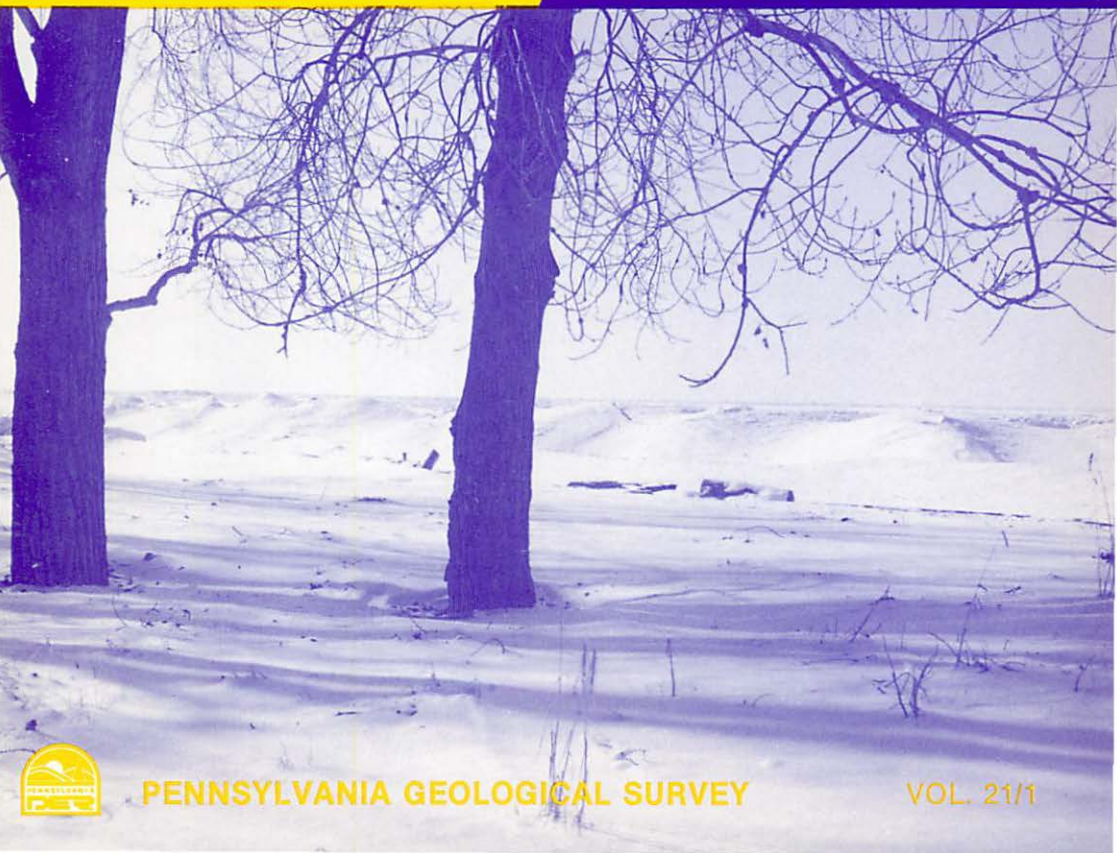
PENNSYLVANIA GEOLOGY



PENNSYLVANIA GEOLOGICAL SURVEY VOL. 21/1

COMMONWEALTH OF PENNSYLVANIA
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ON THE COVER: Unusually well developed ice "dunes" near the lighthouse at Presque Isle State Park, Lake Erie. The "dunes" form in association with pressure ridges in a shelf of lake ice attached to the shore. Wave surge forces water up through cracks in the ice, and it freezes on the surface. Under special conditions, repetition of this process and addition of freezing spray produces a volcano-like structure of layered ice. The ice surface is steep, slippery, and fragile, making close examination of the dunes extremely hazardous. Visitors should admire them from the safety of the beach. This photograph was taken by Helen L. Delano in January 1981, and will be included in an upcoming geologic guide for Presque Isle State Park to be published by the Pennsylvania Geological Survey.

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VOL. 21, NO. 1 **FEBRUARY 1990**

The Unfortunate Rewards of Success—Fossil Collecting at Swatara Gap Site to End

The fossil-collecting locality at picturesque Swatara Gap, renowned throughout Pennsylvania, the United States, and beyond, is likely to be removed from public access. Our bureau has been asked to notify readers of this journal that the Pennsylvania Department of Transportation (PennDOT) is strongly considering the closing of the site to the public.

Swatara Gap has been a favored and well-used collecting locality for over 50 years because of the abundance of the small trilobite *Cryptolithus* and because it is a locality for collecting the very rare Ordovician-age starfish *Protasterina*. The ease of access to this site (it is on public property, a PennDOT right-of-way) and the abundance and variety of fossils there have made the locality famous among researchers, serious and amateur collectors, school groups, and casual visitors.

But our success in advertising the locality as a recommended collecting site has led to its overuse and to extensive removal of rock to the point that the safety of the berm supporting the southbound lane of Interstate 81, which crosses over the collecting site, may be threatened if further collecting is allowed.

We urge that all who plan to visit the site use restraint and caution. If collecting remains allowed, it should be done only from loose material that has naturally weathered; do not "quarry" the outcrops. If the locality becomes posted, do not attempt to ignore the warnings. The safety of the highway traffic above is more important than the collection of fossils.

We will work with PennDOT to try to arrange that the locality remains available to researchers and for academic purposes. We will need your support and patience in this matter.

Removal of localities from public access has occurred in the past and will occur in the future as more and more people who are interested in natural objects take advantage of available sites that have been made publicly known. Many of these sites are on private property and have been freely opened to the public by the property owners. Visitors to these sites should conduct themselves as guests. Whether the sites are on public or private property, collectors should recognize that they have a responsibility to ensure that localities are not abused to the point that they become unavailable for public use.

