Reactivated Paleokarst in Northern Audrain County, Missouri

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Three sinkholes opening in Audrain County, Missouri in 2008 offered a rare opportunity to examine karst features in an environment in which they rarely occur. The regional geology around the site consists of Mississippian-age limestone, overlain by thick Pennsylvanian-age cyclothems of shale, sandstone, limestone and coal, covered with thick glacial tills from multiple Neogene-age glacial episodes. Site investigations revealed that the sinkholes contained intact lithified sediments deposited at the end of the Mississippian. This paleofill material has rarely been found in other sinkholes within Missouri. The paleofill demonstrates that karst in this region of Missouri is potentially a phenomenon formed during an episode of regression. During this regression, subaerial exposure allowed karst processes to form the sinkholes, or paleosinks, which were subsequently filled with colluvial materials. These materials, consisting of sand, clay and chert derived from nearby siliciclastic sources south of the site, were deposited in the open sinkhole after Mississippian time. The sediments were buried deeply enough during early Pennsylvanian time to weakly alter the sediments, allowing diagenesis to compact clay into shale and cement sand into sandstone. Chert clasts were also incorporated into these deposits. Carbonaceous deposits at the base of the sediments indicate organic material deposition. These materials could have provided sulfur for pyrite deposits observed in fossil molds in the chert-rich sediment.

The paleosinks indicate the possible existence of a more extensive, contiguous zone of karst that could have existed in northern Missouri, eastern Iowa, and into southern Wisconsin. Observations around the site may indicate a multi-story karst aquifer could have existed in the area before the beginning of post-Cretaceous glacial cycles. Similar paleokarst sites may also lie hidden near areas where active stream downcutting has removed the glacial and Pennsylvanian overburden, and could be hydrologically reactivating other quiescent sinkholes in the area around the site.

Keywords: karst, hydrology, Mississippian, Pennsylvanian, Missouri, Audrain County.

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CHAPTER 1 INTRODUCTION

The opening of three sinkholes in north-central Missouri in 2008 has offered a unique opportunity to study rare paleokarst that was preserved, obscured by glaciation and subsequently reactivated by a combination of natural and man-made causes (Smotherman, 2008). This paleokarst was identified by the presence of paleofill, sediments that filled the sinkholes far back in geologic time and that were subsequently lithified by shallow diagenetic compaction and cementation. These sinkholes, or 'paleosinks', provide valuable information about the geologic processes that have affected the state of Missouri during the Kaskaskia Regression, a hiatus in the depositional record of Missouri during which no marine rocks are deposited and in which the terrestrial environment must be inferred in other ways, including the analysis of paleofill materials that were deposited in karst features during the subaerial exposure of the carbonates during the regression. Sinkholes such as these are sources of potential environmental concern in other parts of the state and are thoroughly studied for their potential impact on groundwater resources in those areas. In northern Missouri, they are largely unknown and their study may well change many of the assumptions made about the safety of shallow groundwater resources in this portion of the state.

The Audrain County Paleokarst Site (ACPS) is located in the northwest corner of Audrain County in North-Central Missouri (Figure 1.1). It is in a geologically and hydrologically complex, but little-studied, area. The landscape surface consists of ridges of glacially derived sand, silt, clay and gravel. In the numerous streams and rivers that dissect the glacial upland, bedrock outcrops of Pennsylvanian and Mississippian-age bedrock are often exposed (Figure 1.2). The most prevalent formations in the vicinity of the site are the Pennsylvanian-age Cherokee Group and the Mississippian-age Burlington Limestone (Osagean Series) (Gentile and Thompson, 2003; Thompson, 1995) (Figure 1.3). The Cherokee Group is predominantly black organic and carbonaceous shales with occasional sandstones and limestones (Gentile and Thompson, 2003). The Burlington Limestone is a coarse-crystalline, fossiliferous limestone with significant secondary, localized weathering (Thompson, 1995).

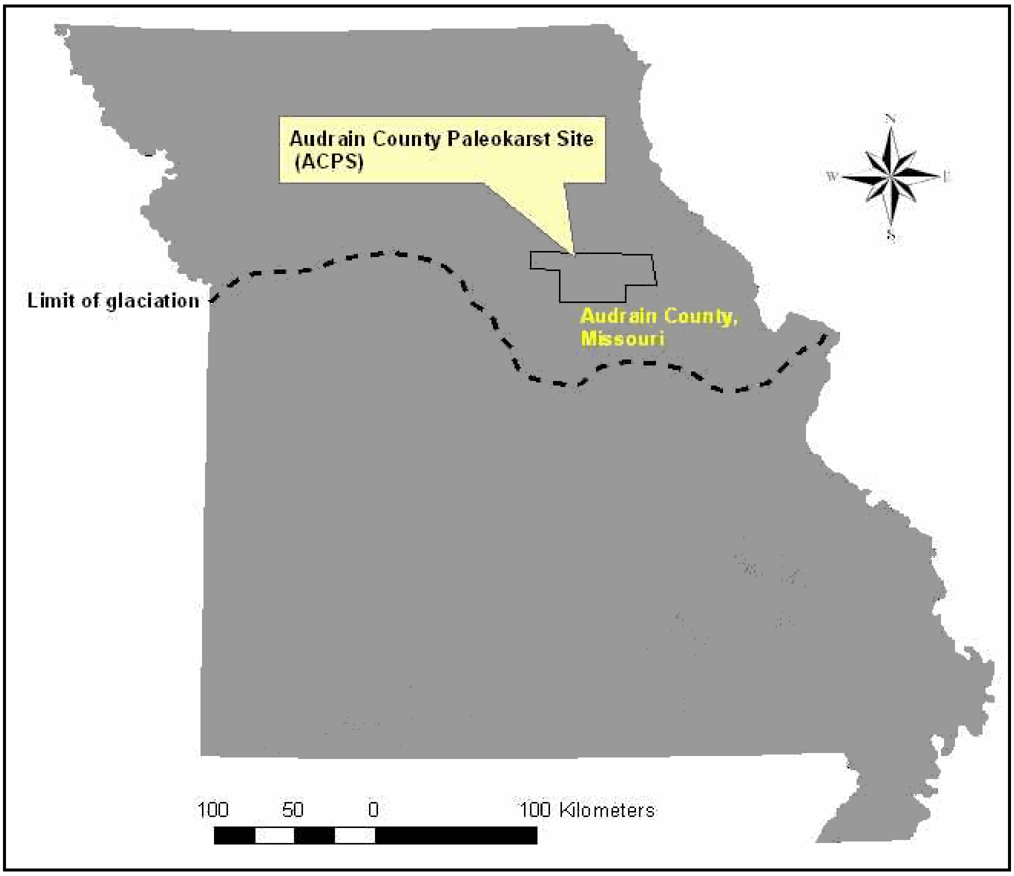

Figure 1.1 State of Missouri and the location of the Audrain County Paleokarst Site (ACPS)

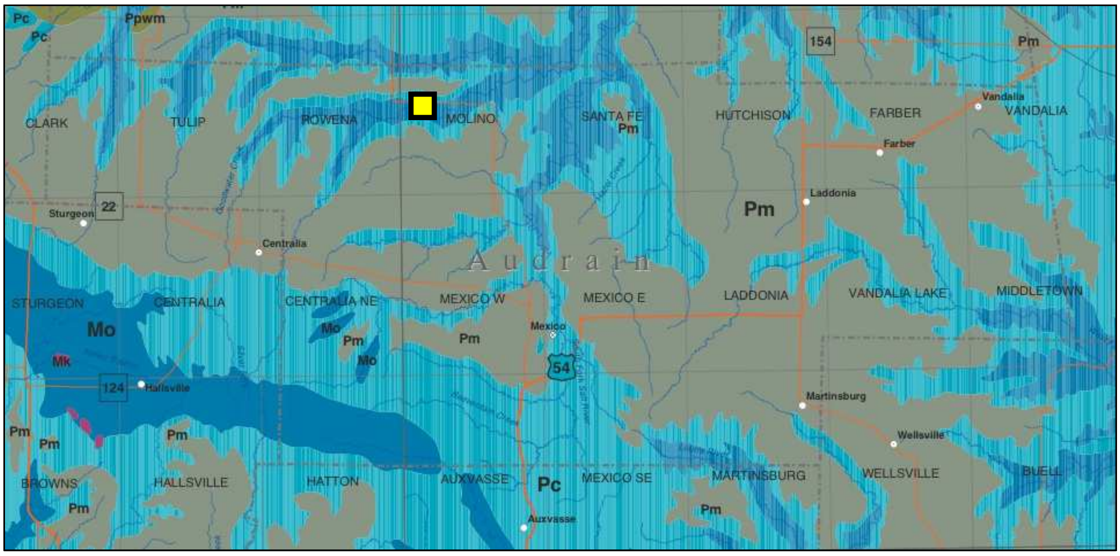

Figure 1.2 Bedrock geologic map of Audrain County, from the 2003 Geologic Map of Missouri. The ACPS is the yellow square in the upper left. Mo – Mississippian Subsystem, Osagean Series; Pc – Pennsylvanian Subsystem, Cherokee Group; Pm – Pennsylvanian Subsystem, Marmaton Group.

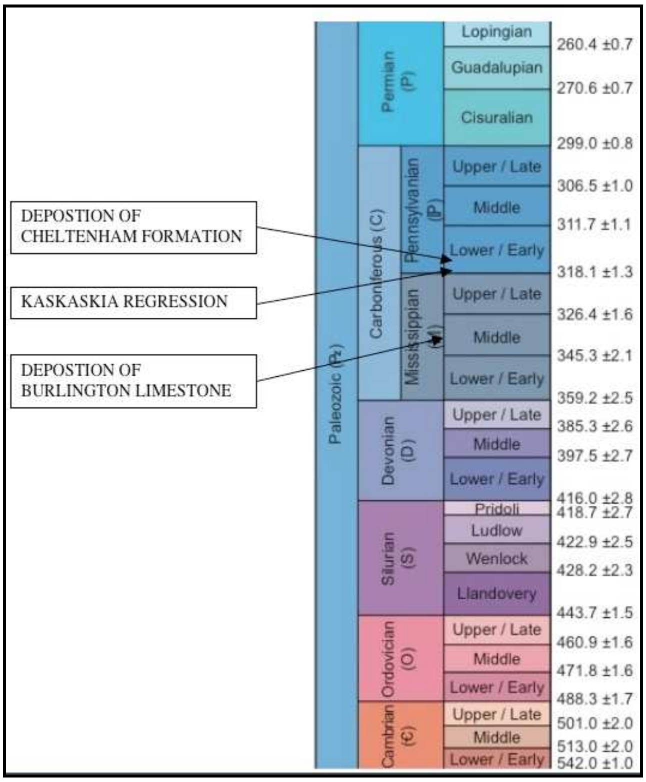

Figure 1.3 Paleozoic stratigraphic relationships between bedrock formations and time periods at the ACPS.

1.1 Research Statement and Objectives

Paleokarst in northern Missouri is little known and little understood. Occurrences are uncommon and have never been examined for character of paleofill. Reactivation of the paleokarst in the ACPS provided a rare opportunity to examine features not previously described.

The goal of this research was to first determine the site was reactivated paleokarst rather than collapse related to a different cause, based on the presence of paleofill within the karst conduits. The second objective was to show that geologic materials in this paleokarst were the result of deposition in the Paleozoic rather than being recent materials. The third objective was to show that paleokarst at this location is similar to comparable formations in other states.

The geologic analysis performed to meet these objectives consisted of:

- identification of bedrock lithology, stratigraphy and structure,
- sedimentological analysis of consolidated paleofill material, and
- sedimentological analysis of the unconsolidated surficial materials.

The significance of this study is that few paleokarst sites have been identified with intact paleofill that could confirm that such deposits formed in the Paleozoic, rather than resulting from geologically recent weathering features. Such sites indicate an older age for karst in Missouri than is typically recognized.

CHAPTER 2 BACKGROUND

2.1 Karst Overview

Karst is defined as the formation of subsurface openings in soluble bedrock that function as recharge and discharge points for groundwater. Karst investigations should initially be delimited by a conceptual model of how the karst functions within its geologic environment (Taylor and Greene, 2008). It is an oversimplification to view karst as a recharge-discharge phenomenon, as the dynamics of a karst conduit system can become infinitely complex as it interacts with variations in lithology, stratigraphy, structure and geochemistry (Fetter, 2001; Ford and Williams, 2007).

2.2 Karst Geology and Hydrogeology

A karst hydrological system is characterized by rapid surface drainage of meteoric water, and rapid subsurface transmission of groundwater through soluble bedrock (Ford and Williams, 2007; White, 1988). Due to controls on solubility by structure, sedimentology, stratigraphy and geochemistry, a vast array of surface, subsurface, erosional and depositional features related to karst formation can be observed (Ford and Williams, 2007; White, 1988). The following sources form a significant theoretical framework of karst studies.

2.2.1 Freeze and Cherry Perspective on Groundwater and Karst

Freeze and Cherry (1979) condensed much of groundwater hydrology into a single reference. This text comprehensively describes the assumptions for the interpretation of groundwater flow through the subsurface and into wells. The universal theme in their interpretation of groundwater flow is the homogeneity and isotropy that is exhibited by saturated low permeability materials (Freeze and Cherry, 1979). They also effectively demonstrated and quantified flow in confined conditions, driven by pressure gradients from recharge to discharge; and unconfined flow, or specific yield, under the influence of gravity. The text briefly addresses research performed on non-Darcian flow regimes in highly porous and fractured media but uses specific examples to justify fluid flow equations that can only be applied to hypothetical or highly specific fractured media flow environments.

2.2.2 White (1988); Crawford and White (2008)

White (1988) performed critical quantitative research on the theory of unsaturated turbulent flow within solution-weathered karst aquifer systems, as well as on the interplay between the flow of these waters and how they drive the continued development of the karst system. His research explored more complicated interpretations of karst systems than those addressed by Freeze and Cherry (1979). By exploring karst systems as complex plumbing systems capable of Darcian and turbulent flow conditions, this work more accurately described the flow regime in a karst aquifer, as well as identifying new caveats in attempts to model solution-weathered media (White, 1988).

Crawford and White (2008) synthesized the theoretical aspects of White's earlier research with the case studies of Crawford that were derived from hundreds of dye traces and hydrogeological research projects performed in numerous karst environments, primarily in the southeastern United States (Crawford and White, 2008).

2.3 Karst Concepts and Definitions

A karst terrain describes a landscape developed on soluble bedrock such as limestone, dolostone/dolomite, marble or gypsum that is characterized by a landscape with an extensive subsurface system for conducting meteoric and shallow groundwater

(Ford and Williams, 2007). This underground system is often part of a complex hydrologic exchange system with open surficial orifices called dolines (White, 1988), more commonly known as sinkholes, as well as weathered bedrock fractures and joints acting as zones of recharge into the subsurface component of the hydrologic system. Subsurface flow can occur in open conduits or through highly porous and permeable limestone aquifers. Springs and seeps act as zones of discharge from the subsurface into streams, rivers and lakes. The hydrogeologic characteristics of karst can vary due to geologic, hydrologic, climatic and local structural control (Crawford and White, 2008; Fetter, 2001; Ford and Williams, 2007).

Karst terrains have been studied as local geologic occurrences (Plotnick et. al, 2009; Vandike, 1985; Vandike, 1995); broad hydrogeologic phenomena (Aley, 1975; Fetter, 2001; White, 1988) mapped and described in a piece-meal fashion based on local studies (Harvey et. al, 1973; Miller et. al, 1974; Vineyard et. al, 1974); tracer studies (White, 1988; White and Crawford, 2008) or as an impedance to development that should be solved by various geotechnical engineering schemes (Coduto, 1999).

