Sequence Stratigraphy of the Lower Chesterian (Mississippian) Strata of the Illinois Basin

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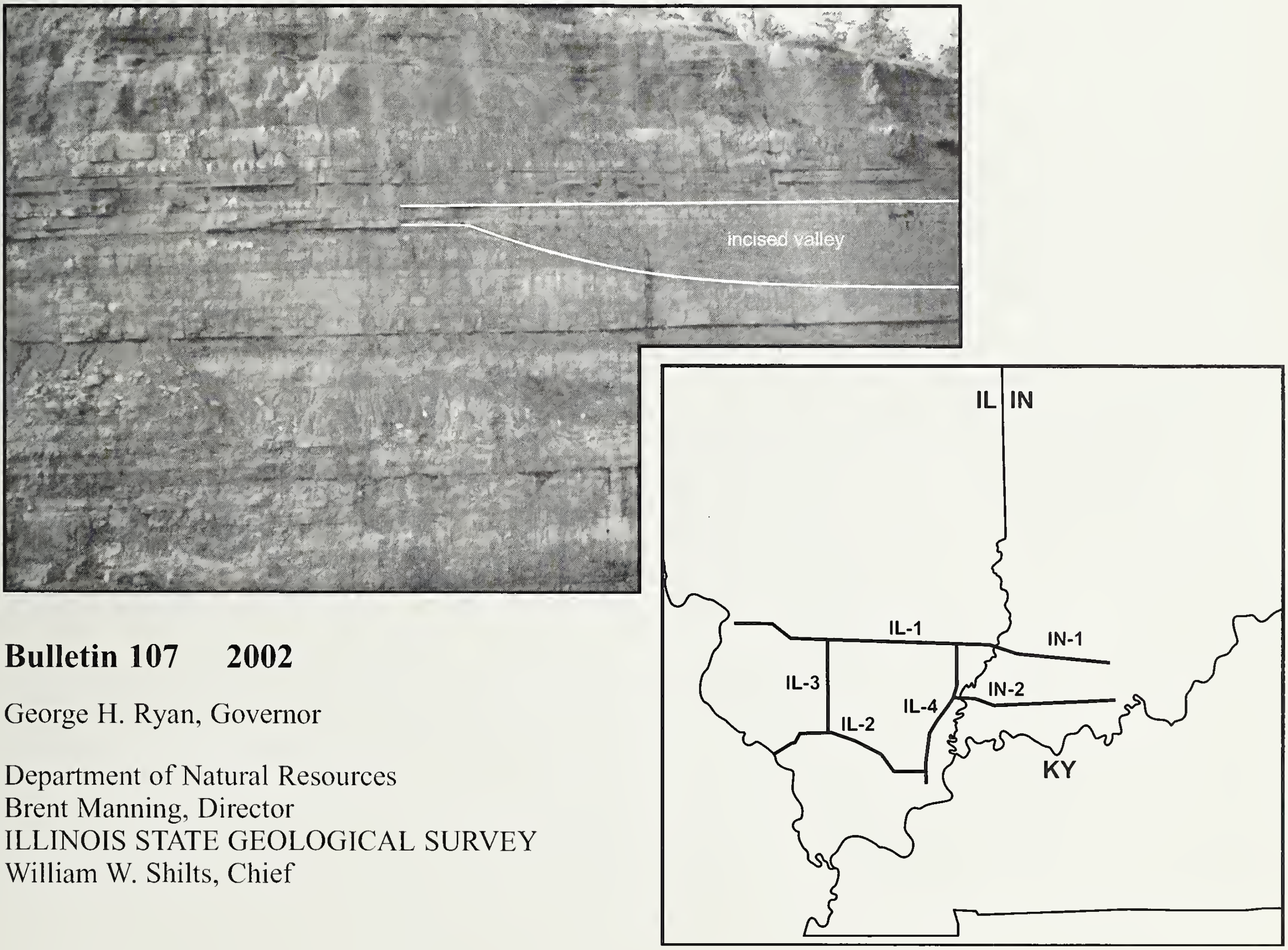

Bulletin 107 2002

George H. Ryan, Governor

Department of Natural Resources
Brent Manning, Director
ILLINOIS STATE GEOLOGICAL SURVEY
William W. Shilts, Chief

Dedication

This report is dedicated to the late Elwood Atherton (1909–2000), stratigrapher at the Illinois State Geological Survey from 1937 through 1983. Dr. Atherton was instrumental in developing the current classification of Chesterian rocks, mainly through interpretation of electric logs and well samples. In particular, he described in detail the samples from hundreds of wells penetrating Chesterian rocks throughout Illinois. These sample logs mention many features of great significance to sequences stratigraphy. Without Elwood Atherton's sample logs, our own report might never have been undertaken.

Front Cover Photo showing highwall of Cape Sandy quarry in Crawford County, Indiana. Map showing the locations of the cross sections in the Illinois Basin.

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ABSTRACT

A regional study of the Ste. Genevieve Limestone through the Glen Dean Limestone (lower Chesterian; Upper Mississippian) in the Illinois Basin was carried out using outcrop and borehole data. This interval of rocks is divided into eleven sequences that are bounded by unconformities. Sequence boundaries represent lowstands of the sea, during which all or most of the Illinois Basin was subjected to subaerial erosion, weathering, and soil formation. Some sequence boundaries are erosional unconformities marked by incised valleys as deep as 75 m. Others are not erosional but are distinguished by features such as carbonate breccias, caliche, eolian sediments, coal beds, rooted zones, and variegated mudstones. Most, but not all, erosional sequence boundaries are in the central part of the basin and are associated with sandstones. Non-erosional sequence boundaries are developed mostly on the bordering shelves and in carbonate sequences.

Lowstand deposits are seldom preserved; a few deep incised valleys contain fluvial sandstones interpreted as lowstand sediment. Transgressive deposits include estuarine valley fill and extensive subtidal carbonate and quartzose sands. Marine currents reworked these into sets of elongate bars aligned with the long axis of the basin. Highstand deposits include limestones that exhibit upward-shoaling facies and siliciclastic rocks that progress from shallow subtidal to tidal flat and marsh.

Most Chesterian siliciclastic units, including the Spar Mountain, Aux Vases, Bethel, Sample, Cypress, Big Clifty, and Hardinsburg Formations, are divided between two sequences. The older part of each unit represents highstand deposits of one sequence; the younger part comprises valley-filling lowstand and transgressive sediments of the following sequence.

The Illinois Basin area was a cratonic ramp during early Chesterian time. Relative subsidence rates of the central basin and shelves varied through time. Tectonic faults in the southern part of the basin were intermittently active, particularly the Wabash Valley Fault System and faults in the Rough Creek Graben and Reelfoot Rift. From Ste. Genevieve through Yankeetown deposition, the principal source of clastic sediment was the Transcontinental Arch, north and northwest of Illinois. The Bethel Sandstone and younger sandstones were derived chiefly from the northeast, except that the Big Clifty Sandstone apparently had a source in the southern Appalachians, east of the southern Illinois Basin.

Sequence stratigraphy can guide the search for oil and gas in these rocks, which account for three-fourths of cumulative production from the Illinois Basin. Oolite and quartz sand ridges are the leading types of reservoir; valley-fill sandstone provides reservoirs in several giant fields where structural closure is present.

INTRODUCTION

A series of cross sections based on outcrops and well records (plates 1 through 7) was used to correlate lower Chesterian strata (Ste. Genevieve Limestone through Glen Dean Limestone) of the Illinois Basin. Eleven depositional sequences, bounded by regional unconformities, were identified from this work. Sequence stratigraphy enables a better understanding of the distribution and geometry of thin units within the Chesterian, including oil and gas reservoir facies, and it also provides a framework for future regional and site-specific studies.

Method of Study

Outcrop Cross Sections

Outcrop study was conducted chiefly by Smith (1996), who measured 75 detailed sections around the rim of the Illinois Basin (figs. 1 and 2). Most sections were described at artificial exposures, such as quarries and road cuts, that provided 30 m or more of continuous vertical exposure. Surface sections were supplemented by continuous cores that were drilled close to the outcrop belt. Most of these are at least 100 m long; some encompass the entire Chesterian Series. Outcrop and core data were used to construct a series of cross sections (plate 1); the outcrops and cores that were used in these sections are listed in appendix 1.

Additional information on outcropping Chesterian rocks was gleaned by Nelson from geologic quadrangle maps (scale 1:24,000) from southern Illinois and western Kentucky. Stratigraphic columns on these maps are a storehouse of information on lithology, lateral relations of units, and paleontology. Two cross sections in western Kentucky were constructed on the basis of data from geologic quadrangle maps.

Subsurface Cross Sections

Nelson, Treworgy, Furer, and Keith constructed six regional cross sections (plates 2 through 7) using 364 well logs in southern Indiana and Illinois. Subsurface sections are tied to key cores and outcrops on outcrop sections (fig. 1). Wells used in subsurface sections are listed in appendix 2.

Subsurface sections are based mainly on wireline logs, most of which are electric logs. Gamma ray, density, and neutron logs are available for some wells and are especially useful in carbonate rocks. Where possible, we maintained an average well spacing of about 1 mile (1.6 km). For lithologic control, we sought wells for which sample studies by geologists had been made. Logs of samples are needed to identify many key features of sequences, including variegated mudstones, eolian limestones, caliches, and carbonate breccias. We tried to include at least one sample study per 6 linear miles of cross section, using samples on file at the Indiana Geological Survey and the Illinois State Geological Survey.