Perhaps it is time to consider whether special localities containing abundant or unusual fossils or minerals could become part of some system of natural sites to be made available to the public for educational and recreational purposes. If you have comments on this subject, we would appreciate hearing from you.

Donald M. Hoskins

Donald M. Hoskins
State Geologist

IN MEMORIAM

Tracy V. Buckwalter (1918-1989)

Dr. Tracy V. Buckwalter, Professor Emeritus of the Geography and Earth Science Department at Clarion University of Pennsylvania, died at his home in Shippenville, August 15, 1989. He was 71 years old. At the time of his retirement in 1983, he had spent 34 years teaching geology, first at the University of Pittsburgh from 1949 to 1965, and then at Clarion State College, as it was formerly known, from 1965 to 1983. From 1972 to 1979 he chaired the department at Clarion.

Trained as a "hard-rock" geologist, "Buck," as he was known to his colleagues, did extensive field work in eastern Pennsylvania in the Reading Prong as a cooperating geologist with the Pennsylvania Geological Survey. In a decade of intensive summers' field work (1951-60), Buck examined the Reading Prong rocks from Womelsdorf to the Macungie area. A conscientious and energetic field geologist of the "old school," he proved well suited to the task. The 10 summers and much laboratory work led to 10 significant papers on the geology of the area, four of which were published by the Pennsylvania Geological Survey.

In an area of poor exposure, he was precluded from making facile generalizations. As a result, his field work was meticulous. Initially Buck's field work vindicated the classic interpretation of the Reading Prong as a rooted anticline. Geophysical investigations and changed paradigms of orogenic processes in the decades following his work led to the collapse of the anticlinal interpretation. However, modern recognition of the rootless characteristics of the Reading Prong in no way invalidated his mapping. Buck's relentless dedication to recording the data as it appeared in the field, unbiased by the accepted interpretation of that era, makes his data as valid today as ever.

In addition to his academic and Survey activities, Dr. Buckwalter at various times was a geologist for the U.S. Army Corps of Engineers, the U.S. Atomic Energy Commission, and the Texas Company, and was also a private consultant.

Dr. Buckwalter received his academic degrees—Bachelor of Science (1940), Master of Science (1946), and Doctorate (1950)—from the University of Michigan, where he had a predoctoral fellowship from the National Research Council from 1946 to 1949.

Buck was an enthusiastic member of the Field Conference of Pennsylvania Geologists and hardly missed a field trip since its inception, even attending a few after suffering a stroke in 1980. He was a dedicated teacher and practitioner of "old-fashioned" foot-slogging geologic mapping, utilizing his mapping for the Pennsylvania Geological Survey to educate University of Pittsburgh graduate students, who often accompanied him during the summertime. He also served as president of the Pittsburgh Geological Society and was a member of the North Appalachian Geological Society. His students, academic colleagues, and Survey friends remember his gentleness, quiet humor, and widely ranging and perceptive mind. We are all diminished by his death.

by Theodore F. Buckwalter

The Importance of Serendipity: Dorcie Calhoun and the Leidy Gas Field

by John A. Harper
Pennsylvania Geological Survey

Every now and then we hear about an actual incident so outrageous that a fiction writer would be ashamed to admit that he had written such a story. Luck, or serendipity, typically has a great deal to do with such tales. The story of how Dorcie Calhoun discovered natural gas in the Ridgeley Sandstone in the Leidy field, and in so doing ushered in a new age of deep drilling in the Appalachian basin, is just such a tale. It may have been embellished a bit in the many retellings, but it is nonetheless a true story worth repeating.

The Leidy field is situated in Clinton and Potter Counties in north-central Pennsylvania (Figure 1). It consists of one pool in the Upper Devonian Lock Haven Formation (not shown) and five pools in the Lower Devonian Ridgeley Sandstone, all of which occur on the flanks

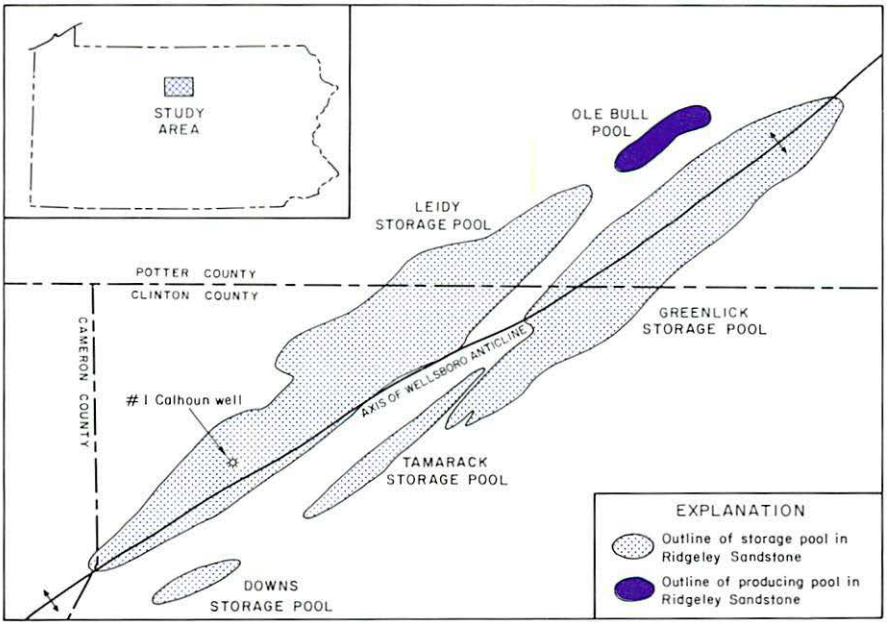

Figure 1. Map showing the location of Ridgeley gas pools in the Leidy field and the surface axis of the Wellsboro anticline. The gas well symbol shows the location of Dorcie Calhoun's discovery well.

of the Wellsboro anticline. The field had estimated ultimate recoverable reserves in excess of 175 billion cubic feet of gas; the pools are largely depleted now, however, and most of the field is being used to store gas produced elsewhere.