The following terms define solution features that are the most diagnostic of karst terrains.

2.3.1 Sinkholes

Sinkholes, often referred to in academic literature as 'dolines', are the archetypal solution feature in karst regions (Ford and Williams, 2007). In Missouri, these features commonly form over solution-weathered fractures, which in turn recharge underlying karst aquifers (Figures 2.1 and 2.2). Sinkholes also form over bedrock joints or faults. More rarely, they propagate from phreatic tubes that form in underlying cave systems that

Figure 2.1 An example of a typical sinkhole in southwest Missouri. Circular void is propagating from a bedrock fracture approximately 6.1 meters (20 feet) deep. Residual clay is seen at the rim of the sinkhole.

Figure 2.2 Sinkhole from Figure 2.1 viewed from the edge. The solution-enlarged fracture is in dolomite bedrock. Note the residual gravels near the top of bedrock. Water was heard moving through the sinkhole when the photo was taken.

formerly existed near the vadose/phreatic interface (Ford and Williams, 2007; White, 1988).

2.3.2 Bedrock Fractures

Bedrock fractures are separations between bedrock blocks that can conduct groundwater through the subsurface. These fractures begin as planar weaknesses in the rock, usually a bedding plane, joint or fault. The influence of these features on groundwater flow is briefly summarized below.

All fractures have the potential to serve as preferential pathways for the flow of shallow groundwater deeper into the subsurface. Meteoric and shallow groundwater traveling through these features is generally under-saturated with respect to calcite or dolomite (Drever, 1982; Freeze and Cherry, 1979), and dissolves these minerals as it passes through the fracture. This process further enlarges these pathways (Figure 2.3), enhancing karst development within the aquifer and increasing its ability to rapidly transmit groundwater (Ford and Williams, 2007; White, 1988; White and Crawford, 2008).

Fractures can also locally impede the flow of groundwater by reducing permeability due to secondary mineralization in the pore spaces and fractures of the surrounding bedrock (Fetter, 2001). When these minerals recrystallize in available pore and fracture space away from the dissolution site, they diminish the ability of these spaces to further transmit groundwater (Fetter, 2001).

2.3.3 Losing streams

Influent, or 'losing' streams, contribute flow to deeper subsurface aquifers under a thick unsaturated, or vadose, zone. They often completely lose flow into the subsurface

Figure 2.3 Example of a solution-enlarged fracture, St. Louis, Missouri. The fracture is approximately 4.6 meters (15 feet) deep.

and only conduct surface flow during periods of heavy precipitation. Typical influent streams are observed in arid environments, or environments with exponential changes in surface flow divided into wet and dry seasons. Much of the flow loss in these losing streams is due to high evaporation rates, such as those seen in desert and tropical areas (Freeze and Cherry, 1979).

Losing streams in karst environments serve as conduits into underlying bedrock aquifers (Fetter, 2001; Ford and Williams, 2007). As opposed to effluent streams in arid environments, this flow loss is due to groundwater transmission into subsurface, solution-weathered conduits. Such losing streams are common in Missouri and in other areas underlain by soluble bedrock (Fetter, 2001; Ford and Williams, 2007; Vandike, 1995).

The example of Schluersburg Karst Chasm near St. Louis is shown in Figure 2.4 below. Figure 2.5 shows the same location during the following spring, with stream gravels filling the previously open solution-widened fracture.

Figure 2.4 Schluersburg Karst Chasm, St. Louis area, Missouri. The chasm opened in the bed of a losing stream. Similar fractures underlie many losing streams in Missouri. Photo taken when first discovered in winter. Note geologist in red flannel for scale.

Figure 2.5 Schluersburg Karst Chasm after filling in with chert gravel from flooding in the losing stream channel the following spring.

2.3.4 Paleokarst

Paleokarst refers to karst features that formed in the geologic past, then were covered by subsequent sedimentary deposits (Ford and Williams, 2007). These sediments may be laid down as transgressive systems tract deposits when marine deposition resumes over formerly exposed carbonate shelves (Nichols, 2009). Sediments may also come from residual and colluvial deposits derived from surrounding topographic highs during low stand conditions on a carbonate terrain (Ford and Williams, 2007). Sediments observed in paleosinks often indicate colluvial transport of nearby geologic materials into the karst system at the time of its formation and evolution. Other sediments come from the formation of residual materials as the carbonate component of the rock is dissolved and transported away, leaving insoluble materials such as sands, clays or chert gravels (Ford and Williams, 2007). While these materials are deposited as unconsolidated sediments, post-transgression burial and diagenetic alteration can convert them into quartzites, sandstones and chert conglomerates or breccias, respectively.

Identification of a paleokarst system at the surface is conditional on the location of intact paleofill deposits within (Plotnick, et. al, 2009). Such deposits do not last long once exposed to the surface and near-surface. As doline and conduit systems reactivate and begin to carry turbulent groundwater through them, such materials will be eroded and washed away in relatively short spans of time. Over time, this process can leave the observable parts of the conduit system stripped bare of any paleofill deposits, displaying open dolines, caves and fractures with recently deposited unconsolidated materials within them.

Keller (1952) mapped refractory clay deposits of economic potential in central and northern Missouri. These 'fireclay' deposits were shown to be hosted in solution-weathered features. Solution- weathered surface and pit features were mapped at the Bueker clay pit, as seen in Figure 2.6. Similar deposits were hosted in sinuous fractures in northern Missouri, to the southeast of the ACPS (Figure 2.7).

2.4 Paleokarst Geology and Hydrogeology

While the extent of surface karst topographies has been generally mapped globally (Ford and Williams, 2007), areas of shallow, buried paleokarst have not been extensively investigated, often due to geologic or climatologic conditions that obscure these landscapes after their formation. Paleokarst features formed in the geologic past and have subsequently been rendered inert or inactive with the modern hydrologic regime

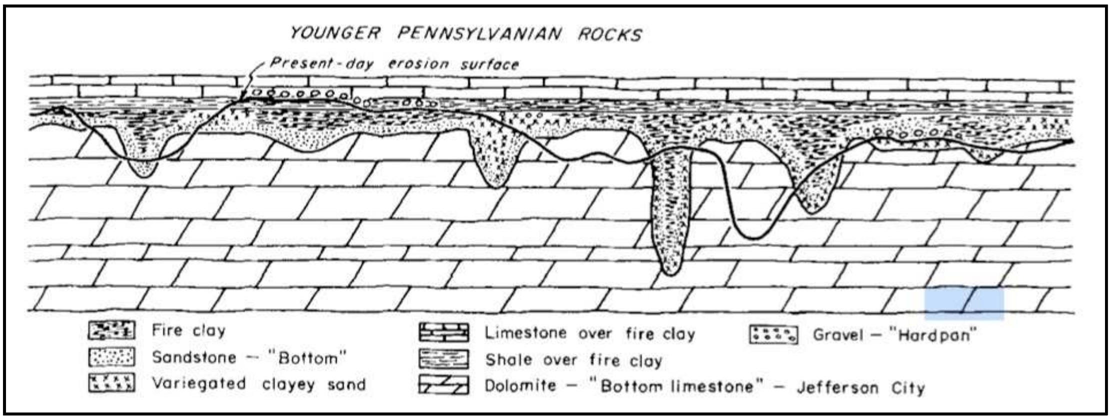

Figure 2.6 Model of Bueker clay pit from Keller (1952) showing fire clay and associated sediments hosted in probable paleosink deposits similar to the karst found at ACPS.

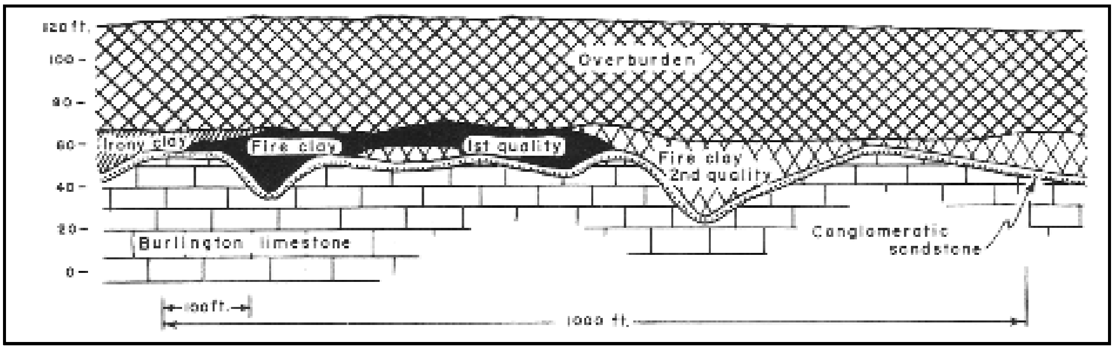

Figure 2.7 Fire clay hosted in Burlington Limestone similar to ACPS. Fire clays are hosted on weathered surface below Pennsylvanian- and Neogene-age materials (Keller, 1952).

by inundation, infilling or burial (Figure 2.8) (Ford and Williams, 2007; Plotnick et. al, 2009). As paleokarst terrains are often buried and lack surface expressions typical of hydrologically active karst terrains, they are often assumed to not be present or to be insignificant in regards to hydrogeologic investigations at the surface (Ford and Williams, 2007). As paleokarst represents the totality of karst created in the geologic past that has not subsequently eroded away, its potential extent is much greater than the existing karst actively forming at the surface.

Figure 2.8 Example of stratified paleofill from paleokarst deposit near Branson Airport, southern Missouri.

2.5 Bedrock Geology in Northern Audrain County, Missouri

Bedrock geology in northern Audrain County, site of the ACPS, is characterized by Mississippian-age Burlington Limestone (Osagean Series) comprising the lower portions of drainage systems (Figure 1.2). The upper sides of drainage systems are the

Pennsylvanian-age Cherokee Group; ridges are capped by the Pennsylvanian-age Marmaton Group.

The Burlington Limestone is a major karst-forming unit in southern Missouri. The formation is described by Thompson (1995) as "a white to gray, medium to coarsely crystalline, medium to coarsely crinoidal, medium to thick bedded, often cross-bedded, chert free to sparsely cherty limestone". The Burlington Limestone averages about 100 feet thick across Missouri (Thompson, 1995). Though described as chert free to sparsely cherty, zones of silicified limestone up to 10 feet thick (Thompson, 1995) are observed at many outcrops in the state. This chert is typically white to dark gray, and has replaced the pre-existing carbonate, as can be seen by the identical texture of crinoid molds and other fossils within the chert as well as the surrounding limestone bedrock.

CHAPTER 3 METHODOLOGY

3.1 Methodology of ACPS Site Investigations

The geologic investigation at the ACPS consisted of bedrock elevation; bedrock lithology; sedimentological descriptions; stratigraphic position and geologic structures. Information was collected on bedrock and surgical exposures and on paleosink fill material. Geologic interpretation was made of karst features at the site. The geologic data was obtained during field surveys performed from 2008 to 2011. During the field survey of 2008, a baseline site investigation was performed (Smotherman, 2008) which is detailed in Chapter 4. Features were mapped and recorded that were representative of the geologic nature of the site. These features were used to develop a conceptual model of the bedrock weathering that has formed and modified the paleokarst at the site over time.

The field survey consisted of a site survey and background research on any investigations previously performed at the site or in the vicinity of the site. This included an inventory of geologically significant features including: bedrock outcrops, physical or structural features, topographic changes, human-made structures or alteration to the landscape, soil types and other characteristics. These were used to produce a conceptual model of the subsurface geology. This model was further refined by consulting previous geologic, environmental or geotechnical investigations performed in the vicinity of the site. The accuracy of this model, in turn, was tested with a further, more detailed investigation.

3.1.1 Geologic Investigation Methodologies

The initial investigation into the ACPS was based on a reconnaissance-level survey and identification of key features of the site. This centered on activities related to identification, basic mapping and photographic recording of the relevant geologic features at the site. The features were identified, named and described according to morphology, visual descriptors, and basic measurements.

Measurements of each geologic surface feature were made using a variety of field methods, including measuring tape, Jacob's staff, and Estwing rock hammer for scale. Each geologic feature was photographed from multiple angles, over four different field investigations from 2008 to 2011.

The uppermost bedrock unit at the site was stratigraphically identified using mineralogic, sedimentologic and paleontologic diagnostics established in Thompson (1995) and Thompson (1986). Mineralogy of the bedrock was tested with field methods such as relative hardness to steel and reaction to 10% dilute hydrochloric acid. Laboratory methods to confirm these observations relied on more refined hardness testing and reflected light microscopic examination of rock samples from the site. The lithology and sedimentology of the bedrock was analyzed using the modified Folk and Dunham scale (1974) and relied on observations of approximate proportion values of fossil grains to carbonate mud matrix. Paleontologic evidence required representative sampling of macrofauna and comparison to previous research literature that corroborated observations in the field.

The karst features at the site were originally described as sinkholes based on diagnostics established in Crawford and White (2008), Ford and Williams (2007), Fetter (2001) and White (1988). One of the main diagnostics was the presence of a large opening that exhibited internal drainage in an uppermost carbonate bedrock known to exhibit deep solution weathering in many other parts of Missouri where it represents the uppermost stratigraphic unit. Investigation of *in situ* fill material revealed that these features were not recent karst formations, but paleokarst formed in the geologic past that has been reactivated and incorporated into the modern hydrogeologic system present at the ACPS. Chert clasts were identified as derived from Burlington Limestone based on the abundant presence of crinoids. Shales were identified based on the presence of compacted mudstones that exhibited fissility and hardness consistent with that rock type. Sandstones were identified based on the presence of chert and quartzose grains of clastic material. The diagnostics for determining the existence of paleokarst were taken from Plotnick (2009), Ford and Williams (2007), Fetter (2001) and White (1988).

Each paleokarst feature was georeferenced and placed into ESRI Arcview GIS software, Version 9.3 and Version 10.0 base maps of the site to allow for greater geospatial analysis of the site features with each other, as well as to compare the site to other karst and paleokarst features in close proximity to the site. By placing the site features within the regional geologic, geographic and hydrologic framework of Audrain County and northern Missouri, comparisons for the topographic and hydrogeologic context of the ACPS became more apparent.

The unconsolidated materials at the surface of the site were analyzed based on combination of the USDA Soils Method and the Unified Soils Classification System (USCS). Larger gravels were identified as residual or glacial materials based on field diagnostics such as hardness, color, opacity, translucence, fossils and secondary mineralization. Silts and clays were classified according to the USCS classification system, as well as by identification of larger particles that indicated if they were residual, alluvial or glacial in origin. Limited subsurface investigations of the unconsolidated surficial materials were also performed with a sharpshooter shovel and an Oakfield manual soil auger. These investigations were not deeper than 24 to 36 inches due to refusal on chert gravel.

3.1.2 Methods of Karst Analysis

Researchers investigating karst hydrogeology have contributed to the current state of the discipline through either expansive, general theories on karst development or site-specific descriptions and analyses. Recent work outlining the state of the practice in karst hydrogeological research (Ford and Williams, 2007; Taylor and Greene, 2008; White and Crawford, 2008) represent the culmination of a discipline that is still actively developing rigorous theoretical and methodological standards while attempting to remain flexible enough to accommodate the wide continuum of global karst phenomena.

