Well-developed micritic envelopes (0.125 - 0.5mm thick) surround many of the allochems. Burrows (1mm) noted. Spar filled voids include moldic (3 – 5mm) and intergranular pores (1 – 3mm). Shelter pores common. Samples taken from edge of paleo-doline, where they were originally covered by red paleosol. Hematitization in this unit pervasive in some samples. Samples 5.7 and 5.4 were almost entirely composed of hematite cements. Upper contact gradational.
	Samples:	5.1, 5.7, 5.2, 5.4
Unit 4:	Thickness:	1.20 meters
	Cum. thick.:	1.90 meters
	Classification:	Skeletal Packstone to Grainstone
	Color:	Light olive gray (5Y 6/1) with variations dependant on iron oxide staining: Grayish orange (10 YR 7/4) to Yellowish gray (5Y 7/2) to Grayish red (5R 4/2)
	Description:	High amounts of fossils include brachiopods, crinoids, and ostracodes. Intraclasts with skeletal allochems found throughout unit. Occasional 0.25mm clay seams noted. Spar filled moldic (2 – 4mm), shelter, intergranular and intragranular (0.1mm) pores. Iron oxide staining increasingly common, hematite and ankeritic siderite blebs found in matrix. Exposed surfaces often completely hematitized. Unconformable surface marks the upper contact of this unit.
	Samples:	5.3, 5.5

Transect 6 Field Descriptions

Unit 1:	Thickness:	Pre-section
	Cum. thick.:	Covered Section – only upper surface exposed
	Classification:	Dolomitized Mudstone
	Color:	Dark greenish gray (5GY 4/1) to Grayish olive green (5 GY 3/2)
	Description:	Extensively brecciated dolomicrite, dolo-spar veins run

horizontally and vertically (0.23 – 1mm) through sample, horizontal cracks parallel what appear to be highly brecciated stromatolitic laminae. Only allochems noted are intraclasts (4 – 5mm) and pellets (0.05 – 0.1mm). Some intraclasts selectively brecciated in an oriented fashion. Clay lined grikes or fractures throughout unit. Highly weathered, due to exposure at erosional surface, some iron oxide staining following fractures.

Sample: 6.1

Unit 2: **Thickness:** 0.42 meters
Cum. thick.: 0.42 meters
Classification: Skeletal Wackestone to Packstone
Color: Brownish black (5YR 2/1) to Grayish black (N2)
Description: Extensive vertical fissures, small-scale horizontal clay seams (0.25 – 0.5mm thick) common, mottled texture due to presence of burrows (1 – 2mm), iron staining rare - but when present follows fractures. Skeletal allochems seen in hand-sample include ostracode, echinoderm, and brachiopod; Spar filled moldic porosity. Upper contact gradational.

Samples: 6.2

Unit 3: **Thickness:** 1.28 meters
Cum. thick.: 1.70 meters
Classification: Peloidal Wackestone to Packstone
Color: Yellowish gray (5Y 8/1) to Light olive gray (5Y 6/1)
Description: Diagnostic oncolitic allochems, other obvious allochems in hand sample include gastropods and brachiopods. Well-developed micritic envelopes (0.125 - 0.5mm thick) surround many of the allochems. Burrows (1mm) noted. Spar filled voids include moldic (3 – 5mm) and intergranular pores (1 – 3mm). Shelter pores common. Upper contact gradational.

Samples: 6.3, 6.4a, 6.4b, 6.5

Unit 4: **Thickness:** 2.10 meters
Cum. thick.: 3.80 meters
Classification: Skeletal Packstone to Grainstone
Color: Light olive gray (5Y 6/1) with variations dependant on iron oxide staining: Grayish orange (10 YR 7/4) to Yellowish gray (5Y 7/2) to Grayish red (5R 4/2)
Description: High amounts of fossils include brachiopods, crinoids, and ostracodes. Intraclasts with skeletal allochems found throughout unit. Microstylolites (0.1mm) noted at top of

unit. Burrows filled with laminated ooids cortoids? found at top of unit. Spar filled moldic (2 – 4mm), shelter, intergranular, and intragranular (0.1mm) pores. Iron oxide staining increasingly common, hematite and ankeritic siderite blebs found in matrix. Unconformable surface marks the upper contact of this unit.

Samples: 6.6, 6.7, 6.8, 6.9, 6.10

Transect 7 Field Descriptions

Unit 3: **Thickness:** 1.25 meters
Cum. thick.: 1.25 meters
Classification: Peloidal Wackestone to Packstone
Color: Yellowish gray (5Y 8/1) to Light olive gray (5Y 6/1)
Description: Diagnostic oncolitic allochems, other obvious allochems in hand sample include gastropods and brachiopods. Well-developed micritic envelopes (0.125 - 0.5mm thick) surround many of the allochems. Burrows (1mm) noted. Spar filled voids include moldic (3 – 5mm) and intergranular pores (1 – 3mm). Shelter pores common. Upper contact gradational.