Geologic Setting

The Illinois Basin (also called Eastern Interior Basin) is an intracratonic basin that covers central and southern Illinois, southwestern Indiana, western Kentucky, and a small part of Missouri (figs. 3A and 4). The basin is bounded by the Ozark Dome on the west, Wisconsin Arch on the north, Kankakee Arch on the northeast, and Cincinnati Arch on the southeast (fig. 2). The southern end of the Illinois Basin is complexly faulted and overlapped by Cretaceous and younger sediments of the Mississippi Embayment.

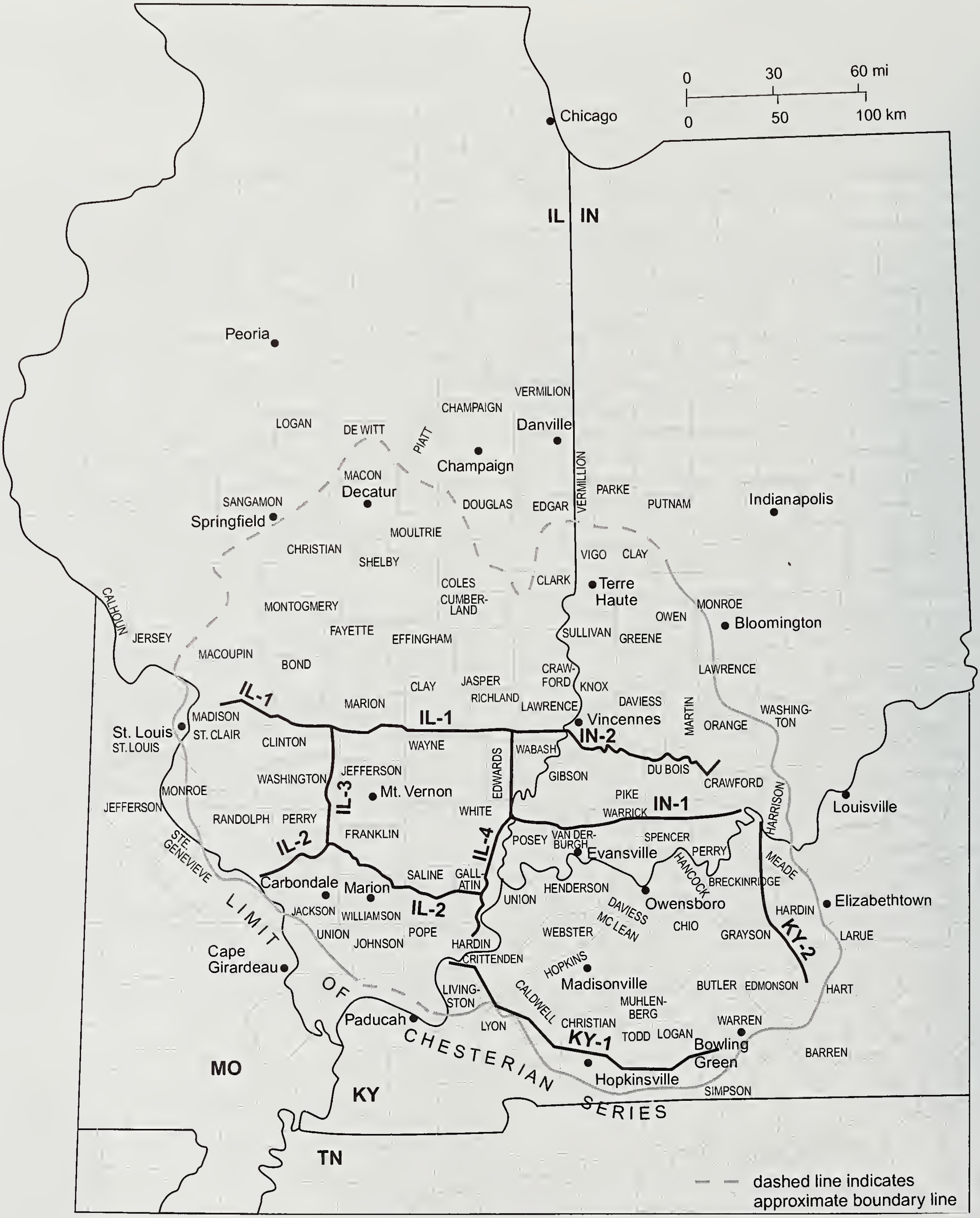


Figure 1 Location map showing counties and subsurface cross sections in the Illinois Basin.