The geologic investigation of the ACPS consisted of traditional geologic surface mapping of sinkhole features, bedrock outcrops, bedrock structure and surficial materials (Evans, 2009). The three paleosinks developed in underlying paleokarst were mapped and photographed. The fill material within Paleosink 1 and the associated feature Fracture 1 was recorded according to vertical succession from top to base. The total vertical depth of Paleosink 1 was explored to the swallet at the base of the feature. The residual material/bedrock interface within Paleosink 1 was studied in place and photographed. Paleosink 1 was examined for evidence of structural deformation by faulting. Fracture 1 was measured over the course of three years for recorded linear expansion and vertical subsidence. All paleosinks were photographed and observed for continued subsidence or expansion. Bedrock samples were taken from Paleosink 1, Fracture 2, Outcrop 1 and Outcrop 2 for identification based on lithology, sedimentology and paleontology. Chert samples were taken from Fracture 2 to confirm the lithology of the bedrock they were weathered from and to compare to chert and limestone samples from the outcrops. Samples of unconsolidated earthen materials were taken across the site to determine if they were residual, glacial or alluvial, and to determine any controls on deposition based on elevation, deposition or geographic zonation. U.S. Geological Survey 1:24,000 maps were used to look at any geologic or geomorphologic features of interest that had been recorded in the past. Geologic maps from the Missouri Geological Survey were consulted to compare the site to previously identified lithology and stratigraphy. GIS software was used to georeference all geologic features for inter- and intra-site comparison, as well as with similar features in other parts of northern Missouri.

CHAPTER 4 AUDRAIN COUNTY PALEOKARST SITE GEOLOGIC INVESTIGATION

During the initial investigation (Smotherman, 2008), geologic mapping of features at the surface and subsurface was performed according to Missouri Geological Survey standard site investigation procedure, as well as with methods that are considered best general practice in geologic field techniques. Subsequent surveys refined the geologic mapping and recorded the continued expansion of the paleokarst features at the site. These features were mapped and entered into a georeferenced base map using geographic information system (GIS) software. This base map was used to analyze the spatial relationship of geologic features at the site and to design the subsequent geophysical and hydrological investigations.

4.1 Description of Paleokarst Features at the ACPS

Paleokarst and related geologic features at the ACPS are divided into paleosinks, solution-enlarged fractures and bedrock outcrops. The individual features are described in the following sections.

4.1.1 Paleosink 1

Paleosink 1 (Figure 4.1) is the largest sinkhole at the site, and is covered by a cave-like roof of residual clay and chert, with a few suspended limestone pendants (Figure 4.2). It forms a dome that ranges from 1.52 meters (5 feet) tall at its opening to approximately 16.72 meters (55 feet) from the gravel eye at the base of the paleosink to the top of the room. Residual materials on the floor of the paleosink form a ramp leading between two walls of bedrock down to a gravel swallet at the bottom. The ramp of residuum proceeds to a depth of approximately 10.64 meters (35 feet) deep. At the base

Figure 4.1 Map of the major geologic features at the ACPS. Red circles are paleosinks. Yellow circles are outcrops. Yellow lines are fractures.

of the ramp is the eye of Paleosink 1. This eye consists of white residual chert gravel, with very few fines.

In 2009 and 2011, Paleosink 1 experienced continued expansion at its opening, as was observed by the addition of fresh chert and clay breakdown on the slope that leads into the swallet of the paleosink (Figure 4.3). Fracture 1 (discussed below) was also observed to have subsided almost 0.91 meters (3 feet) in depth, as well as extending an additional 1.52 to 1.82 meters (5 to 6 feet) (Figure 4.4).

Figure 4.2 Paleosink 1 in 2008. The author (green hat) is standing at the entrance. The observer is approximately 6.1 meters (20 feet) away. The observer in the foreground is standing in Fracture 1.

Figure 4.3 Paleosink 1 and Fracture 1 in 2009. Photo facing to the east.

Figure 4.4 Fracture 1 in 2009. Photo taken from above entrance to Paleosink 1. A new subsidence scarp 1.31 meters (4.3 feet) had formed since 2008 (see Jacob's staff next to black labrador retriever).

4.1.2 Paleosink 2

Paleosink 2 (Figure 4.1) was first observed in 2008 a month after it had drained the 3.3- acre lake at the ACPS. At that time, it was approximately 4.56 meters (15 feet) in diameter and 0.91 meters (3 feet) from the surface of the lakebed to the eye of the sinkhole. The open void was surrounded by a distinctive yellow residual clay and white, angular chert gravels. At the time of the initial investigation, the void was still taking in water from a small side channel that had been formed during the draining of the lake, as the sinkhole is in the southeastern quadrant of the lake (Figure 4.5). The farm lake had been on the site for at least 23 years according to the landowner. The time of the sinkhole collapses occurred after an unusually dry summer, followed by the passage of Hurricane Ike in the fall of 2008. In 2009, Paleosink 2 was not taking in as much water as had been observed in 2008, but the channel that had developed along the clay of the lake bed between the lowest point in the former lake and the sinkhole indicated that it could take on additional flow from the stream during precipitation events (Figures 4.6 and 4.7).

Figure 4.5 Paleosink 2 as it was draining the lake in 2008. Water is flowing from the lakebed into the sinkhole. Photo facing southwest.

Figure 4.6 Paleosink 2 in 2009. The black oval encircles the swallet of the paleosink, with yellow residual clay within. Note the expansive clay fracturing in the lakebed.

In 2011, the lakebed had become grown over with tall, woody vegetation (Figure 4.8). Paleosink 2 was observed to have sloughed inward, obscuring the clay and gravel eye. It also appeared to have subsided further, now appearing about 1.52 meters (5 feet) deep. In order to inject dye into the sinkhole, a 0.91-meter (3 feet) deep hole was dug to refusal.

Figure 4.7 Paleosink 2 from the southwest in 2009.

Figure 4.8 Paleosink 2 in 2011during the dye trace. The black shovel handle is next to the swallet that is observed taking on water in the 2008 photo. The black oval is the approximate boundary of the paleosink. Photo taken facing northeast.

4.1.3 Paleosink 3

Paleosink 3 is 6.08 meters (20 feet) higher in elevation than the other two sinkholes, having formed on the ridge close to the landowner's home (Figure 4.1). Like the other two paleosinks, it has expanded since first being observed in 2008 (Figures 4.9 and 4.10). Paleosink 3 is observed to have a much higher percentage of sand in the surficial materials. Other investigations along the west ridge indicate that it has till with underlying sandstone residuum that was not seen during subsurface testing on the eastern ridge.

Figure 4.9 Paleosink 3 in 2008.

Figure 4.10 Paleosink 3 in 2009. Photo facing northwest.

4.1.4 Fracture 1

Fracture 1 is a linear subsidence feature extending from the entrance of Paleosink 1 (Figures 4.1 and 4.11). It was approximately 3.6 meters (12 feet) wide and 7.9 meters (26 feet) long during the initial investigations in 2008. It has continued to grow and subside since, reaching a width of 5.16 meters (17 feet) and a length of 10 meters (33 feet). Paleosink 1 lies in a direct line with the apparent strike of the subsidence (Figure 4.1).

4.1.5 Fracture 2

Fracture 2 is a linear feature that is on an apparent strike with Paleosink 2 to the northwest (Figure 4.1). The feature consists of a channel 7.6 meters (25 feet) wide and

Figure 4.11 Paleosink 1 and Fracture 1 (yellow outline) in 2009. Photo facing north. Note the white pin flags in the lower left corner of the picture that were placed to monitor expansion of Fracture 1.

39.5 meters (130 feet) long. It contains chert gravels and limestone boulders extending from the dam of the former lake to the edge of Youngs Creek (Figure 4.12).

4.1.6 Outcrop 1

This outcrop stretches 70.1 meters (230 feet) along the north bank of Youngs Creek in the southeast corner of the site (Figures 4.1 and 4.13). The outcrop consists of Mississippian-age Burlington Limestone (Figure 4.14). The bedrock is identical to that observed in Paleosink 1 and Outcrop 2.

Figure 4.12 Fracture-2 leading to Youngs Creek to the southeast (black arrow).

Figure 4.13 Outcrop 1 along the north bank of Youngs Creek. Photo taken facing northeast.

Figure 4.14 Crinoid fossils in limestone matrix at Outcrop 2.

CHAPTER 5 RESULTS

5.1 Geologic Investigation

The geologic data was obtained during field surveys performed from 2008 to 2011. During the field survey of 2008, a baseline site investigation was performed (Smotherman, 2008) which is detailed in Chapter 3. Features were mapped and recorded that were representative of the geologic nature of the site. These features were used to develop a conceptual model of the bedrock weathering that has formed and modified the paleokarst at the site over time. This model included the following hypotheses, examined in this chapter:

- The sinkholes at the site formed in paleokarst that developed between the Mississippian and the Pennsylvanian, and is not a karst formed in recent geologic time. This is consistent with paleokarst of the same age and in the same formation in Oklahoma and Texas.
- The subsidence-related features at the site represent open conduits into underlying paleokarst that is laterally continuous across the ACPS.
- These subsidence-related features are the result of recent hydrologic activity within the underlying paleokarst.
- The reactivated paleokarst is likely to expand its areal extent, as well as its interactions with the surface hydrology and the groundwater hydrology of the Mississippian Aquifer in the future.
- The bedrock observed in outcrop at the site represents the bedrock across the entire site. Bedrock outcrops are observed in the subsidence called Paleosink 1, a

surface outcrop on the southeast side of the site called Outcrop 1, and an outcrop observed at the northwest side of the site called Outcrop 2 (Figure 5.1).

- The bedrock observed at the site is part of the Mississippian Aquifer, an unconfined bedrock aquifer in this portion of Audrain County, Missouri (Emmett and Imes, 1984; Knight and Emmett, 1979). Portions of this aquifer are known to be solution-weathered, but rarely exhibit characteristics of a karst aquifer due to saturation associated with thick surficial materials, residual clays and high groundwater elevation.
- Based on initial observations at the site, a complex hydrogeological environment exists that allows gaining conditions to exist in close proximity to open, unsaturated, reactivated paleokarst. Such karst typically represents the presence of losing conditions in Missouri. Losing conditions refer to 30 percent or greater flow loss of surface water into the subsurface (Fetter, 2001). However, Youngs Creek and other streams in close proximity to the ACPS were observed to exhibit gaining characteristics during the research time period, from 2008 to 2011.

5.2 Geologic Analysis

The geologic observations consist of identification and interpretation of the uppermost bedrock; topographic evidence for joint control underlying the site; analysis of the paleofill materials within Paleosink 1; and the distribution of the surficial materials across the site.

5.2.1. Bedrock Outcrop Description

Outcrop 1 (Figure 5.1) consists of an exposed section of fossiliferous limestone that runs along the north bank of Youngs Creek. The outcrop is a weathered, grain-supported limestone that consists of approximately 90 percent crinoid fossil debris, similar to exposures in southwest Missouri (Figure 5.2). The level of disarticulation in the fossils indicates an environment of deposition with minimal wave action, enough to scatter the crinoid columnals without significantly abrading them. Weathering features include stalagmite-shaped vertical pendants (Figure 5.3), as well as bedrock fractures and the possible entrance to a shallow cave. This last feature could not be confirmed due to being covered over by blocks and slabs of limestone rubble.

Figure 5.1 Map of the major geologic features at the ACPS. Red circles are paleosinks. Yellow circles are outcrops. Yellow lines are fractures.

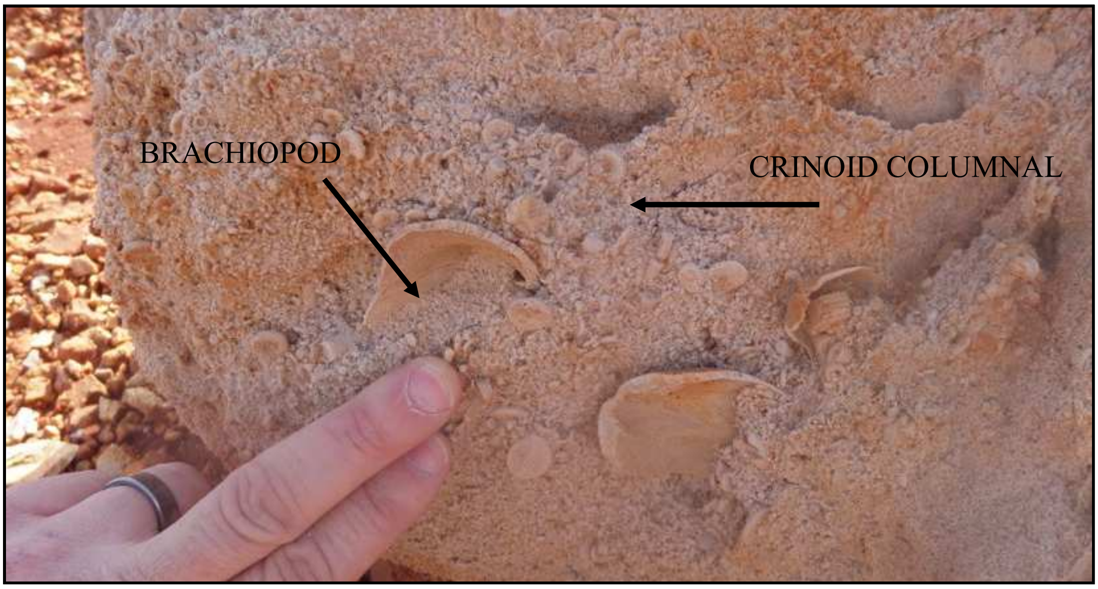

Figure 5.2 Sample of typical Burlington Limestone, southwest Missouri. It mostly consists of crinoid columnals. This sample also has large brachiopod fragments, as well as small trilobite ossicles.

Figure 5.3 Burlington Limestone from Outcrop-1. Note the weathered limestone pendants, indicating downward vertical movement of groundwater undersaturated with respect to calcite.

Figure 5.4 Limestone boulder and chert gravel from Fracture 2. Lithologic material is the same as bedrock and chert gravels observed in Paleosink 1.

Fracture 2 exhibited chert and limestone gravels similar to those seen across the site (Figure 5.4), including the breccia zone within Paleosink 1 (discussed below). These gravels are derived from the Burlington Limestone. The fines observed in Fracture 2 do not appear to be the same as the clay matrix observed in Paleosink 1 and Paleosink 2.

The Burlington Limestone is the uppermost bedrock unit at the ACPS (Figure 5.5). It forms the uppermost hydrostratigraphic unit of the Mississippian Aquifer, which covers extensive parts of northern and southwestern Missouri (Miller and Vandike, 1997). During the Kaskaskia Regression, virtually all Mississippian-age rock was exposed on the North American craton, resulting in the unconformity that separates Mississippian and Pennsylvanian age rocks (Figure 5.5).

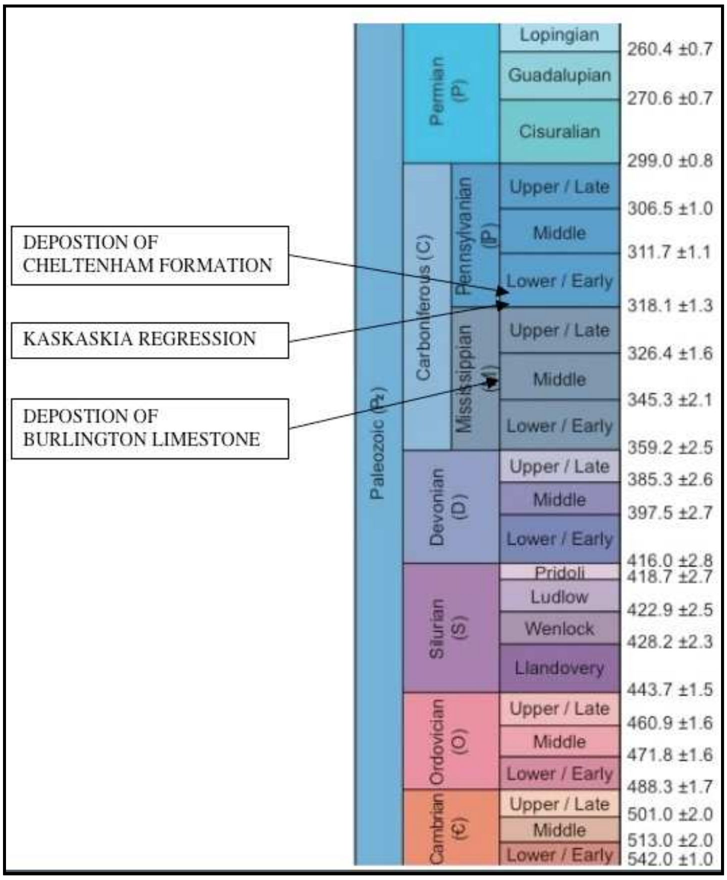

Figure 5.5 Paleozoic stratigraphic relationship between bedrock formations and time periods at the ACPS.