Samples: 7.1, 7.2, 7.3, 7.4

Unit 4: **Thickness:** 1.70 meters
Cum. thick.: 2.95 meters
Classification: Skeletal Packstone to Grainstone
Color: Light olive gray (5Y 6/1) with variations dependant on iron oxide staining: Grayish orange (10 YR 7/4) to Yellowish gray (5Y 7/2) to Grayish red (5R 4/2)
Description: High amounts of fossils include brachiopods, crinoids, and ostracodes. Intraclasts with skeletal allochems found throughout unit. Occasional 0.25mm clay seams noted. Spar filled moldic (2 – 4mm), shelter, intergranular and intragranular (0.1mm) pores. Iron oxide staining increasingly common, hematite and ankeritic siderite blebs found in matrix. Unconformable surface marks the upper contact of this unit.

Samples: 7.5, 7.6, 7.7

Appendix 2

This appendix gives allochemical and orthochemical percentages for each sample taken within the transects of the upper Pennington limestone. For sample placement within the column, refer to the stratigraphic columns found in Figure 6.

When calculating percentages, the method employed was based on Terry and Chilingar's visual estimation charts (1955). Though these percentages are not absolute, they illustrate trends within the different units very well.

There were some problems with the estimates, all of which centered on the peloidal allochems. Firstly, the peloids were commonly compacted and formed a grumeleuse texture, in which the peloids and the micritic matrix were often indistinguishable. In that case, the percentages for micrite went up. The second problem was distinguishing peloids versus cortoids. In the end, it was easier to put the two into a category together, as the origin for the micritic balls was often obscured.

	S 2.1	S 2.2	S 2.3	S 2.4	S 2.5
Allochems					
Echinoderms	3	7	5	6	6
Crinoids	1	3	2	3	3
Echinoids	2	4	3	3	3
Arthropods	3	3	3	4	3
Ostracods	3	2.5	3	3	2
Trilobites	0	0.5	0	1	1
Bryozoans	3	5	4	4	4
Brachiopods	2	2	0	2	1
Mollusks	4	4	4	5	5
Gastropods	2	3	2	2	2
Pelecypods	2	1	2	3	3
Foraminifera	4	5	6	6	5
Miliolid	2	3	3	3	2
Fusilinid	2	2	3	2	1
Biserial	0	0	0	1	2
Algae	1	1	1	1	1
Calcispheres	1	1	1	1	1
Total Skeletal	19	28	24	29	27
Pellets / Cortoids	30	27	25	31	30
Intraclasts	0	2	3	4	5
Oncoids	5	0	2	0	0
Total Allochems	54	57	54	64	62
Orthochems					
Micrite	35	23	34	15	14
Sparite	10	15	10	18	19
Dolomicrite	0	0	0	0	0
Dolosparite	0	0	0	0	0
Other					
Iron Oxides	1	2	2	2	3
Siderite	0	2	0	1	2
Total	100	100	100	100	100

	S 5.1	S 5.7	S 5.2	S 5.4	S 5.3	S 5.5
Allochems						
Echinoderms	4	4	3	2	5	3
Crinoids	2	1	1	1	2	1
Echinoids	2	3	2	1	3	2
Arthropods	3	2	3	1	5	3
Ostracods	3	2	3	0	3	3
Trilobites	0	0	0	0	2	0
Bryozoans	2	0	1	0	2	1
Brachiopods	2	1	1	0	2	1
Mollusks	4	3	4	2	5	3
Gastropods	3	3	2	1	2	1
Pelecypods	1	0	2	1	3	2
Foraminifera	3	2	2	0	2	3
Miliolid	2	1	1	0	1	0
Fusilinid	1	1	1	0	1	0
Biserial	0	0	0	0	0	3
Algae	1	0	0	0	0	1
Calcisphere	1	1	1	0	1	1
Total Skeletal	20	13	15	5	22	16
Pellets / Cortoids	45	15	27	0	36	40
Intraclasts	2	0	5	0	5	0
Oncoids	0	0	0	0	0	0
Total Allochems	67	28	47	5	63	56
Orthochems						
Micrite	15	20	40	0	7	20
Sparite	17	7	10	0	20	15
Dolomicrite	0	0	0	0	0	0
Dolosparite	0	0	0	0	0	0
Other						
Iron Oxides	1	45	3	95	10	7
Siderite	0	0	0	0	0	2
Total	100	100	100	100	100	100

Vitae

Elizabeth Humbert was born in Rogersville, Tennessee on October 26, 1973, where she learned the importance of rocks and dirt at an early age on her family's Choptack farm. The Humbert Family moved to Clinton, South Carolina during her early years, and although there were no rocks, the move allowed her to hone her southern accent. After completing high school in Clinton, Elizabeth went on to garner a BA in Geology at Clemson University. During her time there, she grew to love soft rocks and sedimentology, under the tutelage of Dr. James Castle. Upon graduating from Clemson, she took a brief sojourn to Europe, where she collected rocks from every locality possible. After her trip, Elizabeth moved to Knoxville, Tennessee to begin working on her Master's of Science at UT-K with Dr. Steven G. Driese. Grad school wrought many changes – she quickly got over her fear of math (even calculus), gained a love of teaching (even the intro labs), and began to see art forms in paleokarst (even in the paleo-dolines.) Upon defending her thesis, she moved to Ithaca, New York, where she took a job with the Paleontological Research Institution. Her first duty at the institution was to find and dig up a 12,000 year old mastodon; And, although it was hot and mosquitoey and dirty, she states that it was still a hell of a lot better than field camp.