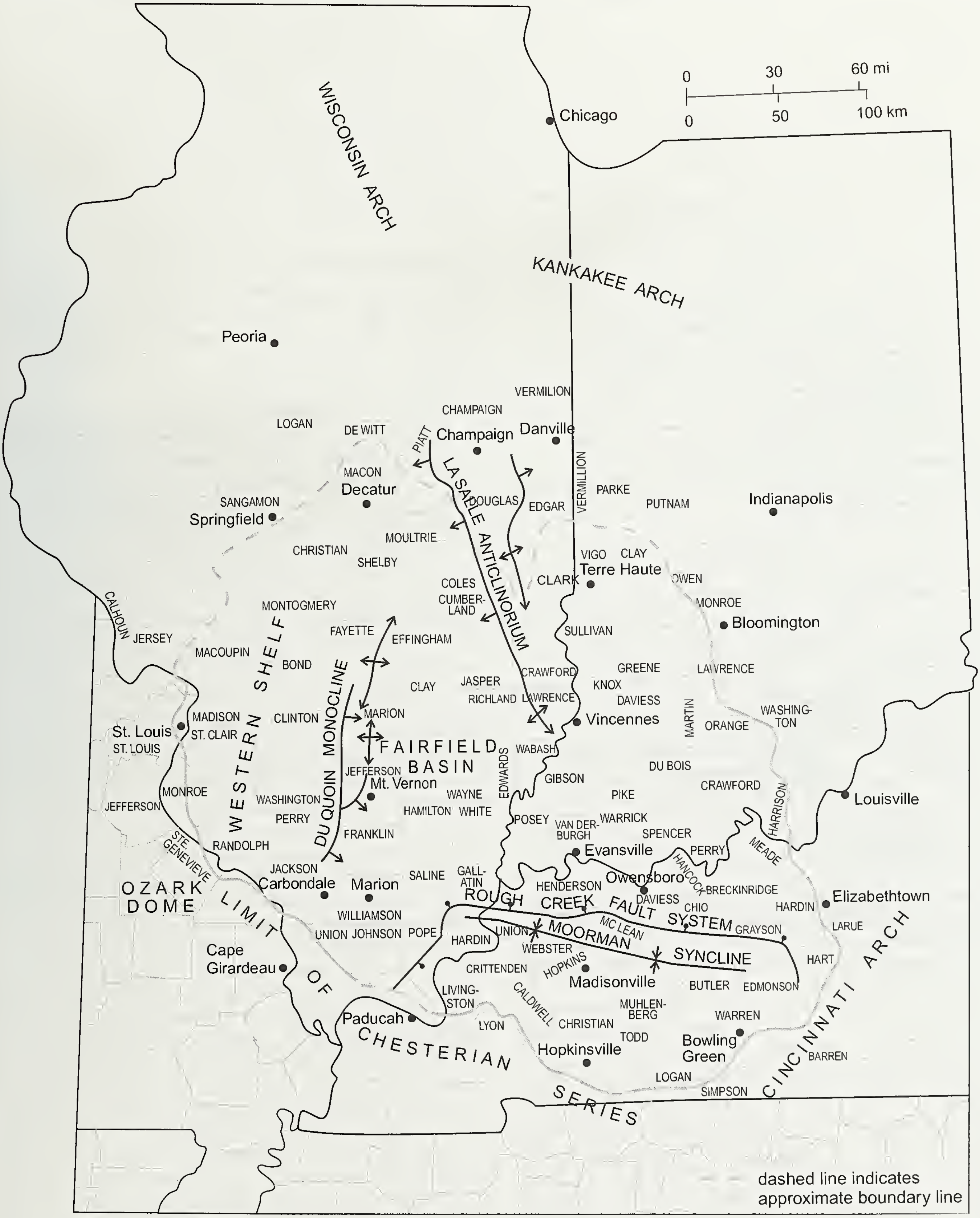


***Figure 2** Structural features map of the Illinois Basin.*

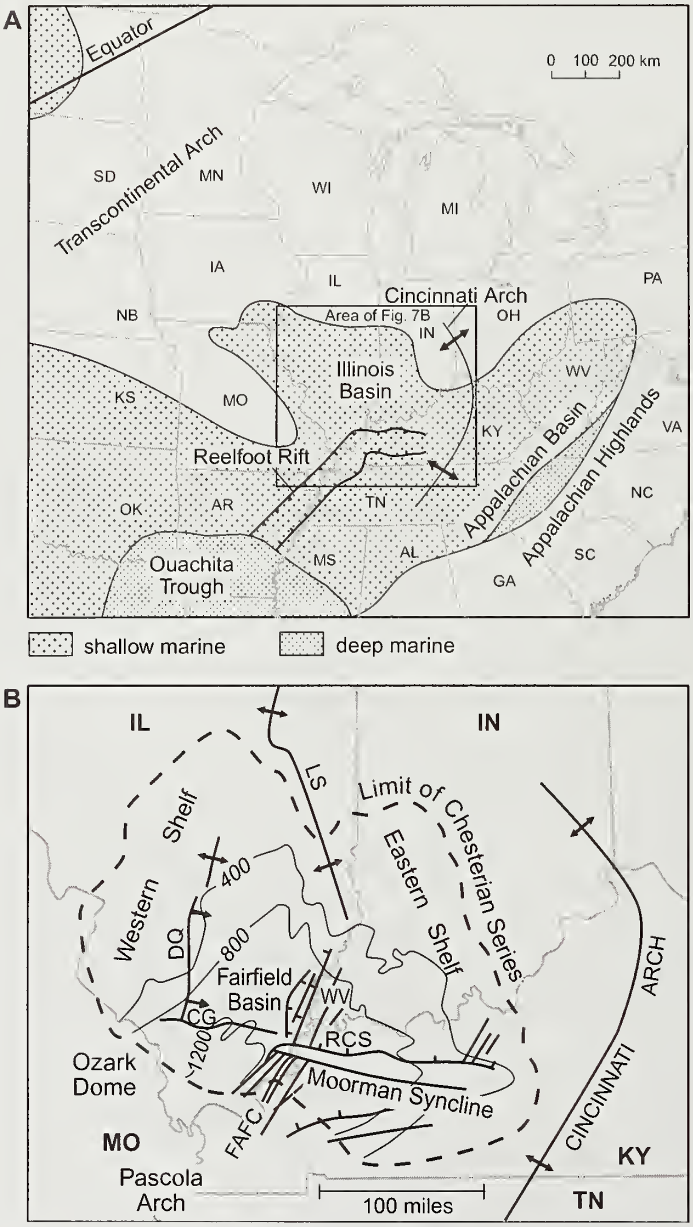


Figure 3 (A) Paleogeographic map, showing the regional setting of the Illinois Basin during Chesterian time (modified from Craig and Connor 1979). (B) Tectonic map of the Illinois Basin from the top of the Bethel Sandstone to the top of the Mississippian (modified from Swann 1963). CG = Cottage Grove Fault System, DQ = Du Quoin Monocline, FAFC = Fluorspar Area Fault Complex, LS = La Salle Anticlinorium, RCS = Rough Creek-Shawneetown Fault System, WV = Wabash Valley Fault System.

During the lower Chesterian (Mississippian), the Illinois Basin was an embayment open to the south, and was part of a carbonate ramp that extended from Virginia to New Mexico (fig. 3A). The southern margin was at the edge of the Ouachita Trough in Arkansas, at least 300 km southwest of the Illinois Basin. The Transcontinental Arch bordered the Illinois Basin on the north and northwest (Craig and Connor 1979). The Illinois Basin area apparently lay in the tropics between 5° and 15° south of the equator during the late Mississippian (Craig and Connor 1979, Scotese and McKerrow 1990).

At this time, the Eastern and Western Shelves were areas of slower subsidence compared with the shallow, but more rapidly subsiding basin interior. After Mississippian time, tectonic movements along the Rough Creek-Shawneetown Fault System partitioned the basin near its southern end (fig. 3B). The area north of the Rough Creek-Shawneetown Fault System became the Fairfield Basin, and the area south of the fault system became the Moorman Syncline. The Illinois Basin was closed off on the south by uplift of the Pascola Arch during the Mesozoic Era (Kolata and Nelson 1991).

Stratigraphic Nomenclature

Several changes to Chesterian stratigraphic nomenclature are proposed in this report. Previous nomenclature is shown in figure 4, and the nomenclature used in this report is shown in figure 5.

Chesterian Series

Like many chronostratigraphic (time-based) units, the Chesterian Series originally was a lithostratigraphic (rock-based) unit. Worthen (1860, 1866) named the Chester Group as an interval of alternating limestones, sandstones, and shales exposed near Chester, Illinois. Worthen's Chester Group extended from the base of the Aux Vases Sandstone to the top of the Mississippian System. The upper boundary has not changed, but the lower one still evokes controversy. E.O. Ulrich (1911, 1922) moved the lower boundary to the base of the Ste. Genevieve Limestone, where he observed a widespread unconformity and marked change in invertebrate fauna. Weller (1913, 1920) maintained the boundary at the base of the Aux Vases, which is a prominent unconformity on much of the Western Shelf. Swann (1963) revised the boundary upward to the top of the Bryantsville Breccia Bed, which coincides with highest occurrence of the crinoid *Platycrinites penicillus* and the lowest occurrence of *Talarocrinus* other than *T. simplex.* Swann's series boundary lies at the top of the Ste. Genevieve Limestone in Kentucky and Indiana and within the Renault Limestone in Illinois (fig. 4). Maples and Waters (1987) returned the series boundary to the base of the Ste. Genevieve, arguing that this contact is generally unconformable and coincides with faunal changes among conodonts, foraminifera, corals, and brachiopods. Brenckle et al. (1988) concurred strongly with the proposal of Maples and Waters (1987) to move the boundary downward but suggested that further study of the biotic changes near the proposed boundary were needed.

In this report, we formally accept the proposal of Maples and Waters (1987) to place the base of the Chesterian Series at the base of the Ste. Genevieve Limestone. Although further paleontological work may indeed be in order, the boundary suggested by Maples and Waters (1987), based on apparently coincident zone boundaries of several fossil groups, is more widely applicable than that of Swann, based on two taxa of crinoids. The boundary chosen by Swann (1963) is usable only in coarse-grained crinoidal limestones of the central and eastern United States. Even in the Illinois Basin, the key crinoids are absent from many outcrops, and there are reports of *P. penicillus* and *Talarocrinus* sp. occurring together (Sandberg and Bowles 1965; Robert D. Cole, personal communication 1992).

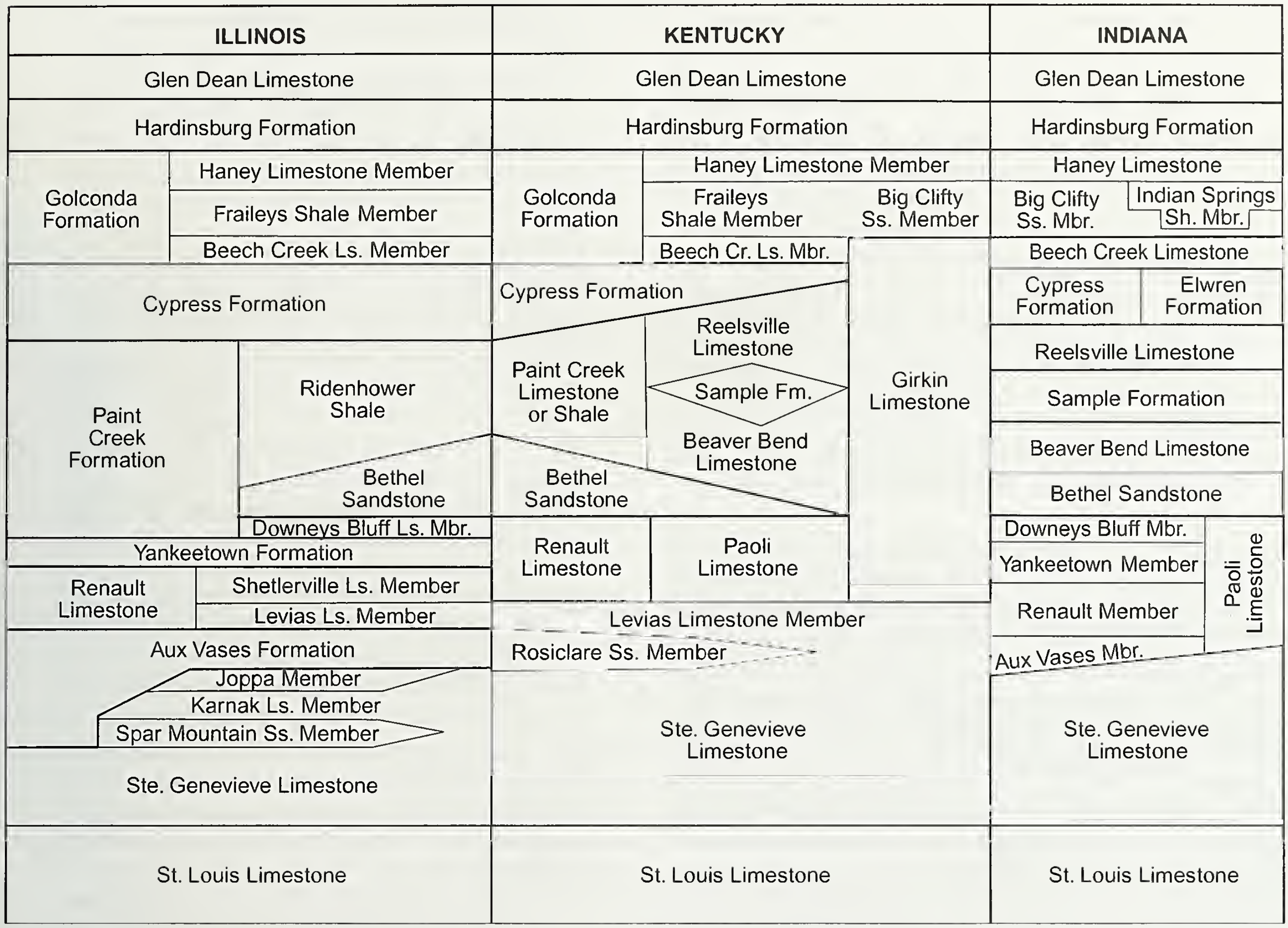


Figure 4 Stratigraphic nomenclature previously used for lower Chesterian rocks in Illinois (modified from Swann 1963), Indiana (from Shaver et al. 1986, Droste and Carpenter 1990), and western Kentucky (from geologic quadrangle maps).