The Leidy field was discovered in 1864 by completion of a gas well drilled into the Lock Haven Formation near Hammersley Fork, Clinton County. The field is best known, however, for its production of natural gas from the Ridgeley Sandstone. Before 1930, the Ridgeley ("Oriskany" of drillers and some authors) was considered to be prohibitively deep throughout most of western and north-central Pennsylvania. At that time, only 36 wells had penetrated to the Ridgeley in the state, without much success (Fettke, 1950). Natural gas was eventually discovered in the Ridgeley in 1930 in south-central New York and in Tioga County, Pennsylvania. This led Stanley Cathcart of the Pennsylvania Geological Survey to research and publish a report on the geology of potential oil and gas deposits in north-central Pennsylvania (Cathcart, 1934) that became something of a bible for companies actively seeking Ridgeley gas. Throughout the 1930's and 1940's, more than 550 "deep" wells were drilled in Pennsylvania in the search for the elusive resource (Fettke, 1950). Only a few fields were discovered during this time, however, and by 1949 drilling was in a declining phase.

Despite stories to the contrary by the popular press (e.g., Davidson, 1951), many geologists thought that the Leidy area had high potential for gas production. By the late 1940's, New York State Natural Gas (now Consolidated Natural Gas Corporation) had acquired leases on about 11,000 acres on the Wellsboro anticline in the vicinity of Leidy (Ingham, 1954). The company was well aware that, as a result of pinchout to the north and west, the Ridgeley Sandstone was absent in a large area of northern Pennsylvania and southern New York. In addition, the sandstone in all of the wells drilled on the Wellsboro anticline in Tioga County, northeast of Leidy, had been too tightly cemented to produce more than a show of gas. As a result, New York State Natural Gas considered the anticline in the Leidy area too risky to explore without further evaluation. However, these concerns meant little to one local citizen whose name has become legend in the oil and gas industry.

As the story goes, Dorcie Calhoun (Figure 2) had "known" that there was gas on the family farm near Leidy since he was a boy. He had even seen it bubbling out of nearby Kettle Creek, where he liked to fish. Dorcie spent years telling folks in the vicinity that there was gas under the Leidy area, but very few people took him seriously. Then in 1949, with the help of Cathcart's report, he finally managed to convince the editor and publisher of the local newspaper to back

him in his venture. This "stamp of approval" from a well-respected member of the community, plus the knowledge that New York State Natural Gas thought enough of the area to lease large tracts of land, suddenly made Dorcie's ideas tenable to the citizens of Clinton County, and other potential investors in the area ran to Dorcie with their share of the stake. After forming the Leidy Prospecting Company, Dorcie bought an old dilapidated drilling rig used in the shallow oil fields around Bradford, McKean County, and hauled it back to Leidy. As luck would have it, it was raining hard when the equipment caravan arrived, and the lead truck got stuck in the mud little more than a few hundred feet up the road to the top of the mountain, the site that had been chosen for the first well. When it became apparent

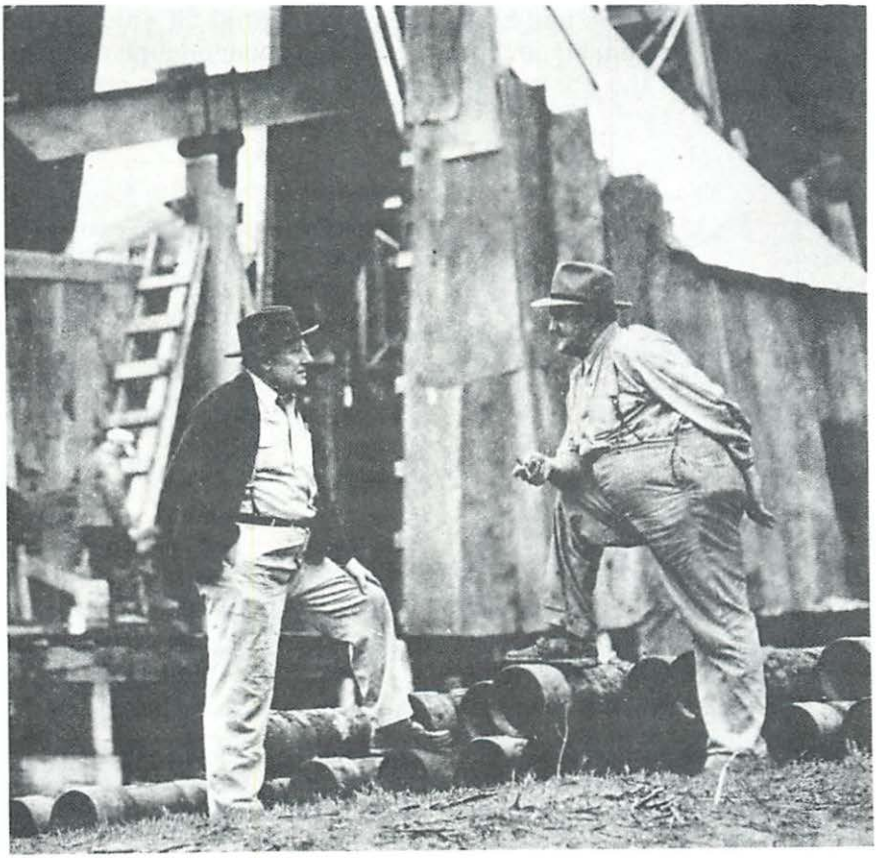

Figure 2. Photograph of Dorcie Calhoun (right) talking with drilling contractor Sam Jack beside a cable-tool rig used to drill to the Ridgeley Sandstone in the Leidy field (photograph reproduced from Philadelphia Inquirer Magazine, November 12, 1950).

that the trucks would not move, Dorcie simply decided to drill on the spot (Figure 3).