5.3 Joint Control at the ACPS

There are four parallel sections of streambed that strongly suggest the presence of an underlying joint set at the ACPS, as indicated in Figure 5.6. The first joint is 222.8 meters (733 feet) upstream from the site. The bend in the stream has a strike of

NW165SE. The second joint is the valley of the unnamed tributary that transects the ACPS. This bend has a nearly identical strike to the first. The third section is 489.4 meters (1,610) feet downstream of the ACPS. The fourth joint is 1.28 kilometers (4,212 feet) downstream of the site. These joints align with regional structural features that also tend to strike northwest to southeast (McCracken, 1971). Oblique joint sets are inferred from other sections of Youngs Creek that form a complementary set of joints striking southwest- to northeast. Joint sets typically form secondary joints perpendicular to the primary joints (Ford and Williams, 2007; Ritter, 2002).

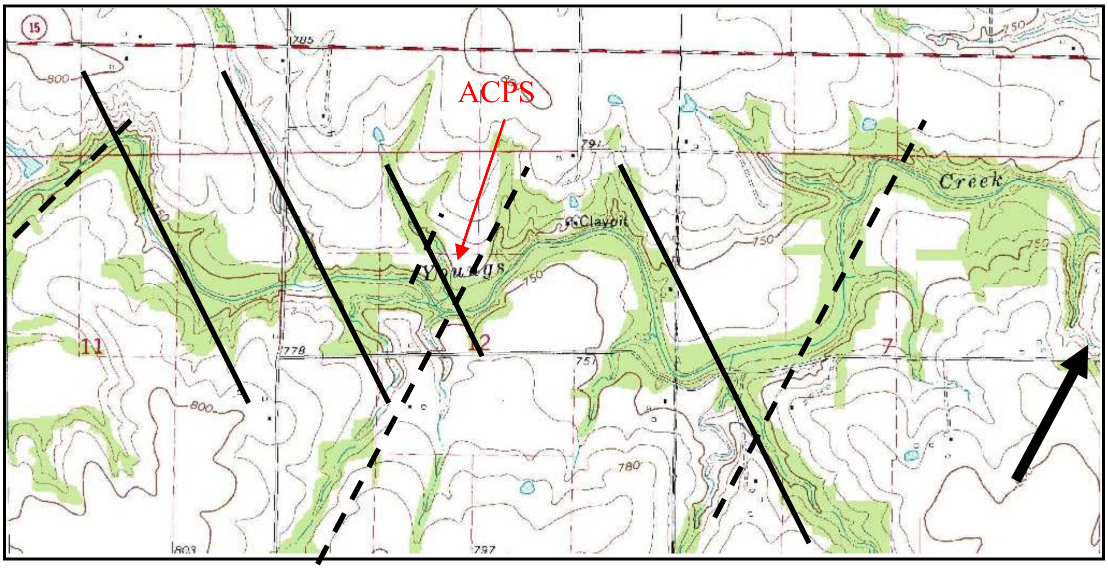

Figure 5.6 Solid black lines indicate primary joints in the vicinity of the ACPS. Complementary joints are indicated by dashed lines. Note an inferred convergence of primary and secondary joints under the ACPS based on the strikes of the unnamed tributary and Fracture 1. Black arrow indicates apparent dip of bedrock to north-northeast.

As seen from the Molino 7.5 minute topographic quadrangle (USGS, 1972), these four stream sections generally strike from the northwest to the southeast, with complementary joint sets striking southwest to northeast. Observations in Paleosink 1 and at Outcrop 1 indicate that the underlying bedrock is dipping to the north. This dipping is consistent with synclinal and anticlinal structures mapped in northern Missouri (McCracken, 1971). This tilting may be the result of a tensional structure in the Mississippian, creating a gradient along the joint set that enhanced solution-weathering along the joints, enlarging the fractures that underlie the paleosinks at the site.

In Paleosink 1, bedrock has an apparent dip to the northeast. It is important to emphasize the 'apparent' aspect of this observation, as it could also be a function of weathering on the bedrock surface. The chert lenses in Paleosink 1 also indicate an apparent negative vertical dip in this direction. Fracture 1 strikes southwest- northeast, and has an apparent dip matching the bedrock in Paleosink 1. Outcrop 1 appears to dip to the north as well.

5.4 Analysis of Paleosink 1 and Fracture 1

Paleosink 1 and Fracture 1 are two inter-related subsidence features that propagate from the same subsurface karst fracture (Figure 5.7). The surficial materials within Fracture 1 dip approximately 10 degrees to the northeast into the opening of Paleosink 1, then increase to approximately 30 degrees along the same strike, to the swallet of Paleosink 1.

The entrance of Paleosink 1 was steep when first investigated in 2008, and by 2011 had become steeper due to continued subsidence along Fracture 1. In 2008, two discrete scarps existed bounding a ramp of residual clay and gravel that entered the paleosink. By 2011, the material had further subsided into a much more distinct linear feature, giving rise to the idea that a solution-enlarged fracture may underlie this subsidence feature, as well as Fracture 2. Subsidence is estimated at about 3.04 meters (10 feet) over three years based on photographs of the feature (Figures 5.8).

Figure 5.7 Fracture 1 in 2008.

In 2011, the opening was measured at 3.9 meters (13 feet) from wall to wall, and 1.7 meters (5.7 feet) tall. Investigations revealed a deposit of claystone and shale, with beds and lenses of quartzose sandstone, forming the archway (Figure 5.19). The sandstone had a small percentage of angular, white chert particles within it that were identical to the chert observed in the shale and the Burlington Limestone. Angular chert

Figure 5.8 Fracture 1 in 2009. Note the subsidence in the floor of the fracture compared to the previous photo taken in 2008.

cobbles were interspersed within the claystone, with abundant pyrite crystals hosted both in the shale and claystone, and in the crinoid vugs within the chert (Figure 5.23).

Inside the enclosed area above the paleosink, the roof had previously been noted to consist of blue-green expansive clay and white chert residuum. This was confirmed during the survey, with the contact between the limestone bedrock and the residual cap obvious throughout the extent of the enclosed space (Figure 5.17). The depth of the enclosed space was measured to 12.7 meters (42 feet). The bottom of the enclosed space within Paleosink 1 was occupied by an approximately 1.5 meter (5-foot) diameter swallet, covered by chert gravel (Figure 5.9).

Figure 5.9 The swallet at the base of Paleosink 1. Note the log in the photo, indicating surface material falling into the paleosink.

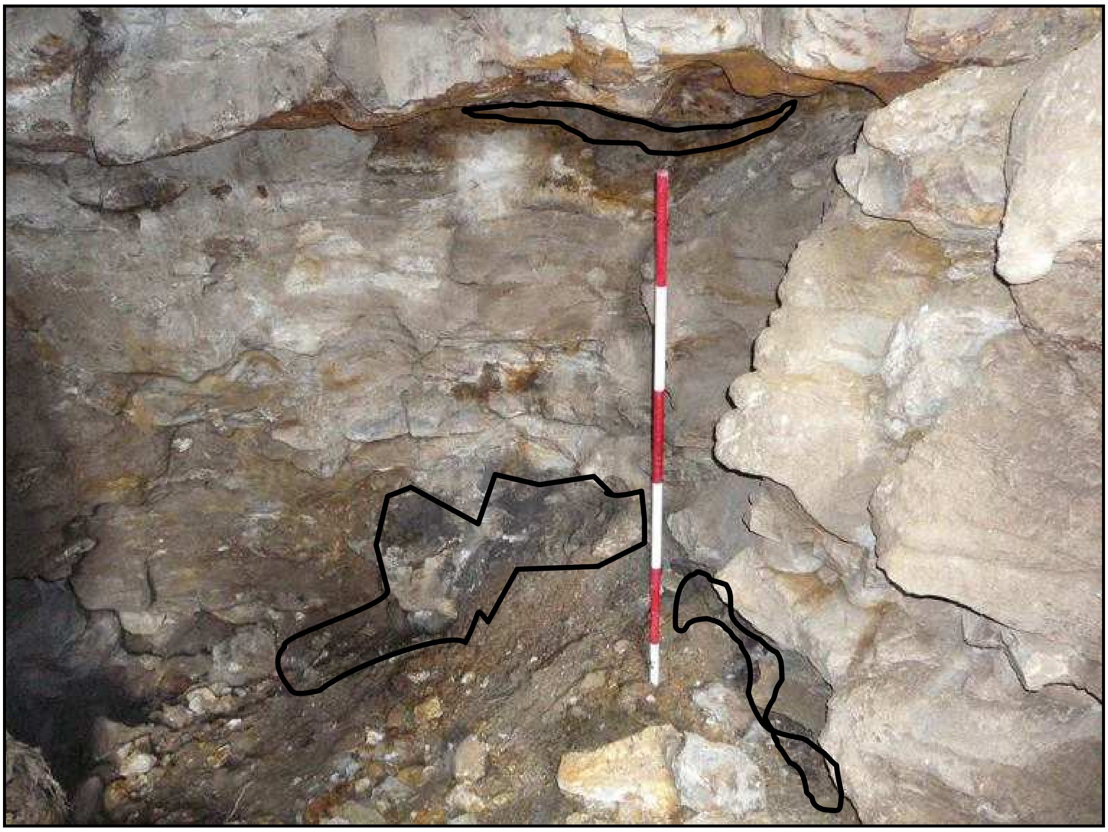

Figure 5.10 Southeast wall with zones of black weathered shale. It is unknown whether this is carbonaceous or reduced material. Similar black shale was observed in paleosink features 103 kilometers (64.28 miles) to the southwest of the site. Uppermost black shale is surrounded by ferric mineralization.

Zones of carbonaceous shale and shale residuum were observed on the southeast wall of Paleosink 1 (Figure 5.10). Similar black shales are typically high in organics and formed in reducing, anaerobic environments. The orange and yellow staining observed on the limestone bedrock bordering the shale may have come from the oxidation of iron sulfides such as pyrite, forming hematite or limonite (Figure 5.11). While pyrite was not observable in the black shales, significant amounts were observed hosted in crinoid molds in the limestone (Figure 5.24).

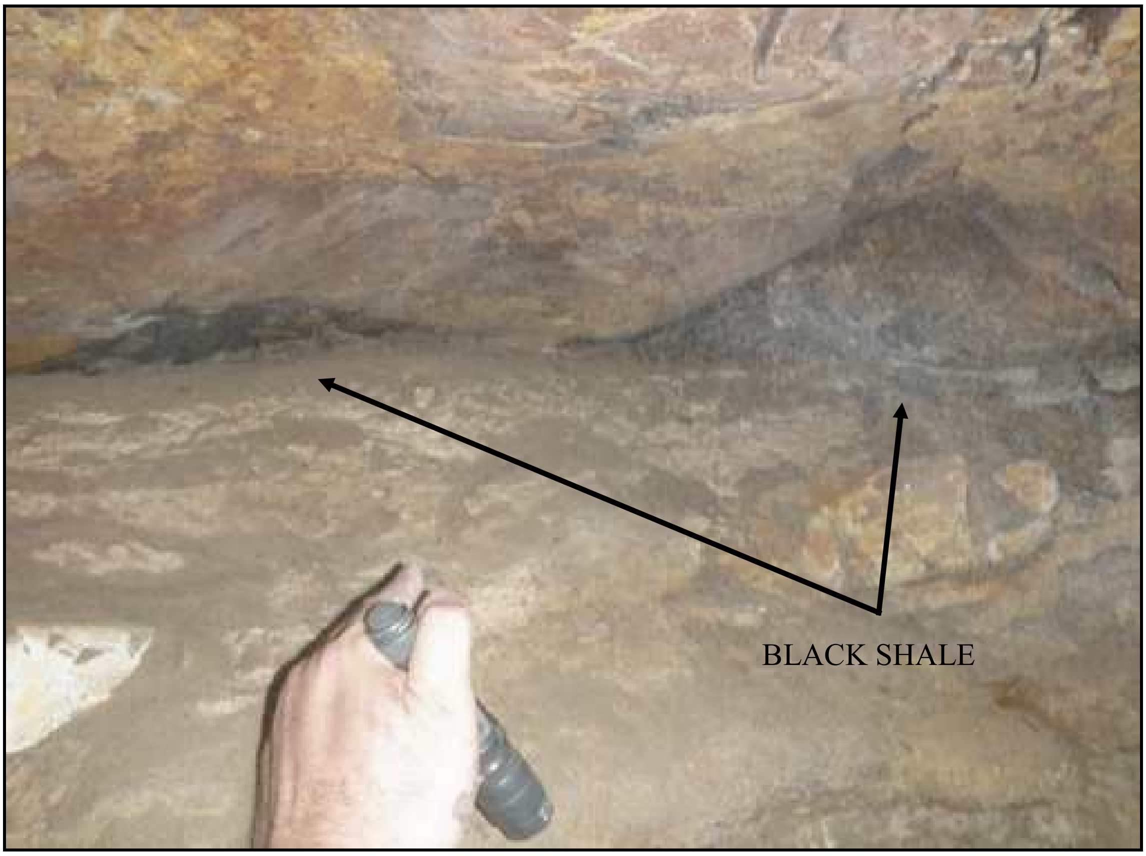

Figure 5.11 Black shale material at same elevation as previous photo, but opposite side of Paleosink 1. This may represent material similar to that seen in paleosink features to the south.

While examining the thin black shale bed, a fracture was observed that may indicate a glide plane along the shale (Figure 5.12). The vertical fracture had a displacement of approximately 9 centimeters (3.5 inches). The shale and bounding bedrock were dipping to the north-northeast.