Groups

Groups are lithostratigraphic units composed of two or more similar or closely related formations (NACSN 1983, Article 28). Middle and Upper Mississippian rocks of the Illinois Basin are divided into the Mammoth Cave Group (older) composed dominantly of limestone and the Pope Group composed of alternating sandstone/shale and limestone/shale formations (Swann and Willman 1961, Nelson 1995b). The boundary between the two groups steps upward to the east. In the western part of the Basin, the Mammoth Cave Group contains the Ste. Genevieve Limestone and several older limestone formations, whereas the Pope Group comprises the Aux Vases Formation and all younger Mississipian rocks. Eastward, the Aux Vases and several younger sandstone-shale units pinch out or grade to limestone. As each younger siliciclastic unit pinches out, the top of the Mammoth Cave Group steps upward, so that it continues to encompass the succession dominated by limestone. On the flank of the Cincinnati Arch, the Mammoth Cave/Pope contact rises to the base of the Big Clifty Sandstone (Swann and Willman 1961).

The pattern of Middle Mississippian limestone and Upper Mississippian mixed carbonates and clastics is found from Pennsylvania to Montana and from Alabama to Utah. Thus, the Mammoth Cave and Pope correspond closely with group divisions used across much of the North American craton. Other Mississippian group names applied in the Illinois Basin (e.g., those of Swann 1963 and Shaver et al. 1986) are not used in this report.

Formations

Chesterian rocks of the Illinois Basin are divided into many formations; their names, definitions, and boundaries change from one area to another (fig. 4). Some changes reflect miscorrelations enshrined by tradition; other changes reflect lateral facies variation, differing philosophies of stratigraphers, and provincialism in the state geological surveys. The resulting multitude of names can baffle even experienced stratigraphers. In an effort to achieve a more uniform, basin-wide classification that is in line with the North American Stratigraphic

Code (NACSN 1983, Article 24), we hereby propose the following changes:

- The Joppa Member of the Ste. Genevieve Limestone is abandoned because the unit is poorly defined and difficult to map.
- The Rosiclare Sandstone Member of the Aux Vases Formation is abandoned as a formal unit because the name Rosiclare is unnecessary and causes confusion between the Aux Vases and Spar Mountain Sandstones.
- The Aux Vases is classified as a formation overlying the Ste. Genevieve wherever the Aux Vases is thick enough to be mapped at the scale in use. In the eastern part of the basin, where the Aux Vases becomes too thin to map, it becomes a member of the Ste. Genevieve Limestone, and the top of the Ste. Genevieve steps up to the top of the Levias Limestone Member.

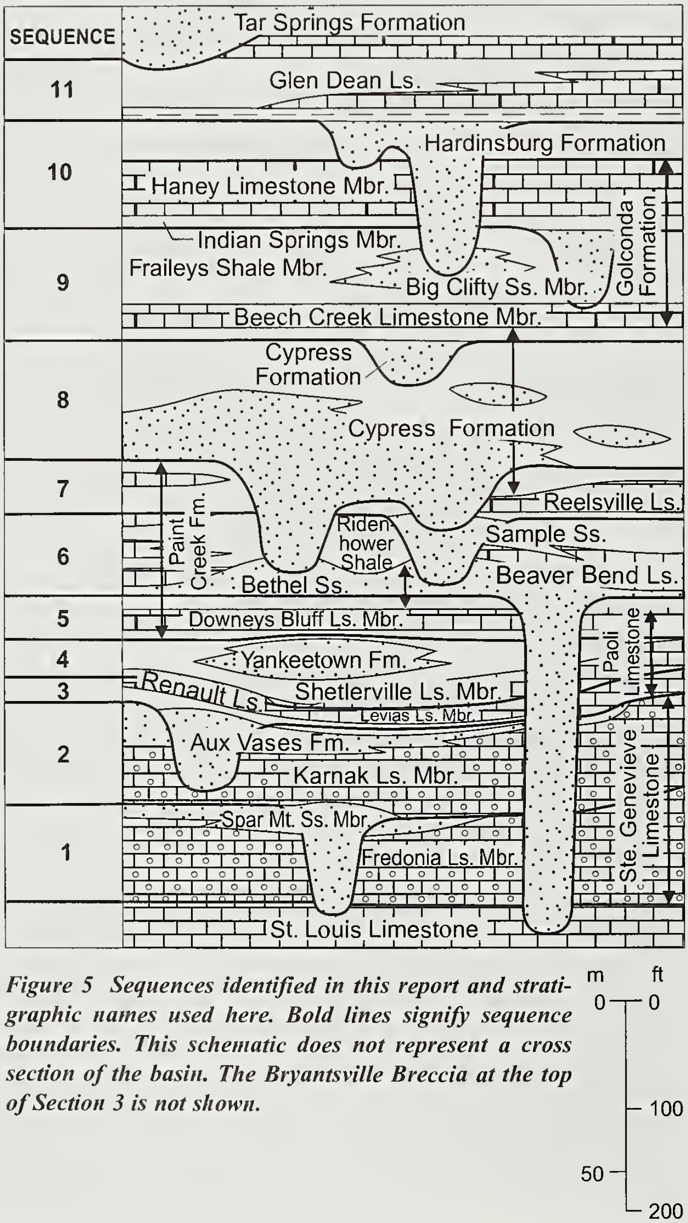


Figure 5 Sequences identified in this report and stratigraphic names used here. Bold lines signify sequence boundaries. This schematic does not represent a cross section of the basin. The Bryantsville Breccia at the top of Section 3 is not shown.

- The Renault Limestone is restricted to southwestern Illinois.
- The Paoli Limestone is extended into southeastern Illinois and most of western Kentucky and is redefined slightly. In areas where the Aux Vases can be mapped as a formation, the Paoli comprises the Levias Limestone (oldest), Shetlerville Limestone, Yankeetown, and Downeys Bluff Limestone Members. In areas where the Aux Vases and Levias are members of the Ste. Genevieve, the Paoli contains the Shetlerville, Yankeetown, and Downeys Bluff Members only.
- The Yankeetown is classified as a formation on the Western Shelf and in the western part of the Fairfield Basin where it contains thick, mappable sandstone bodies. Elsewhere, the Yankeetown is a member of the Paoli Limestone.
- The Downeys Bluff Limestone is the uppermost member of the Paoli Limestone in Indiana, western Kentucky, and eastern Illinois. In western Illinois, the Downeys Bluff is the basal member of the Paint Creek Formation. However, in some areas of Illinois, the Downeys Bluff may be classified as a formation where this unit overlies well-developed Yankeetown Formation (sandstone) and underlies thick Ridenhower Shale.
- The Bethel Sandstone is a formation throughout Indiana and western Kentucky and in areas of Illinois where the sandstone is thick and continuous enough to be mappable. In areas of western Illinois where the sandstone is thin and lenticular, the Bethel becomes a member of the Paint Creek Formation. The name Mooretown Sandstone is abandoned because the Mooretown and Bethel are correlative, and the name Bethel has priority.
- The name Ridenhower Formation (or Shale) is restricted to areas where shale is the dominant rock type constituting the interval between the Bethel Sandstone (or Downeys Bluff Limestone, where the Bethel is absent) and the Cypress Sandstone. The Ridenhower may contain thin limestone and sandstone beds, but these are discontinuous and not readily correlated with named units. The Ridenhower occurs mainly in southern to south-central Illinois.
- The Paint Creek Formation is restricted to the Western Shelf in Illinois and consists of interbedded limestone, shale, mudstone, and thin sandstone. The Paint Creek is laterally equivalent to the Ridenhower Shale plus Downeys Bluff Limestone. Limestone is a significant component of the Paint Creek, whereas shale is prevalent in the Ridenhower. The name Paint Creek should not be used in Kentucky. There, strata previously called Paint Creek are correlative to only the upper part of the type Paint Creek in western Illinois.
- The Beaver Bend Limestone, Sample Formation, and Reelsville Limestone are formations in Indiana,

Kentucky, and eastern Illinois where they are mappable. Elsewhere in Illinois, these units may be classified as members of either the Ridenhower or the Paint Creek Formation.

- The Elwren Formation (in Indiana) is abandoned because the unit is identical to the Cypress Formation, which name has priority.
- The Golconda Formation is extended throughout the Illinois Basin and contains the following members, in ascending order: Beech Creek Limestone, Big Clifty Sandstone, Fraileys Shale, Indian Springs Member, and Haney Limestone. The Fraileys and Big Clifty are facies equivalents, although they occur together in places.
- The Indian Springs Member of the Golconda Formation is redefined to include only marine shale and limestone, excluding the underlying variegated mudstone, which is part of the Fraileys or Big Clifty Member.