The old cable-tool rig spent more time in repair than it did in drilling. The framework had to be rewelded, wooden pieces were replaced by iron or steel ones, sections had to be brought in from outside the area, and additional guy wires were attached to keep the old derrick from falling over. Most of the knowledgeable people who saw it were amazed that it stayed upright and could still be used.

Suddenly, on Sunday afternoon, January 8, 1950, the drillers heard a rumble deep in the ground and began hauling the tools out of the hole as fast as they could. The drilling cable, however, flew out of the hole faster than the bull wheel could reel it in. Realizing the meaning of this phenomenon, the experienced rig hands scattered and took cover. The cable had broken, leaving the drill bit stuck in the hole, but the gas coming up the well bore was under enough pressure to squeeze past the obstruction and still fling the cable out of the

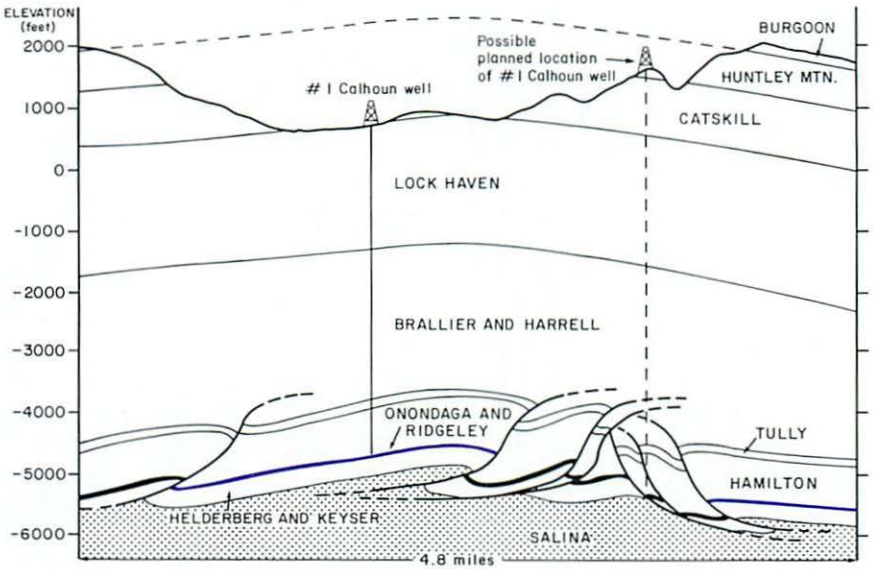

Figure 3. Cross section of a portion of the Leidy field showing the location of Dorcie Calhoun's well, and a possible location of the well as originally planned, in relation to the geologic structure. Notice that the surface and subsurface axes of the Wellsboro anticline are offset, and that the "crest" of the anticline at the depth of the Ridgeley is a graben structure related to salt movement in the Salina Group. Ridgeley gas reservoirs (in color) are restricted to fault-bounded flexures on the flanks of the anticline.

well, where it almost demolished the rig. The well had reached total depth in the Ridgeley at 5,659 feet, and the gas rushing out of the well was estimated at 15 million cubic feet of gas per day, an incredible volume even by today's standards. Dorcie Calhoun and his corporation of farmers and small businessmen had struck it rich and, in the ensuing excitement over this important discovery, ushered in a new era of drilling for oil and gas in the Appalachian basin.

The structure of the Leidy field is illustrated in Figure 3. At the surface the structure consists of a simple asymmetrical anticline, but deep in the subsurface it consists of a central graben (the "crest" of the anticline) flanked by a series of overthrusted limbs; the axis of the anticline is offset to the southeast relative to the surface axis. This effect was created by movement within the ductile layers of salt in the Upper Silurian Salina Group, and probably resulted from a redistribution of salt from the area of the graben to the overthrusted flanks. The exact number and distribution of faults is not known for certain, but they created a set of independent flexures situated on the flanks. The areas of structural closure on these flexures correspond to the gas-producing pools of the Leidy field.

The importance of serendipity in the discovery of oil and natural gas is almost always understated. In fact, without it the Leidy field might still be undiscovered today. New York State Natural Gas was ready to stake a well near Leidy when Dorcie Calhoun began drilling "on a wing and a prayer," and the company decided to hold back, waiting to see what would happen. If it had not been raining that day, Dorcie Calhoun's lead truck would have reached the top of the mountain (possible location shown in Figure 3). The well probably would have been a dry hole drilled into the graben at the "crest" of the subsurface anticline. At that point Leidy Prospecting Company would have failed, New York State Natural Gas would have seen Leidy as a slim prospect for future exploitation, and the drilling "boom" of the 1950's may have been delayed or may never have occurred.

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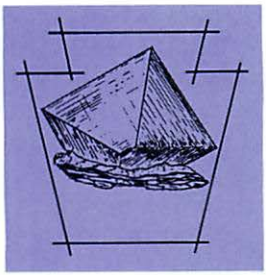

EARTH SCIENCE TEACHERS' CORNER

by James R. Shaulis

Pennsylvania Surfaces in Two New Maps

Those who have been curious about the character, makeup, and origin of the unconsolidated deposits located at or near the surface of Pennsylvania, or who have been wondering how the Piedmont physiographic province differs topographically, compositionally, and structurally from the Ridge and Valley physiographic province need look no further than two maps recently published by the Pennsylvania Geological Survey.

Map 64, **Surficial Materials of Pennsylvania**, colorfully shows the geographic distribution of 12 categories of surficial deposits found across the state. On the reverse side of the map are explanations of the categories, which include stratified sand and gravel, stream terrace deposits, glacial diamicts, residuum, colluvium, and alluvium. The explanation provides general information on areal distribution, thickness, and lithology. Some commonly used surficial geologic terms are also defined. The map will provide both teachers and students of earth science with a general introduction to the surficial geology of Pennsylvania.