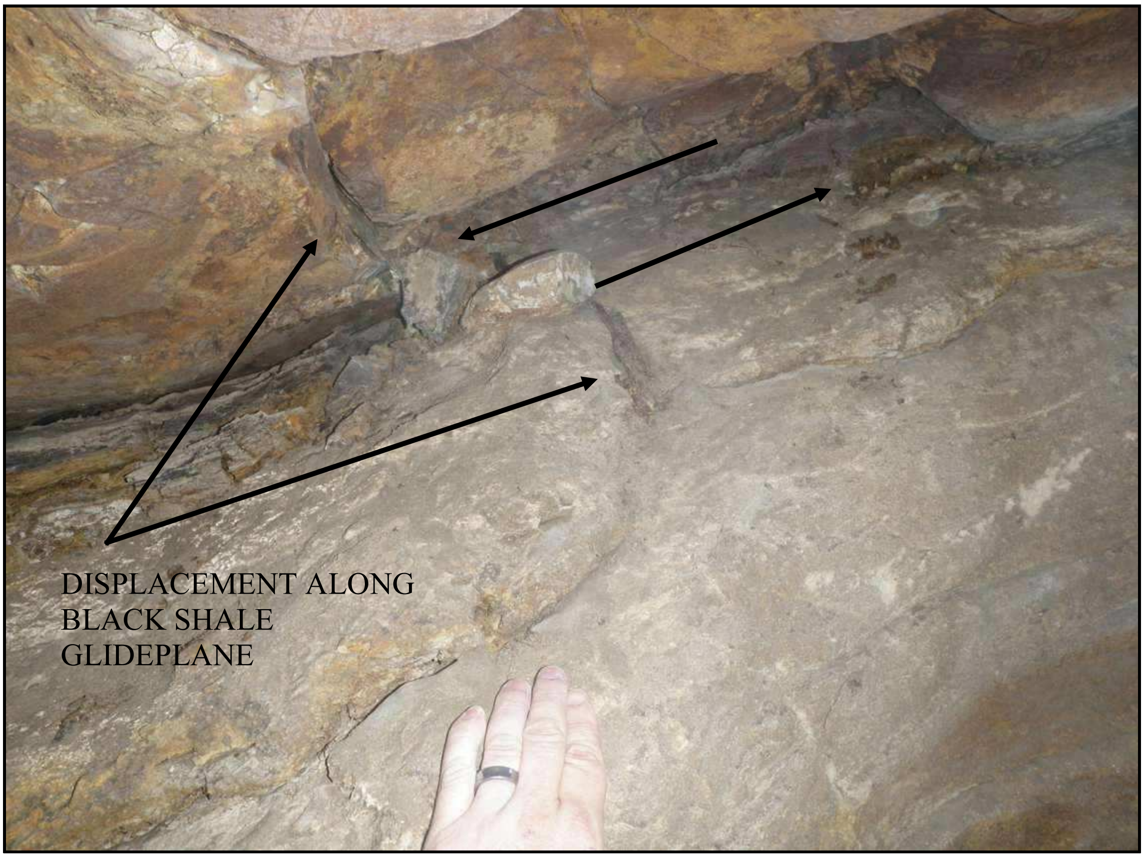

Figure 5.12 Black shale acting as a glide plane between two beds of limestone. Note the displacement in the fracture. Also note oxidation present above the black silt but not below. Dark color of material indicates high carbon content.

During field investigations, black shale was also observed at a separate site southwest of the ACPS (Figure 5.13). Along this road cut, black carbonaceous shales and gray argillaceous shales were observed in Ordovician-age Jefferson City Dolomite south of Jefferson City, Missouri. These shales also had chert clasts within them, but were from Ordovician-age bedrock sources.

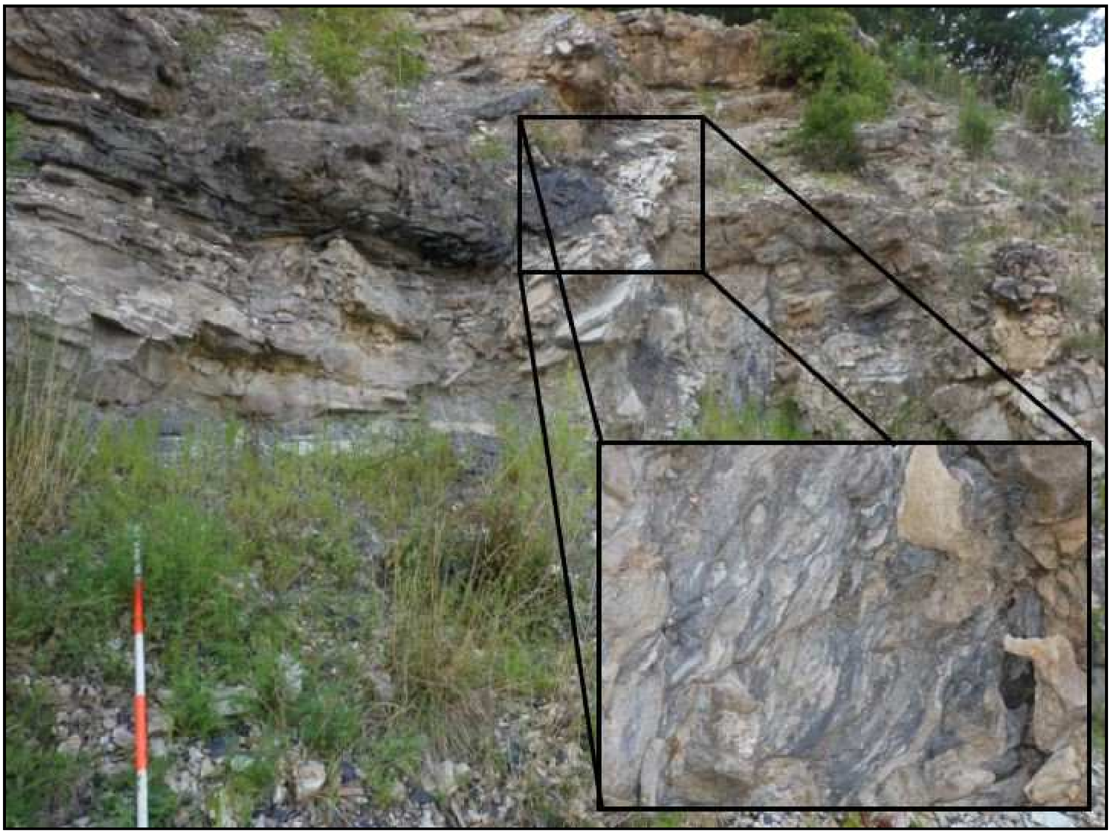

Figure 5.13 This paleosink feature 82 kilometers (51 miles) southwest of the APCS contains laminated and interbedded carbonaceous and argillaceous shale, with chert clasts within it.

Within the entrance of Paleosink 1, a prominent chert bed was observed to transect the length of the void (Figure 5.14). This bed had relatively competent limestone above it and weathered limestone below it. A brecciated zone of white chert and blue-green clay was observed in the southeast wall above the chert bed (Figure 5.15). This breccia zone was continuous with the roof of unconsolidated materials (Figure 5.16). Weathered pendants similar to that observed in Outcrop 1 (Figure 5.3) were observed below the chert bed (Figure 5.17).

Figure 5.14 Opening of Paleosink 1. The black line follows the base of a chert bed that forms a bench above the swallet. The blue-green line marks the edge of a brecciate zone in the southeast wall.

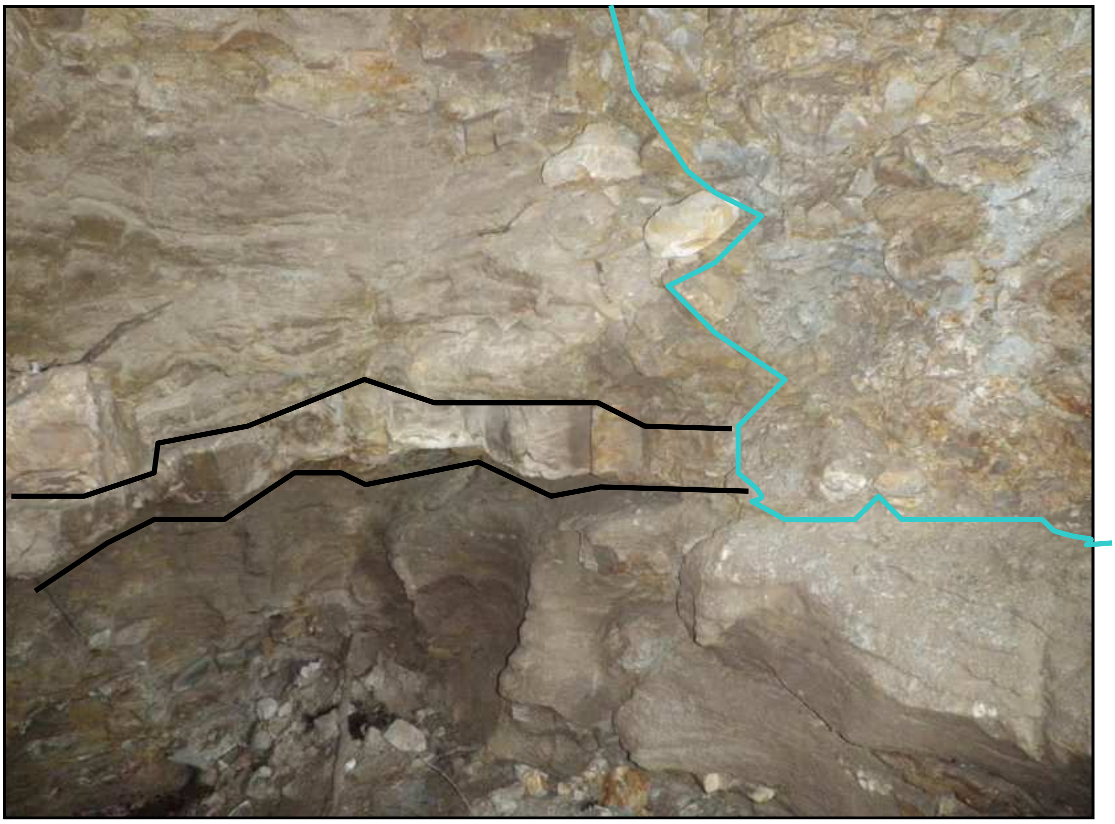

Figure 5.15 A bed of chert that provides structural support over part of the interior of Paleosink 1 is highlighted in black. A weathered breccia zone in the upper right side of the photo is outlined in blue. Note the solution weathering in the limestone below the chert lens in the lower central portion of photograph, indicating the vertical movement of groundwater undersaturated with respect to calcite.

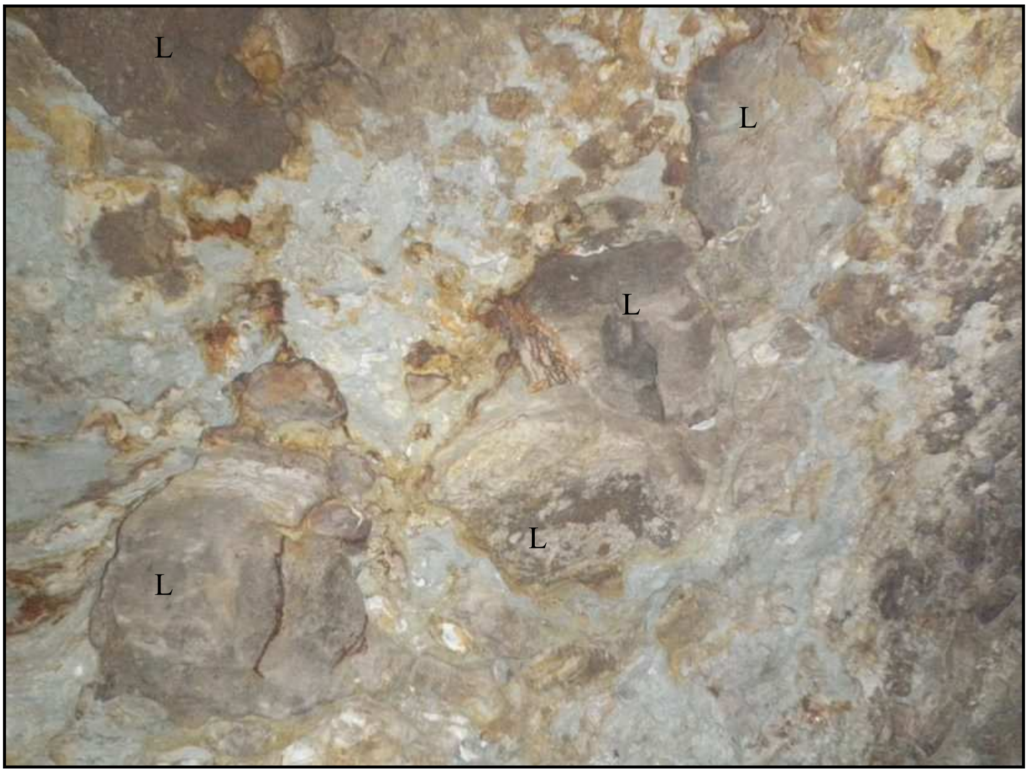

Figure 5.16 Limestone (L) boulders embedded in the residual clay of the roof of Paleosink 1. Note the oxidation of iron minerals in the reduced residual clay. The reduced clay indicates saturation, whereas the oxidation indicates acidic groundwater infiltrating the reduced clay from above. This material is identical to that observed in Fracture 2 to the east, sans the clay residuum.

Figure 5.17 Solution-weathered pendants, indicating downward movement of groundwater undersaturated with respect to calcite.

Numerous chert lenses were observed in the limestone walls of Paleosink 1. Most were roughly parallel lenses typical of soft-sediment structures undergoing tensional deformation (Fossen, 2010). Some of the lenses had subtle bends in them as well. One chert bed displayed a prominent bulb of chert below the lens (Figure 5.18).

Figure 5.18 Chert lens in Paleosink 1. The chert has replaced the limestone during diagenesis. Soft-sediment deformation during diagenesis is indicated in the bend in the chert bed to the right of the photo. Nodular feature is unique to this lens.

Figure 5.19 Paleofill at the entrance of Paleosink 1.

Paleofill observed at the entrance of Paleosink 1 consisted of alternating bands of shale, claystone and sandstone (Figure 5.19). The sandstone was composed of grains of chert and quartz sand. Chert clasts from the Burlington Limestone had been incorporated into the shale (Figures 5.20 and 5.25). Slight soft sediment deformation was present in the layers and the chert clasts included in the shale (Figures 5.20 and 5.24).

Both the shale and sandstone included white to light gray chert gravels from the Burlington Limestone (Figures 5.20 and 5.24). The shale is composed of argillaceous clay particles with chert clasts included. Small amounts of pyrite were observed in the shale, but larger crystals were observed in the chert (Figures 5.21, 5.22 and 5.23).

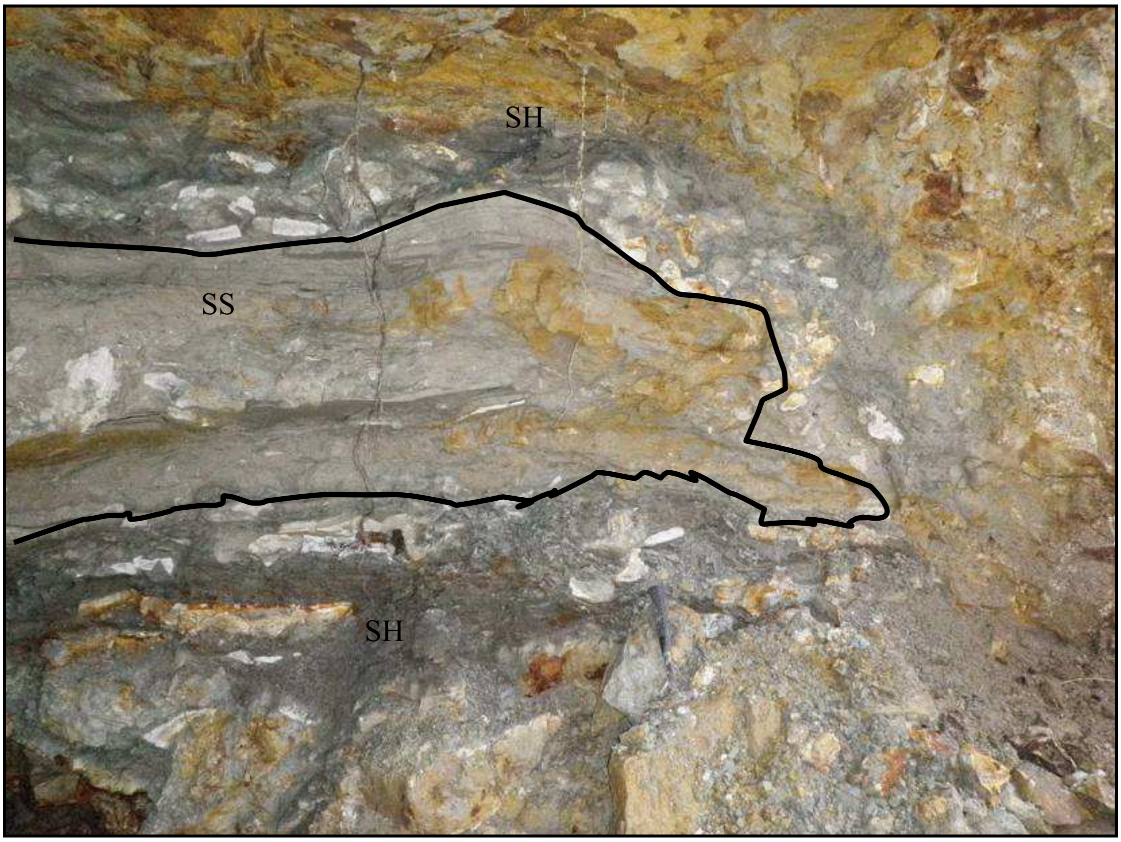

Figure 5.20 Zone of sandstone surrounded by cherty shale. The white chert clasts intruded with the sandstone are also derived from the Burlington Limestone.