These changes are illustrated in figures 4 and 5 and are explained in greater detail in the next section.

SEQUENCE STRATIGRAPHY

What Are Sequences?

Sloss et al. (1949) first used the term "sequence" to designate stratigraphic units bounded by unconformities. The sequences they named are very large packages of rock, separated by unconformities that extend across most of the North American craton. These sequences—called "megasequences" or "supersequences" today—are useful in providing regional overviews (e.g., Leighton et al. 1991).

During the 1970s, a group of geologists working at Exxon Corporation began to apply a form of stratigraphy that recognizes sequences that are much thinner than those named by Sloss et al. (1949). A series of papers written by this group (Payton 1977) introduced the modern concept of sequence stratigraphy. Among the main ideas they proposed are these:

- Unconformities that bound sequences are time-equivalent and controlled by global changes in sea level.
- Several orders of cyclicity were defined, the supersequences of Sloss et al. (1949) being the largest.
- Sequence boundaries that are unconformable on shelves and basin margins become conformable in basin interiors.

Authors in the volume edited by Payton (1977) applied sequence stratigraphy to sedimentary rocks of various geologic ages in many parts of the world. Most of their examples, however, were drawn from deep, rapidly subsiding oceanic and foreland basins in such places as the Gulf Coast, west Texas, offshore West Africa, and the Rocky Mountain foreland. In such areas, sequence stratigraphy gemerally can be interpreted from seismic reflection data. Application of sequence stratigraphy to interior cratonic basins has been slow. Methods and concepts used in deep basins must be modified; because most cratonic sequences are too thin to be resolved on seismic profiles, detailed analysis of cores and outcrops is required.

As used herein, a "sequence" is defined as a succession of strata lacking apparent internal unconformities and bounded by unconformities or their "correlative conformities" (Mitchum and Van Wagoner 1991). The unconformities that bound sequences are regional in extent and therefore are interpreted to reflect global, or eustatic, changes of sea level. Such eustatic changes may be induced by tectonic movements within ocean basins, but cycles of continental glaciation are believed to be the principal cause. Sea level rises when glaciers melt and falls when glaciers grow. Glacial episodes in turn are controlled by changes in global climate. Glacial deposits are known in Mississippian rocks from other parts of the world (Hambrey and Harland 1981, Caputo and Crowell 1985, Ross and Ross 1988).

Why Study Sequences?

Modern sequence stratigraphy is used as a tool to identify hydrocarbon reservoirs in thick, repetitive sedimentary successions where traditional stratigraphic methods fail. The need for new stratigraphic techniques is less obvious in the Illinois Basin, where regionally continuous units such as the Glen Dean and Beech Creek (Barlow) Limestones serve as markers. Nevertheless, sequence concepts have practical use in petroleum exploration in the Illinois Basin. Many sequence boundaries are excellent through-going markers that aid in high-resolution correlation of reservoir facies. For example, red or variegated mudstones, which are easily identified in well cuttings, mark several Chesterian sequence boundaries. Sequence stratigraphy also facilitates interpretation of depositional models and reservoir geometry. Different reservoir models should be applied to transgressive valley fills, transgressive tidal sand ridges, and highstand tidal delta and tidal flat sandstones. Each of these reservoir types occurs at specific positions within a sequence.

Sequence stratigraphy also enhances correlation and clears up inconsistent nomenclature. For example, our study cleared up the consistent miscorrelation of the Aux Vases Sandstone with the Popcorn Sandstone. Sequence stratigraphy also provides a tool to differentiate effects of tectonics, eustasy, climate, and tidal action. For example, this study shows that the Wabash Valley Fault System was active during early Chesterian time, influencing distribution of sand bodies in the Hardinsburg Formation. This fault system previously was regarded as post-Pennsylvanian. The new finding has implications for regional tectonic history and for petroleum exploration.

Identifying Sequence Boundaries

By definition, sequence boundaries are regional. Those recognized in this study extend throughout the Illinois Basin and may reach into adjacent basins. Sequence boundaries should be identifiable wherever good data, such as an outcrop or core, are available. Sequence boundaries formed during lowstands of the sea, when the sediment surface was exposed to the air. Simultaneously, incised valleys were cut while weathering and soil profiles (paleosols) developed on the interfluves. Local erosional surfaces, such as those cut by tidal or deltaic channels, are not associated with paleosols and are not sequence boundaries. Complications occur where local erosional surfaces truncate lowstand sequence boundaries. In such cases, both surfaces must be traced laterally to determine their true nature.

Sequence boundaries are not unconformable everywhere. A basin that subsides rapidly enough is not completely drained during lowstand. The resulting sequence boundary thus is an unconformity around the margins of the basin and a "correlative conformity" in the basin interior. Sedimentary features and fossils may provide evidence of shallowing at the correlative conformity, but such features are not always present.

During the Chesterian Epoch, the Illinois Basin was a shallow cratonic ramp or platform rather than a true basin. Depths below storm-wave base were rarely, if ever, achieved. As a consequence, most Chesterian sequence boundaries are unconformities throughout the basin. An apparent exception is the boundary at the base of Sequence 1, near the base of the Ste. Genevieve Limestone. This contact appears conformable in much of the basin interior; however, few definitive records (such as cores) are available.

Two types of sequence-bounding unconformities are present in the Chesterian of the Illinois Basin (fig. 6). Erosional unconformities are characterized by both subaerial exposure and incision of valleys. Non-erosional unconformities record subaerial exposure without valley cutting and are marked by paleosols.

Incised Valleys

When sea level drops, rivers incise valleys into their coastal plains. Initial deposition of fluvial sediments, largely sand, takes place during this lowstand. Upon transgression, the valley becomes an estuary and rapidly fills with sediments that record tidal action and brackish waters. Thus, incised valleys (fig. 6) typically contain coarse fluvial sandstones in the lower part, overlain by finer grained rocks that show increasing tidal influence upward (Dalrymple et al. 1994, Zaitlin et al. 1994a, b).

Incised valleys can be confused with local tidal and fluvial channels. The surest way to identify an incised valley is to trace its lower bounding unconformity laterally into a paleosol. An excellent Chesterian example is from the Cape Sandy Quarry in Crawford County, Indiana (fig. 7). In Pit 1, the Sample Formation grades from marine shale at the base through nearshore siltstone and sandstone to a paleosol of variegated blocky mudstone at the top. Nearby in Pit 2, a sandstone-filled channel cuts downward from the position of the paleosol, removing the entire marine portion of the Sample Formation and part of the underlying Beaver Bend Limestone. Many other examples of incised valleys that correlate to paleosols are shown on the regional cross sections that accompany this report (plates 1 through 7).

Incised valleys are commonly much wider and deeper than channels formed by other mechanisms. Valley systems of the Cypress (Sequence 8) and Hardinsburg (Sequence 11) are tens of kilometers wide. Such "clastic belts" probably represent major trunk streams of braided river systems. A long period of erosion is required to account for such wide valleys. A paleovalley filled by the Bethel Sandstone (Sequence 6) in western Kentucky is incised up to 75 m into underlying limestone. Incised valleys of the Cypress (Sequence 8) and Hardinsburg (Sequence 11) Formations are as deep as 60 m and 50 m, respectively. These and other Chesterian incised valleys cut entirely through their parent formations into underlying units. Such deep erosion generally does not occur in tidal or deltaic distributary channels, which are eroded at or slightly below mean sea level. More criteria for distinguishing incised valleys from distributary channels are presented by Van Wagoner et al. (1992, p. 36–37).

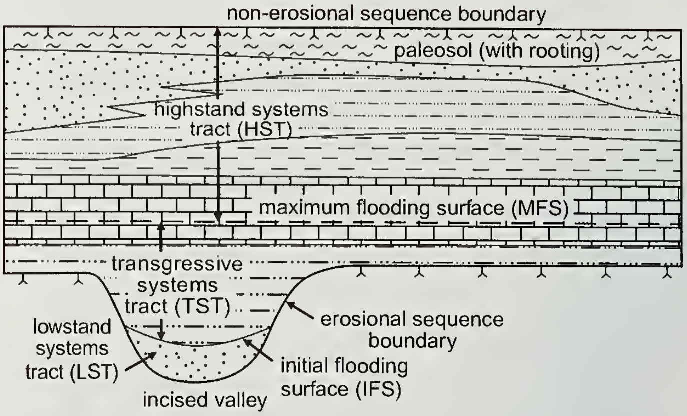


Figure 6 Diagram of idealized Chesterian sequence, showing sequence boundaries, systems tracts, and flooding surfaces.

Paleosols

Paleosols, or ancient soils, developed during periods of subaerial exposure or in very shallow water (as in swamps). Any kind of sediment can provide the parent material. Chesterian paleosols developed in limestones, sandstones, siltstones, shales, and mudstones that were deposited in a variety of environments. The soil-forming process (pedogenesis) introduces many changes through the effects of weathering, repeated wetting and drying, growing plants, and burrowing animals.