Map 13, **Physiographic Provinces of Pennsylvania**, is a significant revision of an earlier version that was compiled over 25 years ago. Boundaries for the physiographic provinces have been revised and, consequently, the names identifying the provinces and sections have been changed in several areas, such as in the plateau region of western Pennsylvania. In addition, a table of descriptive elements (e.g., dominant topographic form, underlying rock type, geologic structure, and drainage patterns) has been printed on the reverse side of the map. This information will help the earth science student to understand the reasons for the geographic distribution of the physiographic provinces in Pennsylvania.

Both maps have been published in a convenient 8½- by 11-inch format, making them well suited as a classroom handout or a notebook supplement. These maps have been printed in bulk quantity and will be provided free to earth science educators, students, and others who wish to know more about the physiography and surficial geology of the Commonwealth. To order copies of Maps 13 and 64, please write to Pennsylvania Geological Survey, P. O. Box 2357, Harrisburg, PA 17105.

Freshwater Limestones of the Allegheny Group

by Suzanne D. Weedman
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INTRODUCTION. Freshwater limestones commonly occur in thin beds below the coals of the upper Allegheny Group of western Pennsylvania (Figure 1). They are easy to pick out in roadcuts or surface-mine highwalls as the knobby, pale-yellow beds about 3 feet below the coal; commonly an underclay occurs between the coal and the limestone. The limestone appears, in places, to be a layer of coalesced nodules having an undulose base and top. Upon close inspection, some of those "nodules" reveal a brecciated texture. Although some of the clasts in this breccia show bedding, internally laminated limestone strata are very rare in outcrop, making an interpretation difficult. In other words, the primary beds that were brecciated are hard to find. Clearly, these rocks have had a complicated history. To compound the enigma of their origin, the freshwater limestones in Pennsylvania are commonly associated with another unusual and poorly understood group of rocks, the flint clays (Bragonier, 1989). The lack of modern analogues, as well as rarity of good exposures in Pennsylvania, has plagued attempts to interpret both rock types.

The earliest occurrence of freshwater limestones in the Appalachian basin is in the Middle Pennsylvanian below the Upper Kittanning coal. Above that horizon, freshwater limestones are a common constituent of the coal cyclothems, both in the relatively nonproductive Conemaugh Group and in the productive coal measures of the upper Allegheny and Monongahela Groups (see Figure 1). Just what "event," or change in the basin dynamics, is the underlying cause of this sedimentologic response remains a controversial topic. To date, very little work has been done on these unusual rocks (Adams, 1954; Williams and others, 1968; Marrs, 1981; Cecil and others, 1985; Weedman, 1988).

The purpose of this paper is to describe the results of a study of the Upper Freeport limestone from the subsurface in Indiana and Armstrong Counties (Figure 2), where the limestone reaches thicknesses as great as 30 feet. Fresh core samples through thick sequences have provided a greater variety of calcareous microfacies, including primary bedding, than have ever been described in outcrop.

GEOLOGIC SETTING. The upper Allegheny Group of western Pennsylvania was deposited in late Middle Pennsylvanian time on an upper delta/alluvial plain of the eastern North American foreland basin.

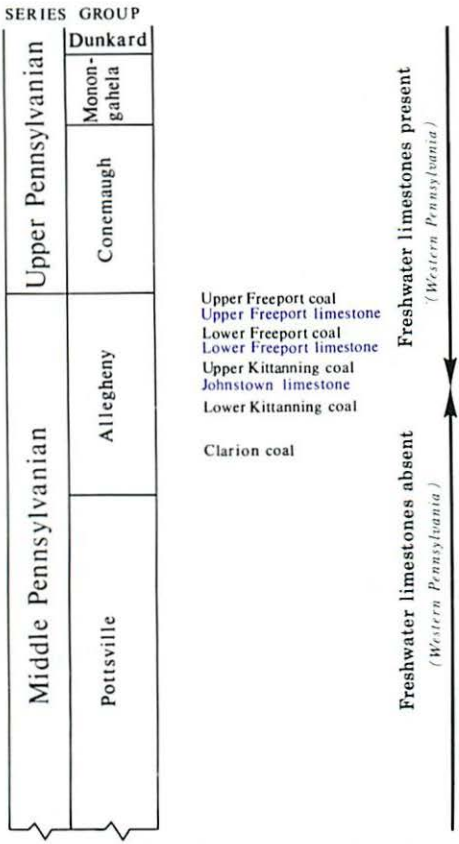

Figure 1. Stratigraphic column of part of the Pennsylvanian System in western Pennsylvania. The major commercial coals and associated freshwater limestones are shown for the Allegheny Group. The distribution of freshwater-limestone-bearing coal cycles is shown by the large vertical arrows.

Sediments infilling the basin were derived primarily from the mountains rising to the south (the Alleghanian orogeny) and are considered to be synorogenic. The upper Allegheny Group limestones—the Johnstown, Lower Freeport, and Upper Freeport—are virtually indistinguishable in the field or in core, and so are assumed to have a similar origin. They appear to have been deposited in broad, shallow alkaline lakes that were subsequently filled in with sediment and peat (which later became the coal). Unfortunately, less is known about the Conemaugh freshwater limestones.

The study was organized around two questions: (1) how do the freshwater limestones fit into the coal-to-coal depositional cycle; and (2) what environmental processes control the unusual appearance of the limestone itself? The first question was answered by a statistical study of vertical lithofacies sequences, as seen in over 450 cores through the upper Allegheny Group, and the second question was answered by an examination of 37 cores of limestone through the same interval.