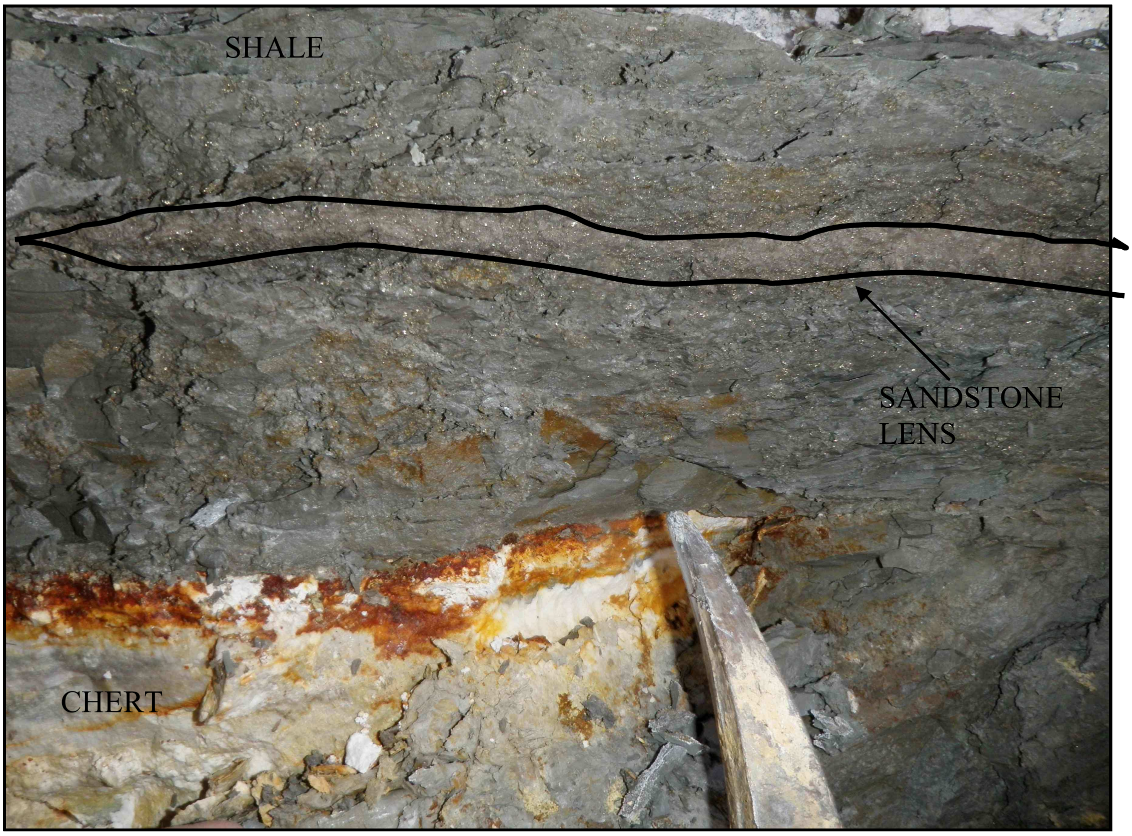

Figure 5.21 Sandstone, shale and claystone at the opening of Paleosink 1. Bright reflectance points in shale matrix are individual pyrite crystals. Note the oxidation near the contact with the white chert clast, indicating the movement of oxidizing groundwater between the two lithologies.

A large chert clast within the shale paleofill displayed a prominent druse quartz feature on its face (Figure 5.22). The druse quartz ranged in color from light tan to dark brown to red. It was surrounded by pyrite skins and veins, as well as clusters of crystals within single crinoid molds (Figure 5.23). A dark gray zone of smaller druse quartz crystals was located to the left of it.

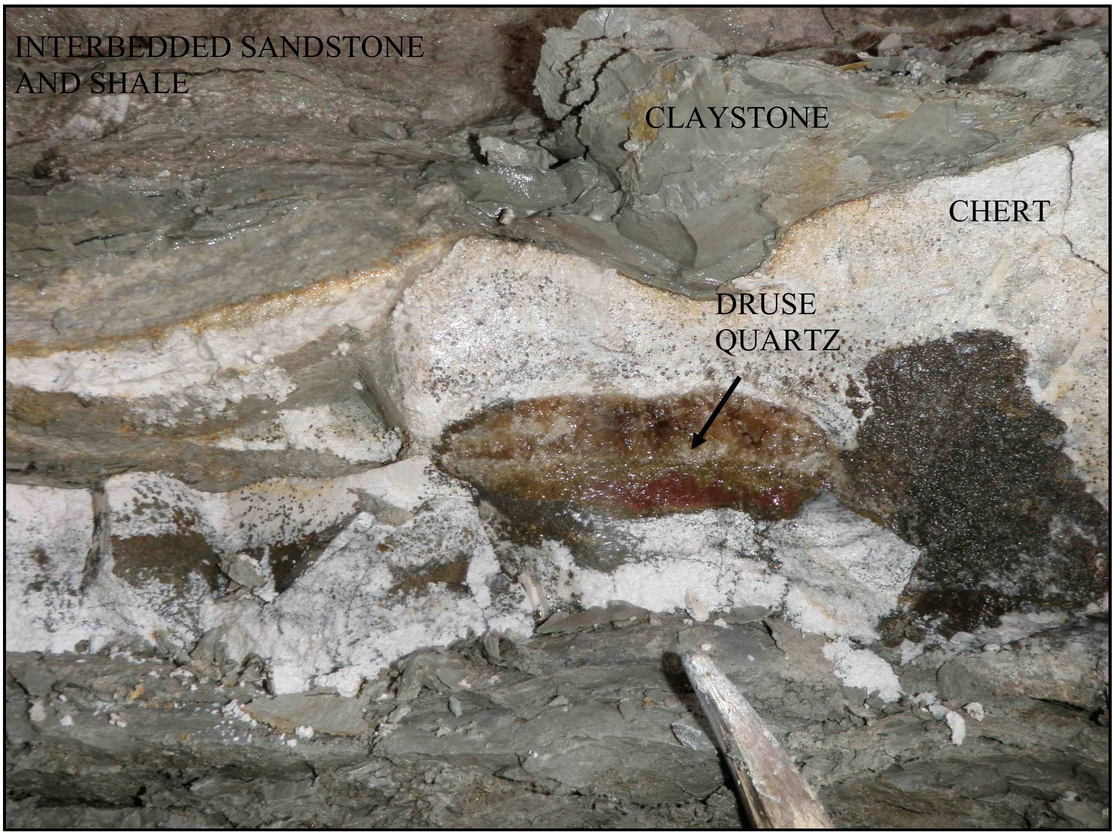

Figure 5.22 Pyritic zone developed on tripolized chert clast within claystone/shale matrix. Dark points are pyrite crystals hosted in crinoid molds. Pyrite skins have formed along fracture planes within chert clasts. Note red-colored zone of recrystallized druse quartz, in close proximity with skins of pyrite.

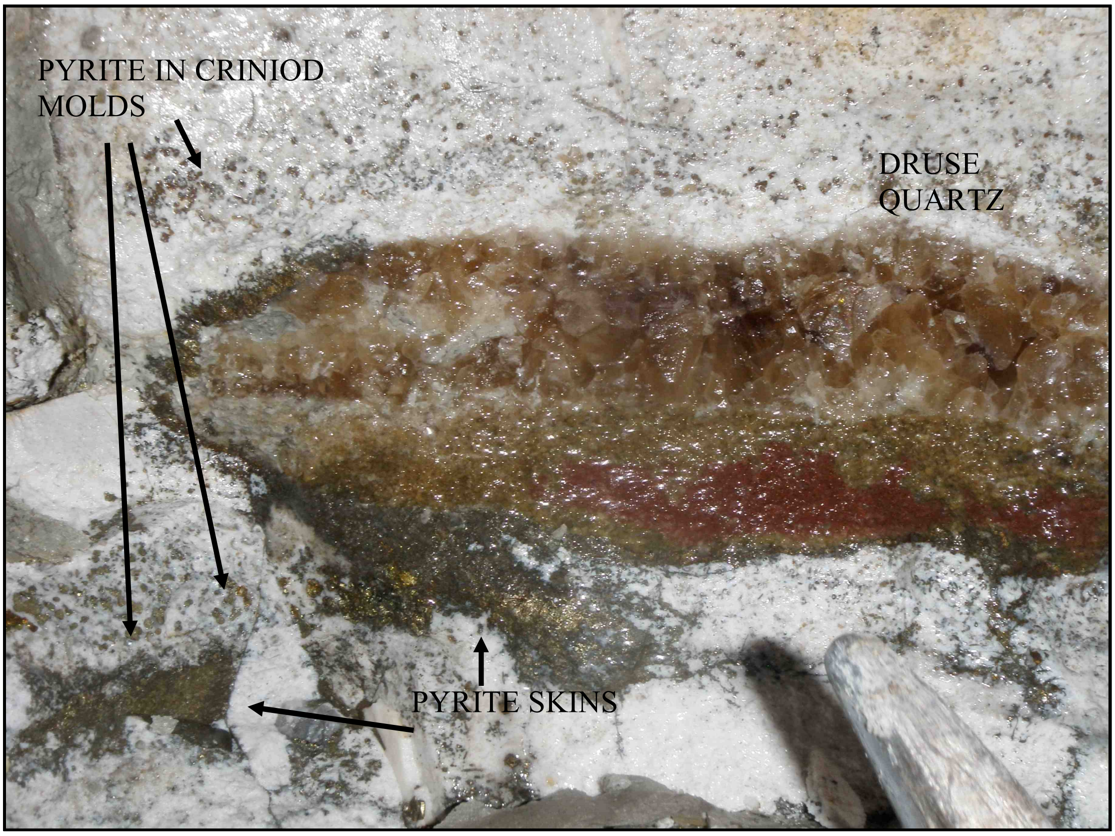

Figure 5.23 Close up of recrystallized quartz feature. Note the pyrite around the feature is hosted in crinoid molds, as well as in skins along fracture planes.

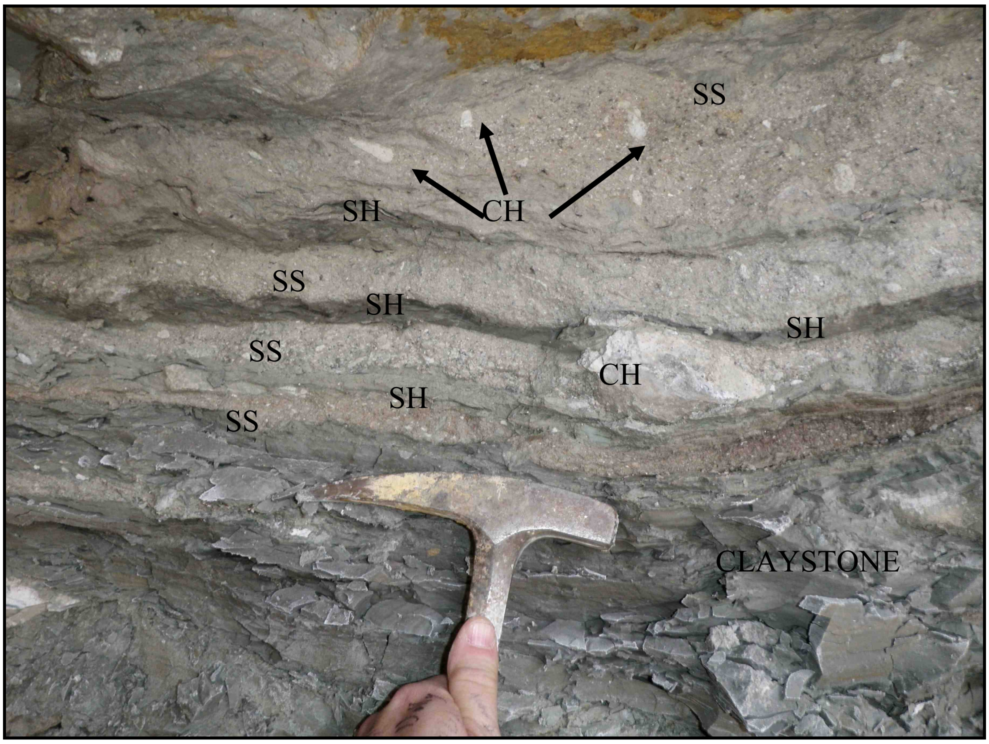

Figure 5.24 Alternating bands of sandstone and shale with chert clasts embedded in both. The lower claystone has a blocky structure compared to the fissile bedding observed in the overlying shale.

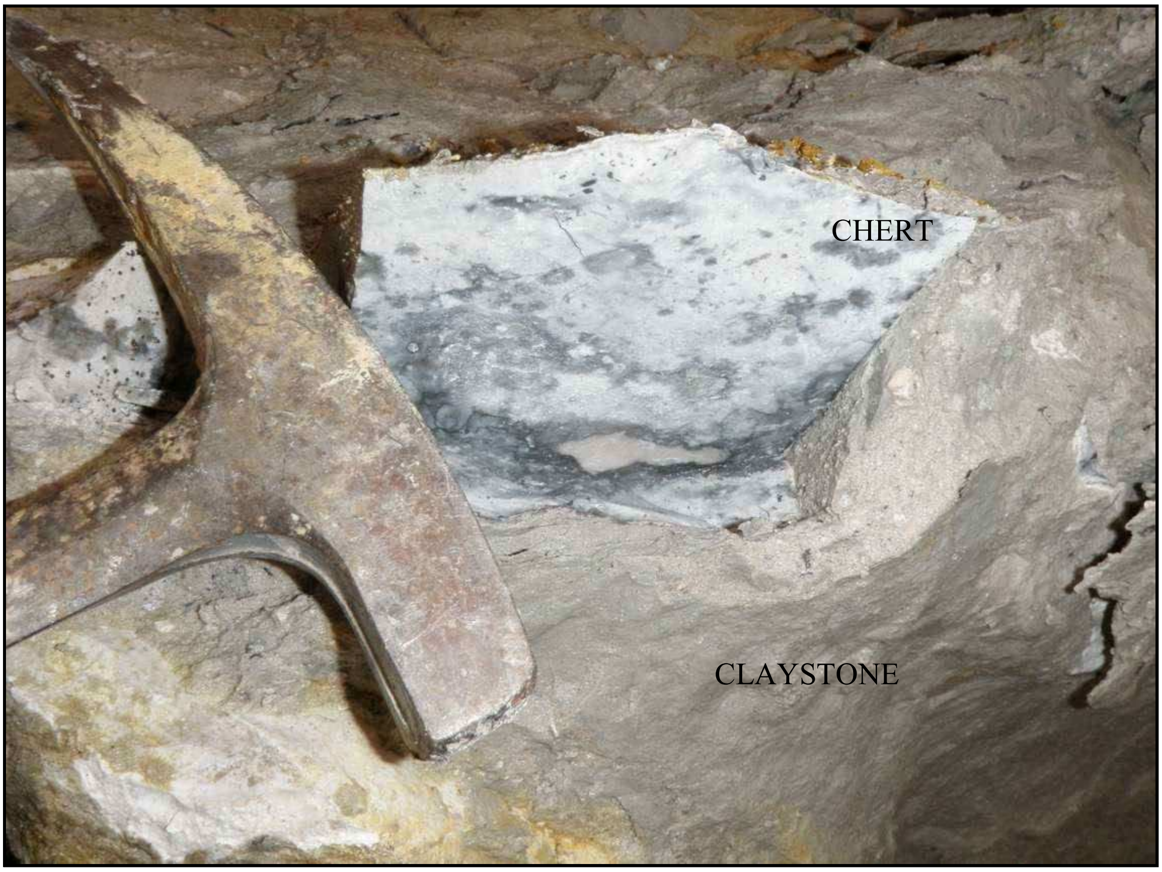

Figure 5.25 Chert clast typical of the Burlington Limestone at the ACPS. The chert clast is hosted in a weakly consolidated claystone.