Paleosols in mudstones are easily recognized. Original lamination is disrupted or destroyed, and a blocky structure prevails. Abundant small slickensides attest to repeated shrinkage and swelling of clays. Coalified roots or root casts are commonly present, as are pedogenic nodules of calcite, dolomite, and siderite. Such nodules are highly irregular and internally brecciated, unlike the regular lenses and bands of the same minerals that occur in water-laid sediments. Colors depend on whether conditions were oxidizing (red, ochre, purple) or reducing (green, brown, olive-gray).

Quartz is less readily altered than clay during pedogenesis, so paleosols in siltstone and sandstone tend to be less obvious than those in mudstone. Root casts or traces, lined with dark clay and disrupting bedding, generally are the best indicators. Prolonged weathering under alkaline conditions may convert

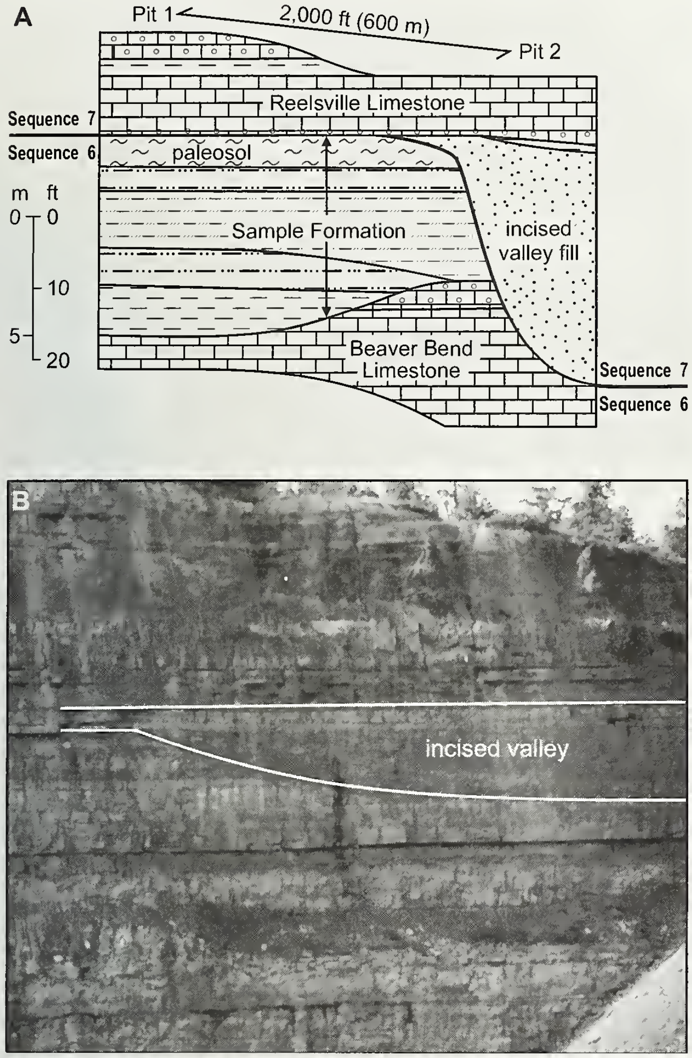


Figure 7 (A) An incised valley: the Sample Formation at the Cape Sandy Quarry in Crawford County, Indiana (modified from Ambers and Petzold 1992). In Pit 1 (left), the boundary between Sequences 6 and 7 is marked by a paleosol at the top of the Sample Formation. In Pit 2 (right), a sandstone-filled incised valley cuts down from the level of the paleosol. The base of the valley-fill deposit represents the sequence boundary. (B) The highwall of the Cape Sandy Quarry, showing an incised valley filled with sandstone in the Sample Formation. The height of the quarry wall is approximately 150 feet.

sandstone to chertlike silcrete or gannister, such as in the Yankeetown "chert" (Sequence 4) in southwestern Illinois.

Limestone paleosols feature pedogenic breccias, caliche, and quartz-peloid packstone. In pedogenic breccias, angular to subrounded limestone and chert clasts form fitted fabrics, and fractures are filled with sparry calcite or muddy sediment (fig. 8F). Thick laminar caliche and silicified limestone commonly occur. Caliche is gray to brown, crinkly laminated to massive, micritic calcite that commonly contains root casts filled with sparry calcite (Walls et al. 1975, Liebold 1982, Ettensohn et al. 1988). Caliche forms laminated mats as thick as 30 cm beneath unconformities (fig. 8E and 9). Caliche also coats grains and lines bedding planes and fractures as far as 4 m below unconformities. Other features of carbonate paleosols are "tepee structures" up to 1 m wide and 30 cm high. The Bryantsville Breccia Bed at the top of Sequence 3 is the outstanding example of a carbonate paleosol (fig. 10).

Eolian Limestone

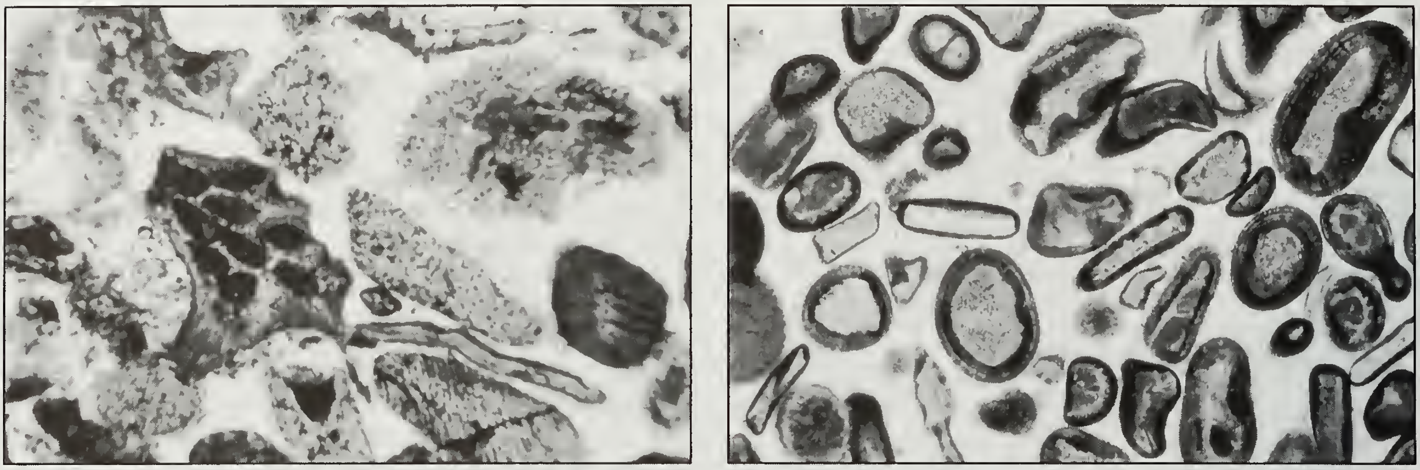
Recent studies (Hunter 1993, Dodd et al. 1993) indicate that some Chesterian limestones in the Illinois Basin are of eolian (wind-blown) origin. The characteristic rock type is quartz-peloid grainstone: a mixture of rounded peloids, broken oolites, and subangular quartz sand grains cemented by sparry calcite (fig. 8D). The grains are well sorted and very fine to fine. Large fossil fragments, presumably too heavy to be carried by the wind, are conspicuously absent. Sedimentary structures include razor-sharp laminae, inversely graded bedding (fig. 11), very thick cross-bed sets with preserved barchan dune crests (fig. 12), root traces (fig. 13), mud cracks (fig. 14), and sets of unusually low-angle (5° to 25° dips) cross-bedding that alternate with beds having nearly horizontal (dips 5) parallel lamination.

Eolian limestone occurs in lenses as thick as 6 m in the Ste. Genevieve Limestone and Aux Vases Formation (Sequences 1 and 2) and in the Downeys Bluff Limestone (Sequence 5). Most reported occurrences are on the Eastern Shelf, but we observed eolian limestone in the southern Fairfield Basin also. Eolian limestone also has been identified in Chesterian rocks of Kansas (Abegg 1994) and the central Appalachian Basin (Al-Tawil and Read 1996). As an indicator of subaerial exposure, eolian limestone is a guide to regressions, lowstands, and sequence boundaries. Eolian limestone generally occurs at or near the tops of sequences in close association with paleosols. However, eolian limestone also occurs above sequence boundaries, especially in the Downeys Bluff (Sequence 5). Such findings supplement other evidence that Chesterian seas were very shallow, even at highstand.