FRESHWATER LIMESTONES AND THE COAL CYCLE. Based on a statistical analysis of lithofacies sequences (a Markov chain analysis), as seen in cores through the upper Allegheny Group in Indiana and Armstrong Counties, the following preferred sequence was identified: coal → black shale → dark gray to black sandy shale → sandstone → gray sandy shale → silty claystone → claystone → limestone → clay-

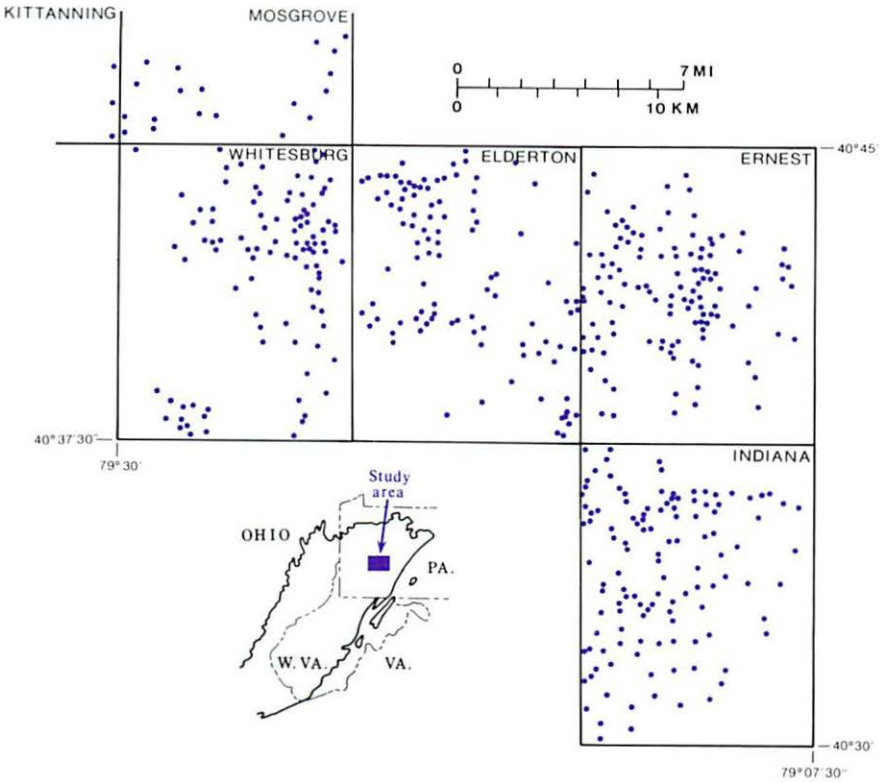

Figure 2. Map of the six-quadrangle study area in western Pennsylvania showing locations of core holes. Core logs from these holes were examined for the interval of the upper Allegheny Group. The inset map shows the location of the study area within the Appalachian basin (bold outline).

stone (underclay) → coal (Figure 3) (Weedman, 1988). This type of analysis provides a convenient way to summarize what is, in fact, a very complex data set. A great deal of variation in vertical lithofacies sequences exists in these sediments; the cycle listed above is only the most frequently occurring and is by no means complete at each site. The method is described in Walker (1984). This cycle looks very much like the classic cyclothem, but it suggests much more variation in lithofacies sequences; note the two-way arrows in Figure 3.

Fossil evidence suggests that the entire interval from the Upper Kittanning coal to the Upper Freeport coal in the study area is nonmarine. The first part of the cycle, from the coal to the sandstone, is a coarsening-upward sequence and is interpreted as the progradational deposits of overbank flows and crevasse splays. The other half of the cycle, from the sandstone to the claystone, is a fining-upward sequence

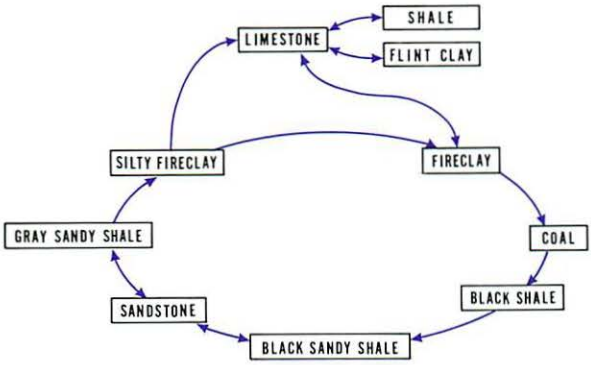

Figure 3. A general lithofacies sequence diagram for the significant lithofacies transitions in the coal-to-coal intervals that contain the Upper Freeport limestone in the upper Allegheny Group in western Pennsylvania. A single arrow (→) means "is overlain by," and a double arrow (↔) means "is interbedded with."

and is interpreted as the deposits that accumulated on the floodplain after the abandonment of the main channel. In other words, detrital deposition was replaced by chemical and organic deposition. Isopach maps of both the sandstone and limestone of the same coal-to-coal interval show that the thickest limestones occur over the thinnest sandstones, and the thinnest limestones occur over the thickest sandstones. Assuming that the thickest sandstones represent channels and the thickest limestones were deposited in the deepest parts of the lakes, this offset relationship suggests that the lakes were floodplain lakes, as opposed to abandoned channel meanders (i.e., oxbow lakes). The lake location was determined, then, by the location of the river or distributary channels, or their levees.

The following depositional scenario is envisioned for the "complete" cycle:

(1) The peat swamp (*coal*) is flooded with sediment-laden water from a nearby newly avulsed channel. The introduction of muddy sediment into the peat swamp produces a fissile dark-gray to black shale (*black shale*).

(2) As progradation of overbank sedimentation continues, organic-rich clays, silt, and sand continue to cover the peat swamp from distal overbank flows (*black sandy shale*).