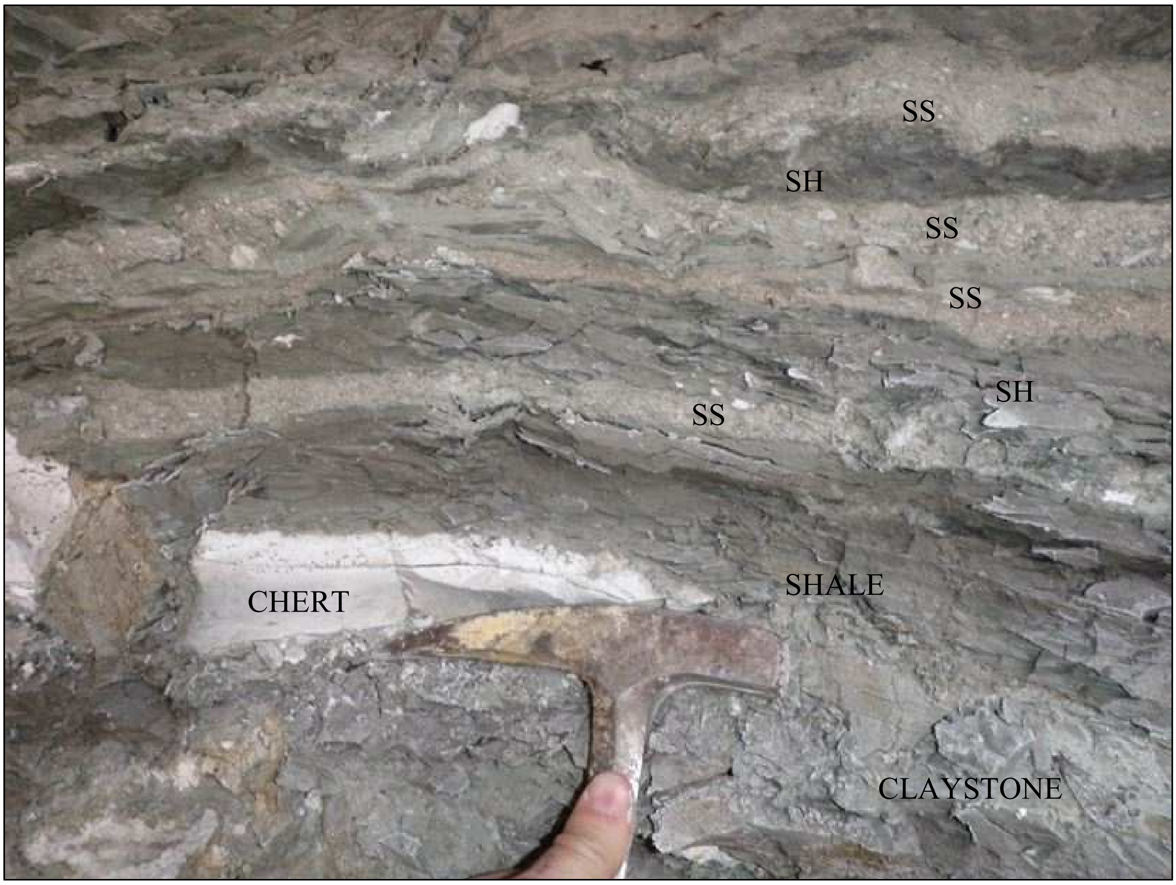

Figure 5.26 Alternating bands of sandstone (SS) and shale (SH). Chert clasts are embedded in both the shale and sandstone.

5.5 Unconsolidated Surficial Materials Analysis

Samples of the unconsolidated surficial materials were gathered and examined during the site investigation. Sediments were identified as originating from glacial, colluvial, alluvial and residual environments (Smotherman, 2008). Particle sizes range across silt, clay, sand, gravel and boulder- sized clasts. These materials were classified in the field using a USCS geotechnical gauge. They were then mapped across the site (Figure 5.27).

Modern Soil Horizons – The uppermost materials consisted of modern soil developed onto loess parent material. The soil column in the scarp displayed a thin A/B horizon developed onto the underlying loess. Modern soil formation and bioturbation has intermixed organic silts deeper into the soil column. Clay minerals within the soil column have stratified, with increases of expansive, moisture retaining clays at increasing depths within the soil column.

Colluvial Material – Loess and sand colluvium derived from glacial and colluvial deposits has eroded from the ridge to the north and redeposited as terrace deposits. They are not believed to be alluvial deposits themselves due to the identification of nodules of sedimentary hematite within the matrix. Sedimentary hematite is a soft mineral and would weather quickly in fluvial or alluvial setting. Slabs of sandstone measuring up to 0.60 m (2 feet) long were identified in these materials. These slabs are interpreted as colluvially transported sandstone residuum. The hematite and much of the sand are interpreted to have eroded from a thin layer of Pennsylvanian bedrock that formerly covered the site.

Overlying quartz sand and quartz erratics indicate a glacial component to the colluvial material. Additional materials consist of reworked sand and silt derived from glacial and windblown materials that have been deposited over the region in late Pleistocene and early Holocene, then colluvially reworked in later Holocene time.

Reworked Mississippian Materials – Within the colluvial material were cherts and fossils derived from Mississippian-age bedrock. Fossils identifying the Mississippian materials were primarily crinoid columnals. Cherts consisting of silicified crinoid columnals and columnal-shaped voids. Some cherts exhibited a distinctive pattern of concentric circles, or 'bulls-eye' pattern. Such a pattern is indicative of the Mississippian-age, Meramecian-series Warsaw Formation (Thompson, 1986). This formation is currently found to the east of the ACPS along the northern edge of the Lincoln Fold.

Figure 5.27 The distribution of surficial materials across the ACPS. USCS field classifications were used.

SAMPLE AREA	SILT %	CLAY %	SAND %	GRAVEL %
WEST RIDGE (SOUTH)	5	5	80	10
WEST RIDGE (NORTH)	5	5	10	80
EAST RIDGE (SOUTH)	10	30	0	60
EAST RIDGE (NORTH)	43	43	9	5
FLOOD-PLAIN	30	5	60	5
TRIBUTARY	45	45	0	10
LOSING SECTION OF TRIBUTARY	5	5	0	90

Figure 5.28 Field estimated percentages of surficial materials across the ACPS.

CHAPTER 6 DATA INTERPRETATION

6.1 Mississippian-age Burlington Limestone

Field and microscopic analysis of bedrock samples of carbonate and siliceous material from the site show that the uppermost bedrock unit is Paleozoic-age, Mississippian system, Osagean series Burlington Limestone.

The sedimentology of the Burlington Limestone at the ACPS consists of a grain-supported matrix composed of over 90% disarticulated crinoid fossils. The fossils are mainly columnal segments, with occasional calyx plates, arm segments and holdfast elements. Where the formation is less fossiliferous, it is composed of an interlocking, recrystallized lime matrix. The rock is classified as a calcirudite according to grain size (Grabau, 1903); a packstone or grainstone with local wackestones based on carbonate textures (Embry and Klovan, 1972); or a biosparite based on fossils and recrystallized calcite (Folk, 1959).

6.2 Joint Control at the ACPS

The weathered fractures that are inferred to underlie the ACPS are interpreted as a joint set due to their influence in the surface topography and drainage in Youngs Creek, as well as the lack of fault breccias observed in the stream gravels downstream from the site (Figure 5.6). Such joints are typical in weathered limestone, and features observed in USGS topographic maps of the ACPS indicate such a joint set exists at the site. The observed features are sharp, parallel bends in Youngs Creek that align with upland tributary streams. Joint sets observed in similar geologic environments form from the removal of overlying pressure by the erosion of bedrock units during epierogenic or tectonic uplift (Ford and Williams, 2007; Ritter, 2002). Once exposed at or near the surface, joints can be further widened by dissolution from chemically aggressive meteoric groundwater.

The northwest-southeast striking joints are interpreted as primary jointing due to their alignment with the dominant structural stress field in the region. This stress field is manifested by numerous parallel synclines and anticlines that strike parallel to the joints in this region of northern Missouri (McCracken, 1971).

6.3 The Identification of Paleokarst from Paleosink 1 Fill Material

The key feature identifying the ACPS as a paleokarst terrain versus a more recent karst terrain is the identification of fill material that has been diagenetically altered into bedrock within Paleosink 1. This material consists of claystone, shale and sandstone that is not stratigraphically related to the Burlington Limestone at the site. Rather, this material represents residual sedimentological material derived from offsite sources, transported to the site, and lithified into these bedrock units. The prevalence of chert clasts representative of the Burlington Limestone demonstrates that some of this material originates from that unit. The presence of sand in the paleofill indicates this material was transported from offsite, as sandstone is not a recognized sedimentological diagnostic in the Burlington Formation of Missouri (Thompson, 1986). The material was weathered during the Kaskaskia regression, then lithified as Pennsylvanian-age sediments.

Bedrock units occupying this stratigraphic position in Missouri that consist of reworked Burlington cherts within a finer sedimentological matrix, are typically associated with the Pennsylvanian-age Graydon and Warner Members of the Cheltenham Formation (Gentile and Thompson, 2003). These basal members represent the available weathered sediment sources and depositional environments that were present in Missouri during the early Pennsylvanian (Figure 6.1). While these formations are highly weathered at the surface in Missouri, they also exist in the Illinois Basin. The members mapped from core in Illinois may better represent the sedimentology that was present in the Cheltenham (Figure 6.2).

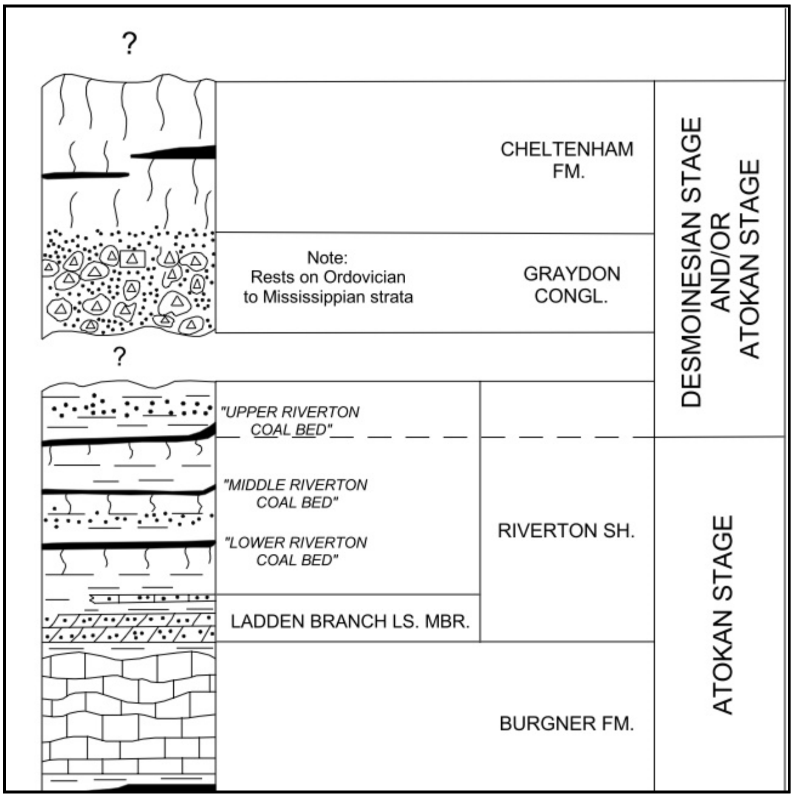

Figure 6.1 Pennsylvanian-age Cheltenham Formation and its stratigraphic relationships in Missouri. Note that the Graydon Conglomerate, one of the basal members of the Cheltenham Formation, is said to rest on Ordovician to Mississippian strata (Gentile and Thompson, 2003).

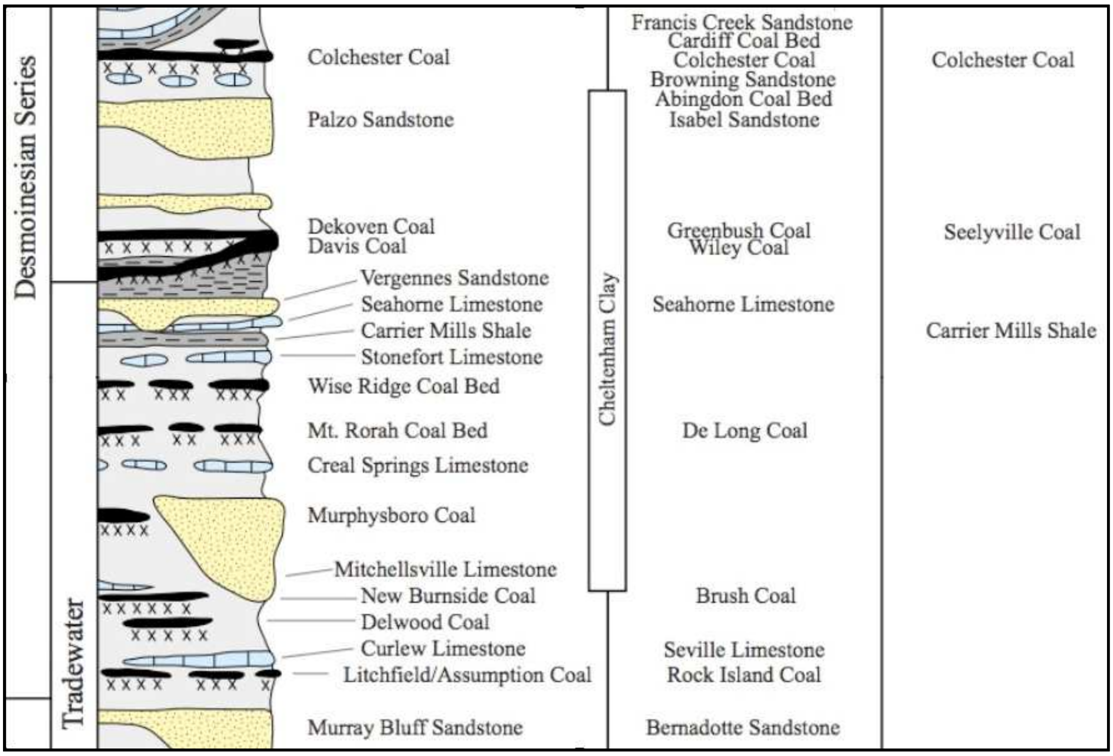

Figure 6.2 Stratigraphic differentiation of the Cheltenham Formation in Illinois (Jacobson et. al, 2002). The variability seen in the intact members in Illinois may better reflect the varied lithology of the formation, whereas in Missouri the formation is weathered and incompletely preserved.