Parasequences

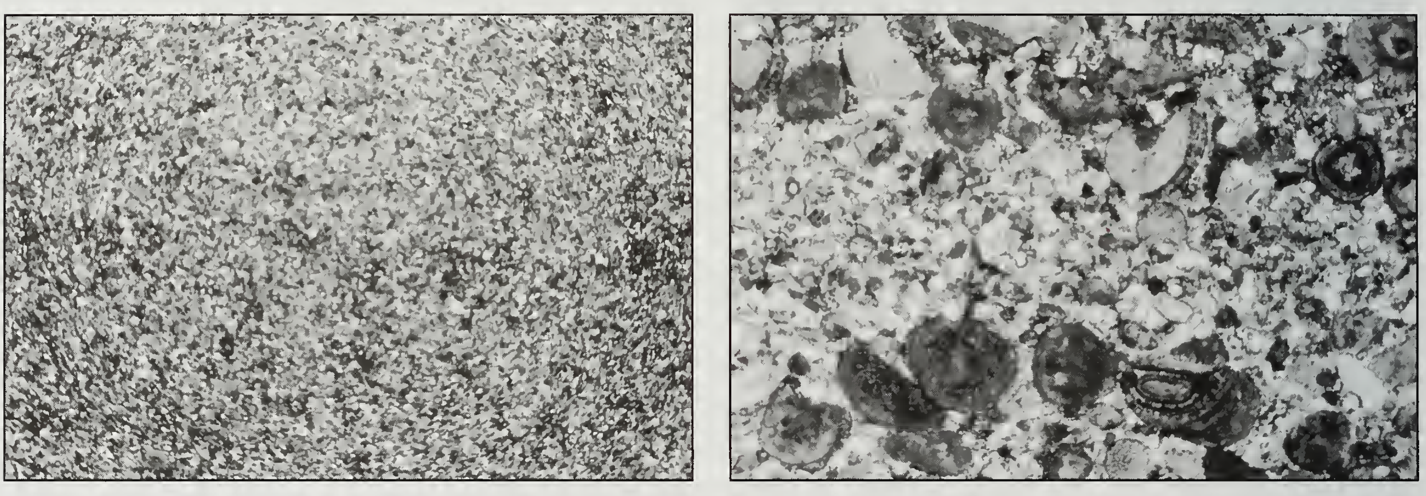
A parasequence is defined as a "relatively conformable succession of beds . . . bounded by marine flooding surfaces and their correlative surfaces" (Mitchum and Van Wagoner 1991, p. 8). A marine flooding surface is a bedding surface that records the onset of transgression. Typically a sharp contact, the surface may record scouring by marine waves and currents.

The parasequence is the smallest unit in sequence stratigraphy. A sequence may contain several parasequences. Facies within parasequences commonly imply an abrupt or rapid transgression, followed by gradual shoaling or regression. Parasequences are similar to "punctuated aggradational cycles" (PACs) described by Goodwin and Anderson (1985) and Mitchum and Van Wagoner (1991). Like sequences, parasequences are regionally extensive, being interpreted as products of eustatic events of higher frequency and lower amplitude than those that produced sequences. These events may have produced brief subaerial exposure and erosion along the basin margins, but not in the basin interior. Hence, parasequence boundaries commonly are not marked by incised valleys or paleosols, as sequence boundaries are.



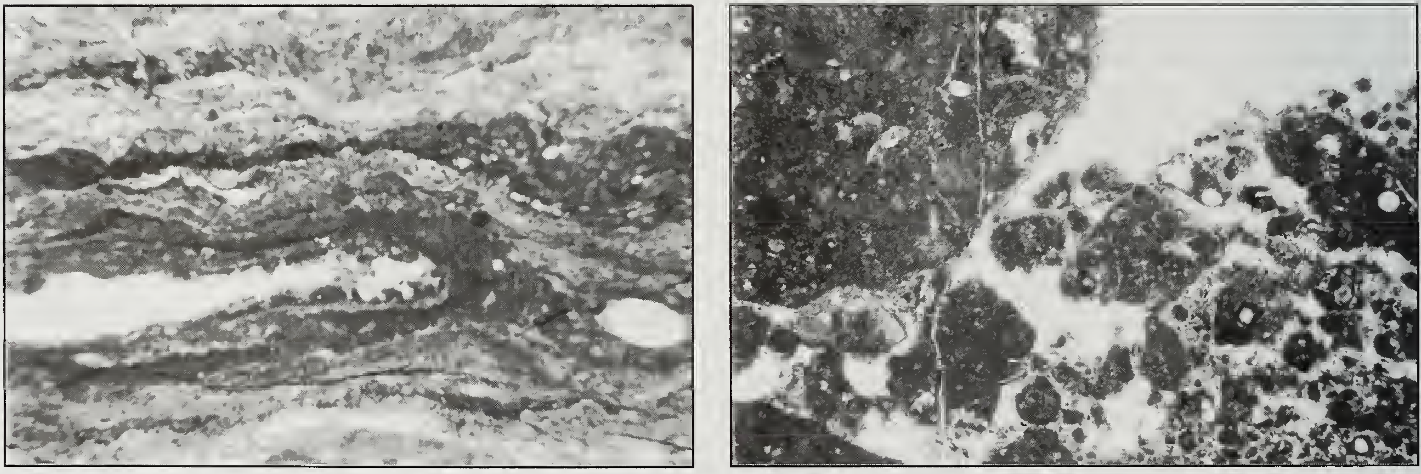
A Skeletal grainstone, composed of fossil fragments such as echinoderms, bryozoans *(left of center)*, and brachiopods *(right of center)*, cemented by clear, sparry calcite.

B Oolitic grainstone, composed of rounded fossil grains that are coated with lime mudstone and cemented by sparry calcite.



C Microcrystalline dolomite, a uniformly textured rock composed of silt-sized dolomite crystals or grains.

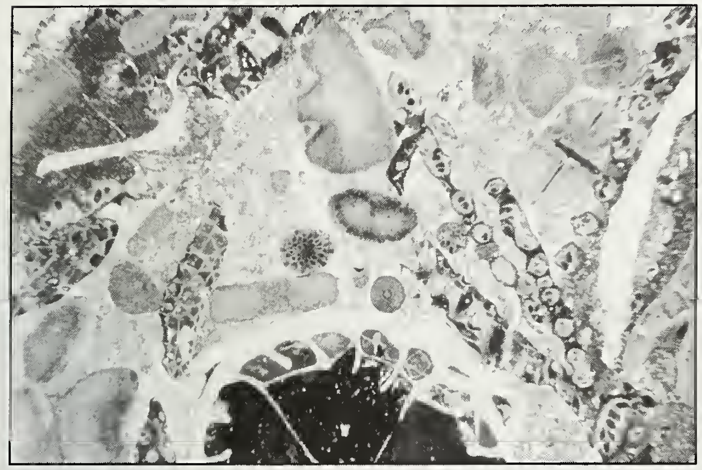
D Quartz-peloid grainstone, a mixture of sand-sized fossil grains, peloids (spheroids of lime mud), and quartz sand, cemented by sparry calcite. Commonly interpreted as eolian.



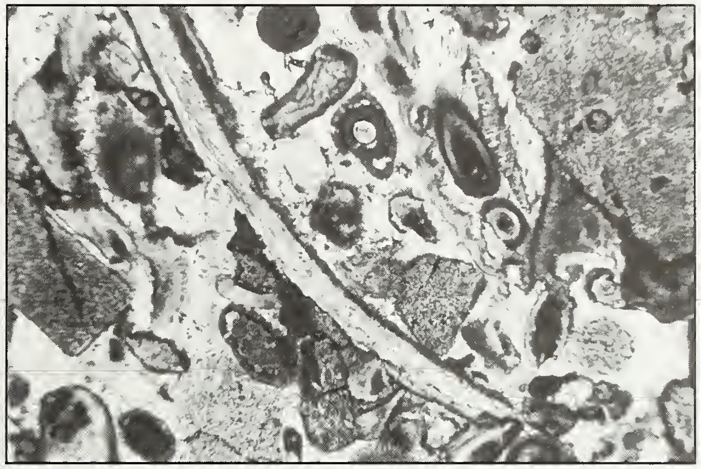
E Caliche, irregular laminae of silty, argillaceous lime mudstone, commonly having voids between the layers; a product of soil formation under semi-arid conditions.

F Breccia, angular fragments of fossiliferous lime mudstone cemented by sparry calcite and interpreted to be of pedogenic origin.

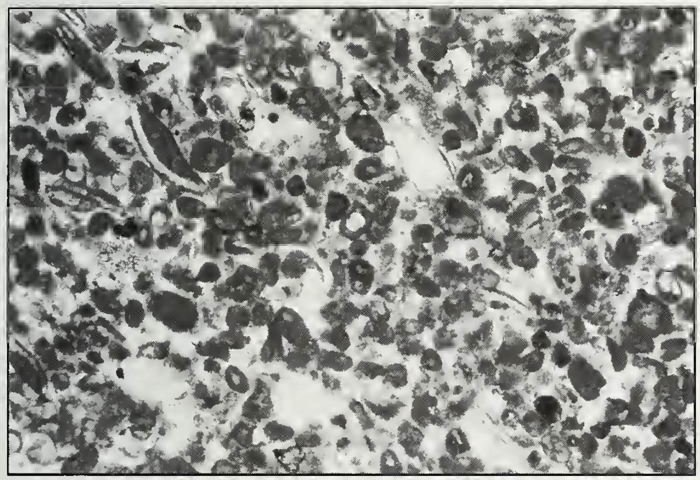
***Figure 8** Photomicrographs of Chesterian rock types: (A) skeletal grainstone, (B) oolitic grainstone, (C) microcrystalline dolomite, (D) quartz-peloid grainstone, (E) caliche, (F) breccia, (G) skeletal packstone, (H) skeletal packstone, (I) peloidal-skeletal packstone, (J) skeletal wackestone, (K) lime mudstone, (L) quartz sandstone. Scale is the same for all photographs.*



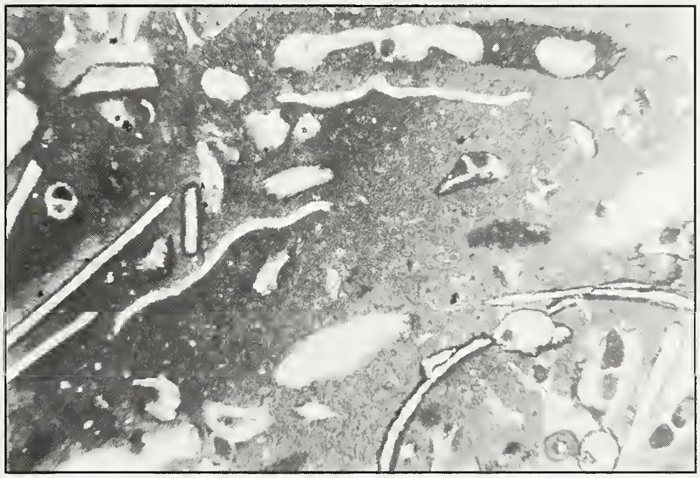
G Skeletal packstone, the fossils include a rugose coral *(bottom center)*, echinoderm fragments (uniform gray color), and bryozoan fragments. The matrix is lime mudstone.