(3) Sand is deposited over the dark sandy mud as more proximal overbank or crevasse flows reach the distal areas of the floodplain; progradation is at a maximum (*sandstone*).

(4) The deposition of light sandy mud suggests that the progradation of crevasse splays is waning. The lighter color can be interpreted as either a decline in vegetation or an increase in subaerial exposure (*gray sandy shale*).

(5) The appearance of a massive silty mud over the sandy mud signifies that the source of coarse sediment has avulsed upstream, and the newly deposited muds have been bioturbated or rooted to oblit-

erate bedding. However, the abandoned channel should still contain water, which transports sediment in suspension, and, during flood, transports the suspended sediment to floodplain lakes; the old channel and levee will be gradually buried in flood sediment (*silty fireclay*).

(6) Levee buildup and progradation during active sediment transport in the channel leads to the formation of topographic highs over the sites of sand deposition. Continued subsidence, combined with a marked decline in sedimentation rates after avulsion, results in perennial flooding of the floodplain. Freshwater lakes form in the low areas, are colonized by cyanobacteria, and are infilled with biogenic carbonate, floodborne mud, and vegetation. Lateral and vertical variation of the various lacustrine facies is controlled by water depth and proximity to both shoreline and sediment source (*limestone, shale, flint clay, fireclay*).

(7) A peat swamp migrates over the lake from the margins as it fills in with sediment and vegetation; the cycle is complete (*coal*).

The cycle can be interrupted at any point by the deposition of a channel or crevasse splay, or a distal equivalent. A block diagram is shown in Figure 4, representing a time just after avulsion but before the maximum expansion of the lake.

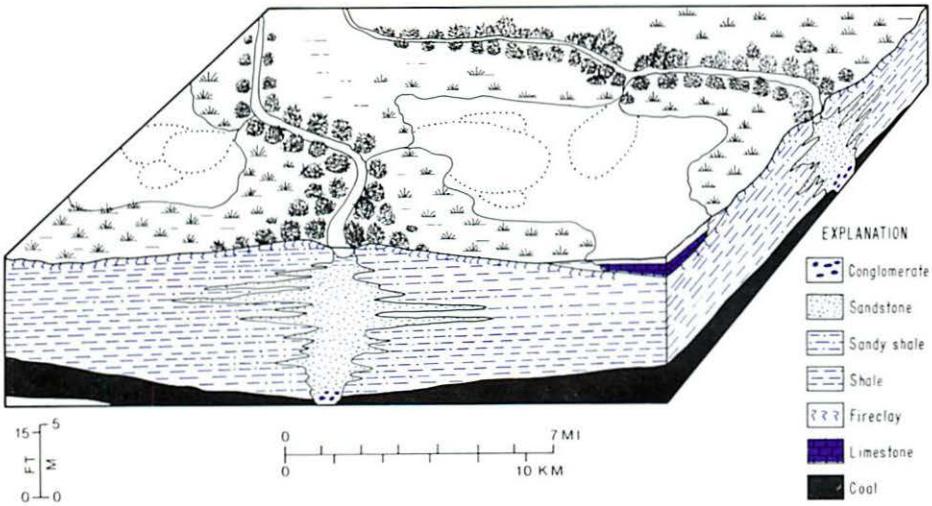

Figure 4. The depositional model for the Upper Freeport limestone and associated lithofacies. The paleogeography depicted in the model represents a time just after the upstream avulsion of the channel but before the maximum lake expansion and peat swamp formation. The form of muddy lacustrine deltas is indicated by the dotted lines in the lake areas. Though the channels are abandoned, they can transport suspended load to the floodplain and lake during flood.

THE LIMESTONE. The abundance of micro-oncolites and "algal" bedding in the limestone suggests that the lakes were colonized by cyanobacteria (Figure 5). Additional fossils include numerous kinds of ostracodes (not yet studied), *Spirorbis* worm tubes, fish bones, freshwater shark teeth, and plants. In eastern Ohio, the cannel coal at the famous Linton deposit, which overlies the Upper Freeport limestone, has yielded an abundance of vertebrate fossils of reptiles, amphibians, fish, and freshwater sharks (Hook, 1985). These fossil remains suggest that an abundance of animal life inhabited the Middle Pennsylvanian lakes and bogs.

The Upper Freeport limestone, from examination in cores, can be divided into seven calcareous microfacies: an encrusted grain microfacies (the micro-oncolites), a massive micrite, a laminated micrite, a clastic limestone, a claystone-limestone disturbed microfacies, a matrix-supported breccia, and a calcareous claystone. Calcite, dolomite, siderite, and ankerite are the only carbonate minerals; no true evaporite minerals have been reported. The calcareous microfacies are interbedded with three detrital lithofacies: claystone, black shale, and gray silty shale.