In southwest Missouri, the Graydon Conglomerate is the basal member of the Cheltenham (Figure 6.3). In this area, it consists of reworked Burlington chert within a hematitic sandstone conglomerate. Geologic maps and surface outcrops of the Graydon indicate that it occurs as thin deposits and can occupy varied depositional environments such as paleokarst, paleo-stream channels and graben structures. The Graydon cherts and sands are well rounded and poorly sorted, indicating a high energy, short distance transport not dissimilar to the streams of the Ozarks today. This could indicate high gradient streams flowing off of the Ozark Plateau during the Pennsylvanian, then being deposited in channel fill, sinkholes and shallow marine graben structures.

Figure 6.3 Boulder of Pennsylvanian-age Graydon Conglomerate, basal Cheltenham, southwest Missouri.

Figure 6.4 Pennsylvanian-age Warner Sandstone overlying Graydon Conglomerate, west-central Missouri.

The Warner Member of the Cheltenham Formation is prevalent in central Missouri (Figure 6.4). This member typically consists of sands with some chert gravels deposited as laterally extensive, thick sheet deposits along the northern edge of the Ozarks Plateau. The immense amount of sand indicates a significant, nearby clastic source, such as the weathering of the Ordovician-age St. Peter Sandstone.

Basal Cheltenham Formation-members interpreted as being contemporaneous with the Graydon and the Warner in the St. Louis, Missouri area consist of Burlington-derived cherts intermixed with red shales more typical of the Cheltenham Formation (Figure 6.5). While this formation most likely represents a red bed-type depositional environment, it is sedimentologically very similar to the shale, claystone and sandstone observed above Paleosink 1, aside from the oxidized state of iron within the clays.

Figure 6.5 Pennsylvanian-age Cheltenham Formation. This red shale is interpreted as residual terra rosa clay weathered off carbonates exposed during the Kaskaskia Regression, then buried and lithified into shale during the Pennsylvanian.

6.4 Geomorphic Interpretation of Surficial Materials

The field analysis of the surficial materials at the ACPS indicates a complex pattern of erosion and deposition. The northern portion of the western ridge and the whole of the eastern ridge indicate colluvial and residual materials developed from the underlying Burlington Limestone. Bedrock outcrops were observed near the surface at both ridges, as well as at Fracture 2 on the south of the eastern ridge. Chert gravels observed at the surface and excavated in the shallow subsurface were eroded from the same bedrock unit. The high percentage of chert gravels on these ridges correlate with similar gravel-supported residual materials observed in the subsurface of Paleosink 1.

A mixture of gravels were observed in the unnamed tributary that transects the site. These gravels appeared to all be Mississippian in age, but came from two formations. Most came from the Burlington Limestone that forms the bedrock of the site. A small percentage came from the Mississippian-age Warsaw Formation, which is not located in close proximity to the site, but is found farther to the east near the Lincoln Fold in northeastern Missouri.

The portion of the western ridge south of the landowners home has a layer of sand and sandstone boulders overlying chert and clay residuum. Similar sandstone gravels were observed in the scarp of Fracture 1 and in the gravels of Fish Branch to the south. The presence of sandstone indicates this is Pennsylvanian-age material, possibly the Warner Sandstone Member of the Cheltenham Formation (Gentile and Thompson, 2003).

CHAPTER 7 CONCLUSIONS

7.1 The Paleokarst at the ACPS

The Audrain County Paleokarst Site is stratigraphically located in the Mississippian-age Burlington Limestone. This bedrock formation is also the uppermost hydrostratigraphic unit of the Mississippian Aquifer in north-central Missouri. In much of northern Missouri, the Mississippian Aquifer is overlain by two other aquifers (or aquicludes, depending on the lithology) composed of Pennsylvanian-age shales and Neogene-age glacial tills. At the ACPS, these units have been removed by erosion and uplift in post-Mississippian time. These natural processes, as well as artificial changes in the surface hydrology at the site, have resulted in the underlying paleokarst within the Burlington Limestone becoming re-incorporated into the modern groundwater hydrologic cycle. This reactivation has caused part of the paleokarst to subside, forming sinkholes similar to other karst areas in Missouri. As far as is known, this is unique to any other sinkholes sites in northern Missouri.

7.2 Conclusions from the Geologic Investigations

The paleokarst at the ACPS represents a tilted and weathered joint system within the Mississippian-age Burlington Limestone. This formation experienced subaerial exposure during the Kaskaskia Regression between Mississippian and Pennsylvanian time, during which a karst system of weathered bedrock joints and sinkholes developed. Regional bedrock exposures, subsurface anticlines, and observations of the attitude of bedrock in Paleosink 1 indicate that the Burlington Limestone has been tilted to the northeast. The paleokarst system was then covered over by siliciclastic material eroding from the uplands to the south and east. The silt, clay and chert parent material was eroded from Burlington Limestone. The sand was presumably eroded from Ordovician-age sandstones and quartzites found in the uplands also to the south and east. These rocks were deposited at the ACPS as the basal Graydon Conglomerate member of the Pennsylvanian-age Cheltenham Formation. Subsequent Pennsylvanian-age Cherokee Group shales and sandstones were deposited over the site. Post-Pennsylvanian uplift, Neogene-age glaciation, as well as downcutting by Youngs Creek, has removed much of the Pennsylvanian-age material at the site with the exception of the Cheltenham-age material preserved in Paleosink 1. Intact Pennsylvanian material probably exists at higher elevations around the site, but is obscured from surface observation by glacial drift.

Evidence of the weathered joints that underlie the paleokarst features at the site are best observed at Paleosink 1, where a linear subsidence feature called Fracture 1 leads into the swallet at the base of the paleosink. The paleosink itself is an expression of an underlying fracture, with the gravel swallet covering a hydrologic access point into this fracture.

Analogues for paleokarst preserved after the Pennsylvanian transgression are abundant in rocks of the same age that are down dip to the west of the Ozark Dome. In Kansas, Oklahoma and Texas, weathered Mississippian-age limestones overlain by Pennsylvanian-age shale and carbonate flooding surfaces are lucrative reservoirs for oil and gas exploration (Hill, 1996). From the high level of characterization in these oil-bearing formations, ample evidence exists that they are paleokarst terrains formed during lowstand conditions that existed during the Kaskaskia Regression (Ford and Williams, 2007; Hill, 1996). This also makes it likely that the karst at the ACPS, as well as other karst terrains in Missouri, also have their origins in paleokarst formed during the Kaskaskia Regression. Unlike the ACPS, the karst in the Ozarks of southern Missouri has experienced repeated episodes of post-Mississippian uplift and minimal Pennsylvanian burial. This terrain has been exposed to substantial modification by meteoric groundwater, which has largely flushed the Ozarks karst clear of any paleofill that would identify it as paleokarst (Ford and Williams, 2007; McCracken, 1971; Bretz, 1965). Recent finds by the author in the southern Ozarks have located other paleokarst sites with intact paleofill that may allow more thorough analysis of the evolution of paleokarst in the Ozarks, including the use of cosmogenic dating.

7.2.1 The Cheltenham Formation at the ACPS

The shale, claystone and sandstone that occur above the Burlington Limestone observed in Paleosink 1 are interpreted as being correlative with the basal Pennsylvanian-age Cheltenham Formation. In other parts of Missouri, a consistent diagnostic of the basal members of this formation is the incorporation of weathered material from the Burlington Limestone into these deposits. In southwest and central Missouri, these reworked materials are chert clasts and sandstones. In the St. Louis area, the reworked material is terra rosa clay residuum that has been diagenetically altered into red shale. The ACPS paleofill contains chert clasts derived from the Burlington Limestone based on the presence of crinoid fossils. The shale is presumed to be derived from clay residuum that was colluvially transported into the sinks and diagenetically altered into shale. The sand is presumed to have been derived from the erosion of Ordovician-age sandstones and quartzites to the south and east of the site.

7.2.2 Carbonaceous Shale and Pyrite in Paleosink 1

The pyrite hosted in the limestone and claystone/shale deposits indicates presence of a sulfur source such as organic material. In this geologic environment, such a source could be Pennsylvanian-age Cherokee shales or reduced organic material preserved in the paleosink. As previously noted, there is a zone of black shale near the base of Paleosink 1. The black color of this material resembles the black shales commonly seen in the Pennsylvanian-age Cherokee Group. Its location under Burlington Limestone residuum at the bedrock contact indicates it may have been deposited as organic material when the paleosink was an open bedrock sinkhole during the Kaskaskia Regression. Staining on the limestone bedrock above the black shale indicates ferric iron precipitate minerals such as hematite, goethite or limonite, which typically come from the oxidation of pyrite in the material by meteoric groundwater. Such waters often perch above low permeability shales and can oxidize iron-bearing minerals such as pyrite and marcasite present in the shale. Subsequent oxidation of sulfides could also produce sulfuric acid, which could weaken the surrounding rocks and contribute to collapse. Additional analysis between this material and similar 'carbonaceous' or 'redoxomorphic' shales in this paleosink and others could provide evidence to their origins.

7.2.3 Geologic Context with Downdip Mississippian Strata

The Mississippian-age paleokarst reservoirs in states to the west of Missouri are in the same Kinderhookian, Osagean and Meramecian-series rocks that make up most of the Mississippian system in Missouri (Hill, 1996; Thompson, 1986). The Mississippian-age rocks in these states did not experience the dramatic uplift that the Ozark Dome did beginning in the Pennsylvanian with the beginning of the assemblage of Pangaea between southern North America and northwestern Africa. After the Kaskaskia Regression, rocks in these states were buried into what would become the Arkoma, Anadarko and Permian Basins. This resulted in the karst in these states being permanently capped with Pennsylvanian-age rocks (Hill, 1996). As these formations were buried deeper, they ceased to become part of the functioning surface hydrological cycle, and eventually became infiltrated with oil and gas migrating upward from the Mississippian-Devonian age Woodford Shale (Hill, 1996).

The stratigraphic continuity between the documented paleokarst to the west of Missouri and the Mississippian-age rocks seen at the ACPS confirms the hypothesis that the solution-weathered fractures found at the ACPS formed as karst system over 300 mya, then became buried during the Pennsylvanian. While these same formations to the west continued to subside after the beginning of the Pennsylvanian and up to the present, the paleokarst at the ACPS represents a terrain that was not buried to these depths, and that has been exposed since the Pennsylvanian during epierogenic uplift, crustal deformation or glaciation.

7.2.4 A Conceptual Model of Regional Paleokarst in Northern Missouri

When compared to the known karst and observable bedrock in the area around the ACPS, an elevation pattern emerges. The Pinnacles Youth Park 33.7 km (21 miles) to the west of the ACPS, is at an elevation of 243.2 meters (800 feet) mean sea level. The Pinnacles display a heavily eroded karst landform with solution-weathered fractures, conduits and caves that stands 30.4 meters (100 feet) above the gaining stream that flows around it (Figure 7.1). The ACPS is at an elevation of 224.9 meters (740 feet) mean sea level. Downgradient bedrock outcrops observed near the site displayed no observable karst features, and are at an elevation of 212.8 meters (700 feet) and lower.

Figure 7.1 Solution-weathered features visible at Pinnacles Youth Park to the west of the ACPS.

While the paleokarst at the ACPS can be observed directly, observations of Burlington Limestone outcrops downstream and downgradient from the site do not display weathered karst topographies. Karsted limestone such as that seen at Pinnacles and at the ACPS appears to have been glacially removed in other areas. Isolated and heavily eroded paleokarst remnants such as these are reminiscent of the Driftless Zone in Wisconsin, a large karst isolate that was bypassed by Neogene glaciations, while similar bedrock and its associated karst system in close proximity was removed.

Figure 7.2 gives some comparative elevations of karst features in the vicinity of the ACPS, and demonstrates how they may represent exposures of the karsted upper portion of the Mississippian Aquifer in this area.

W → E

PINNACLES - 800'

****

CLAY PITS NORTH OF MEXICO- 770'

****

ACPS 740'- 700' (bottom of PS-1)

****

BURLINGTON OUTCROPS DOWNSTREAM OF ACPS 700' - 660'

Figure 7.2 Elevation differences between karst features in the vicinity of the ACPS.

If this conceptual model is accurate, the Pinnacles represent the upper portions of the karst aquifer, with well-developed solution conduits. Features such as the ACPS would represent the base of the karst aquifer, with more restricted solution development at depth and with paleofill materials intact. The outcrops of Burlington Limestone downgradient and topographically lower than these features represent the base of unweathered limestone, where the aquifer would have characteristics more consistent with a non-karsted limestone bedrock aquifer.

7.2.5 Transition from Passive Upland Gradient to Active Downcutting Gradient

One of the likely driving mechanisms for the reactivation of the paleokarst at the ACPS is the presence of topographic factors that can drive steeper groundwater gradients which can establish turbulent subsurface flow within the paleokarst and subsequently physically compact and remove residual material, leaving an open karst conduit that acts as a solution feature that can further drive the opening of the karst system. This topographic gradient appears to increase over time with the downcutting of Youngs Creek into the surficial materials and shallow bedrock at the site. With the constant flow of water through Youngs Creek, the area immediately adjacent to it will tend to stay saturated. The lake provided a discrete, local gradient increase that further accentuated the opening of the underlying paleokarst. Additionally, the surrounding uplands can introduce a passive but constant groundwater gradient that can drive the vertical flow of groundwater, the compaction and removal of residual fines and gravels, and ultimately the reactivation and expansion of the underlying paleokarst.

The increased groundwater gradient produced by the farm lake that formerly occupied the site provided extra hydraulic head over the 20 years it existed. The opening of Paleosink 2 under the lake indicates that there was a significant interaction between the lake water and the underlying fracture. This interaction could have been thinner surficial materials, coarser materials, a thinner lake liner or other factors. The proximity of Paleosink 2 to Fracture 2 and Outcrop 2 indicates that shallow bedrock could exist close the paleosink, and that the fracture could transport fines away from this part of the site, increasing the permeability of the unconsolidated materials immediately underlying the lake liner.

7.2.6 The Future Reactivation of Paleokarst

Observations made at the site concur with the idea that this paleokarst system will continue to expand. Paleosink 1, Paleosink 3 and Fracture 1 have obviously expanded in dimensions since initial observations in 2008. Alternately, Paleosink 2 and Fracture 2 have been relatively quiescent. The surficial materials around the swallet of Paleosink 2 have collapsed into the subsidence, with the swallet now being covered by the silts and clays of the former lakebed. The distinctive yellow clays and white chert gravels observed in 2008 have been covered over, and thick vegetation has begun to take root within much of the lakebed in 2010. While it can still take on water from the unnamed tributary during periods of high precipitation, as evidenced by the dry channel that connects the two, Paleosink 2 has mostly been affected by small-scale geomorphic accommodation, as the unconsolidated silts and clays fill the subsidence feature. Based on the observation that fine unconsolidated materials are filling Paleosink 2, and not being conducted through an open swallet, it appears that Paleosink 2 has become stable in 2011 after the removal of the hydrologic gradient generated by the farm lake.

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