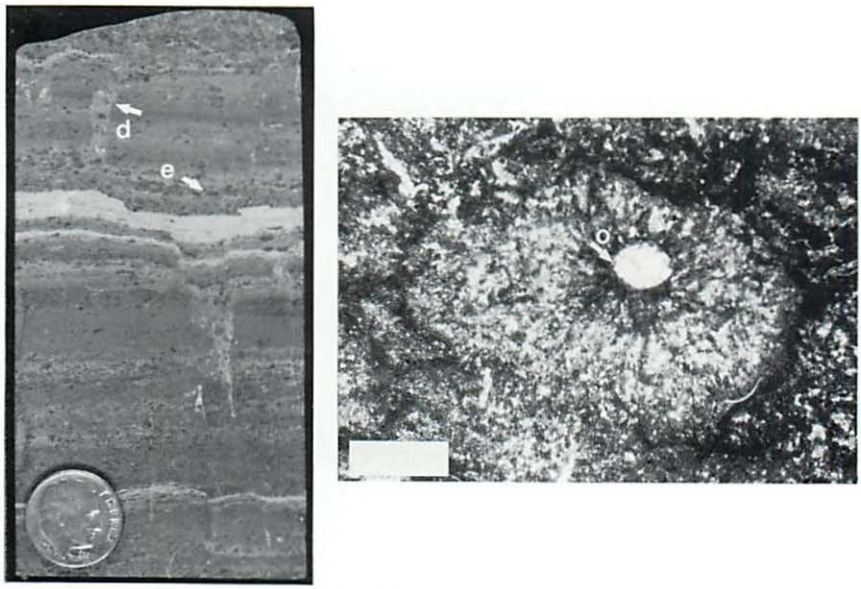

Figure 5. The encrusted grain microfacies (micro-oncolites). A. The core half shows dark-gray encrusted grains (e) in a lighter gray micrite matrix. Clay dikes (d) are filled with darker clasts of wall rock in a lighter clay-rich matrix. B. Photomicrograph of a single ostracode (o) encrusted by radiating cyanobacterial filaments that have been enhanced by etching in 0.1 percent hydrochloric acid. Scale bar is 0.5 mm in length.

In general, the thinnest limestone deposits (3 to 7 feet thick) are dominated by either a matrix-supported breccia or a clastic limestone, and are interpreted as shoreline facies. The thicker limestones (10 to 17 feet) comprise a variety of all of the microfacies, and show well-preserved bedding. The matrix-supported breccia and clastic limestone are absent in the thickest limestone deposit examined (17 feet). The limestones are characterized by abundant dewatering structures that show the injection of shale or claystone into the overlying, early cemented limestone. In plan view, these structures resemble desiccation cracks. The hypothesis is that compactible beds (shales, claystones, etc.) were episodically injected into the relatively early cemented and less permeable calcareous beds when the pore pressures in the shales exceeded the confining pressures of the limestones.

CLIMATE VERSUS BASIN DYNAMICS (OR, WHY ARE THE LIMESTONES WHERE THEY ARE?). Two hypotheses have been proposed for the sudden appearance of lacustrine limestones in the Pennsylvanian. First, their occurrence has been attributed to a change from a relatively wetter to a relatively drier climate during Middle Pennsylvanian time (Cecil and others, 1985; Donaldson and others, 1985). This interpretation is supported by assumed climatically controlled changes in the composition of the coals and sediments that are interbedded with the limestones. The underlying assumption is that, as evaporation increased relative to precipitation, surface waters became more enriched in calcium, and calcite precipitation occurred. Studies of modern lakes, however, have shown that calcite can precipitate in lakes in wet climates if there are limestones exposed in the source area and cyanobacteria available to mediate the precipitation. If the only change in the depositional environment were an increase in dryness, then one would expect all lithofacies of the coal cycle to be slightly calcareous. The general observation, however, is that limestones occur in discrete beds below the coal; small traces of calcite have been reported in the coal itself.

An alternative view is that lacustrine deposition was made possible by a changing fluvial style that favored the formation of lake basins in abandoned areas of the floodplains. That changing fluvial style, from meandering to anastomosed, is attributed to a response to an increase in subsidence rates relative to sedimentation rates, or, in other words, the inability of the surface drainage system to fill in the basin fast enough to keep up with subsidence (Weedman, 1988). The subsidence argument holds that the predominance of subsidence over sedimentation led to the formation of prominent levees along river channels (vertical accretion), to shoestring-shaped sand bodies (unfortunately, only indirect evidence exists for sand-body

shape), and to frequent avulsions. With each avulsion, some area on the floodplain would be left abandoned by the sediment-dispersing channel and would not receive adequate detrital sedimentation to fill in the lows. Those irregularly surfaced, abandoned areas would be ideal locations for calcareous algal (cyanobacterial) marshes and lakes (see Smith and Putnam, 1980, for a discussion of anastomosed river systems).

In summary, one hypothesis is based on the need for an adequate calcium supply in lake water to favor the precipitation of calcite, and the other is based on the need for a cyclic mechanism for the formation of sediment-starved lakes. One hypothesis, of course, does not preclude the other. Further work on the ways in which the depositional environments of the different freshwater limestones in the Appalachian basin changed through time may help to put these two hypotheses in better perspective.

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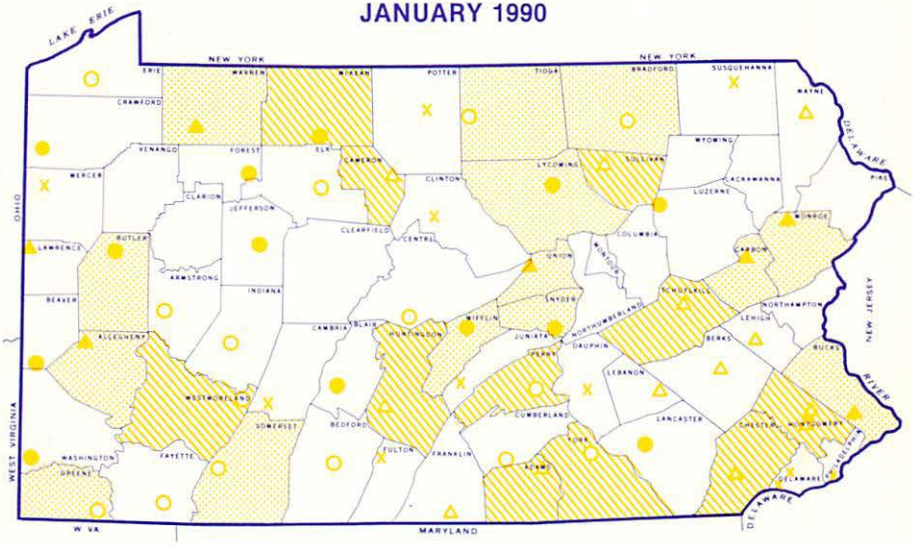

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