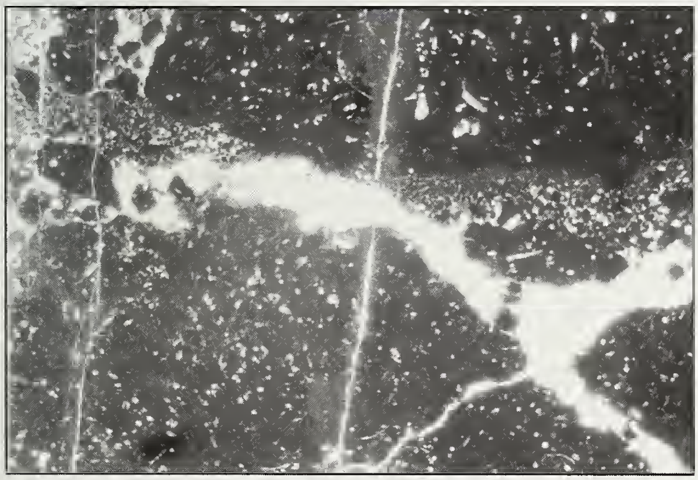
H Skeletal packstone, with echinoderm and bryozoan fragments and a large piece of a brachiopod shell.



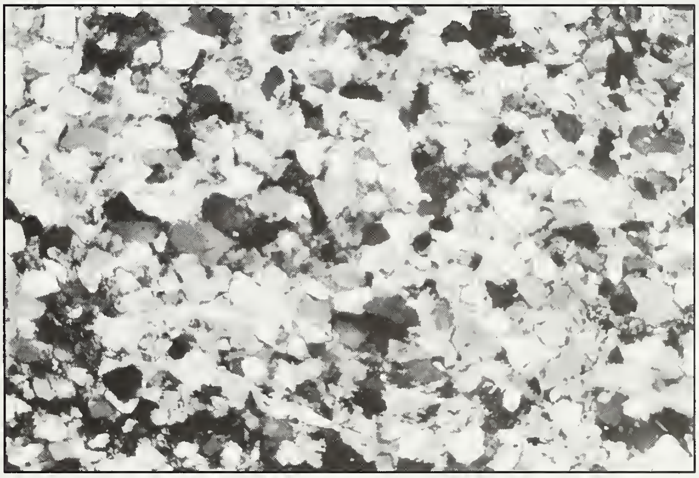
I Peloidal-skeletal packstone, fossils are mainly ostracods (small shells) and echinoderm pieces.



J Skeletal wackestone, the fossil grains float in a matrix of lime mudstone.



K Lime mudstone, containing scattered silt-sized quartz grains and fossil fragments. Clear areas are fractures.



L Quartz sandstone, fine-grained and well-sorted.

Figure 9 Caliche in the Ste. Genevieve Limestone at the South Hopkinsville Quarry in Christian County, Kentucky (outcrop section 22). Pencil for scale.

Among 9 sequences from the Ste. Genevieve through the Glen Dean Limestone (plate 1), Smith (1996) identified 45 parasequences. According to Smith, parasequences in the Paoli Limestone and older strata typically contain oolitic and skeletal grainstone in the lower part and micritic limestone or fossiliferous shale in the upper part. Some parasequences have eolian beds at top and base, and/or a rare basal micritic limestone. Smith (1996) characterized two types of parasequences above the Paoli. One type has sandy beds in the lower part and limestone and shale in the upper part; the other type has skeletal limestone overlain by shale.

Parasequences are not emphasized in this report because the limited database precludes confidently recognizing them, particularly in the subsurface. Many thin cyclic intervals may be products of autogenic processes, such as lateral shifting of delta lobes, crevasse splays, and tidal channels. Intensive study of closely spaced, high-resolution data, such as cores, is required to verify whether small Chesterian cyclic units are parasequences.

Flooding Surfaces and Systems Tracts

Flooding surfaces are bedding surfaces that represent significant events of a eustatic cycle. The initial flooding surface (IFS) marks the onset of transgression (fig. 6). Hence, it is a surface on which marine rocks overlie non-marine rocks. The IFS commonly is a minor unconformity, overlain by a thin conglomerate produced when ocean waves scoured the land. In some cases, substantial submarine erosion took place at the IFS, which may be called a "ravinement surface." The maximum flooding surface (MFS) defines the high-water mark of a transgression. To locate the MFS, one searches for deposits that represent the deepest water. In deep basins, maximum flooding often induced sediment-starved conditions under which a "condensed section" of black, phosphatic shale was deposited. During Chesterian time, the Illinois Basin generally was not deep enough to form condensed sections, and the MFS commonly lies within a dark gray shale or dark, micritic limestone.

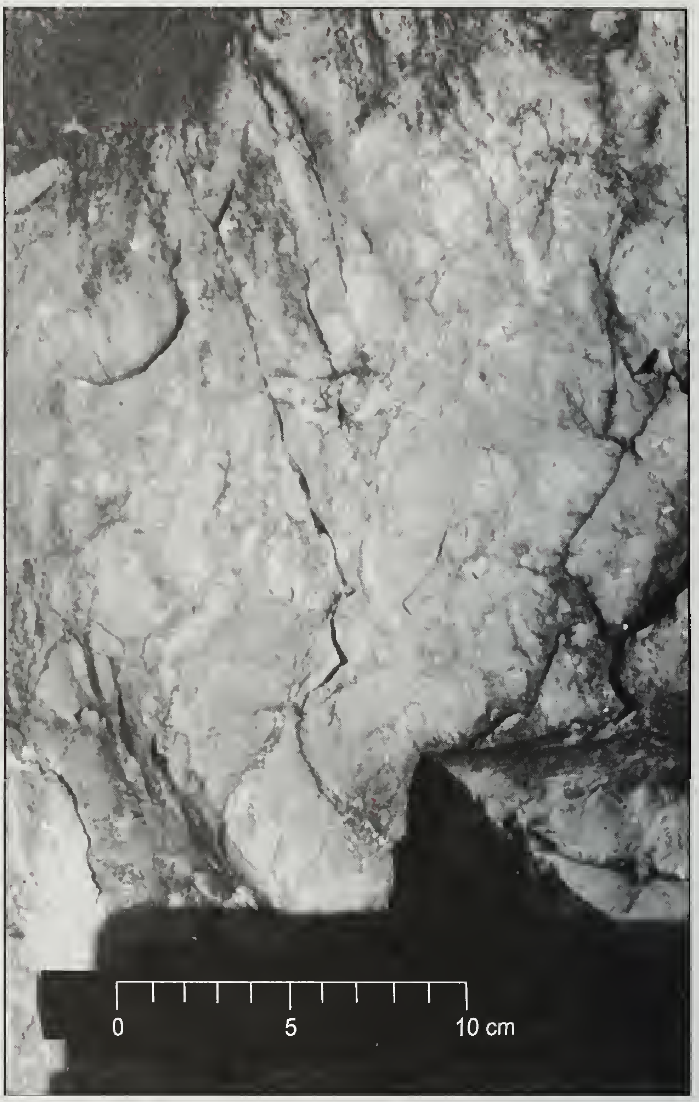


Figure 10 The Bryantsville Breccia Bed, a pedogenic breccia at the top of the Levias Limestone (Sequence 3). Location is the Mitchell Quarry, Lawrence County, Indiana (outcrop section 64). This photograph is a vertical surface with the top of bedding at the top of the photograph.

Systems tracts are packages of strata bounded by flooding surfaces (Vail 1987, Van Wagoner et al. 1992). Theoretically, each sequence should contain three systems tracts. The lowstand systems tract (LST) comprises sediments deposited during low sea level. The LST is bounded by the lower sequence boundary below and the IFS above (fig. 6). Because the Illinois Basin was so shallow, LSTs are poorly represented here. The basin area was largely dry land during lowstands, and rivers carried nearly all of the sediment through the region toward the Ouachita trough. Some fluvial sediment, largely sand, was deposited in

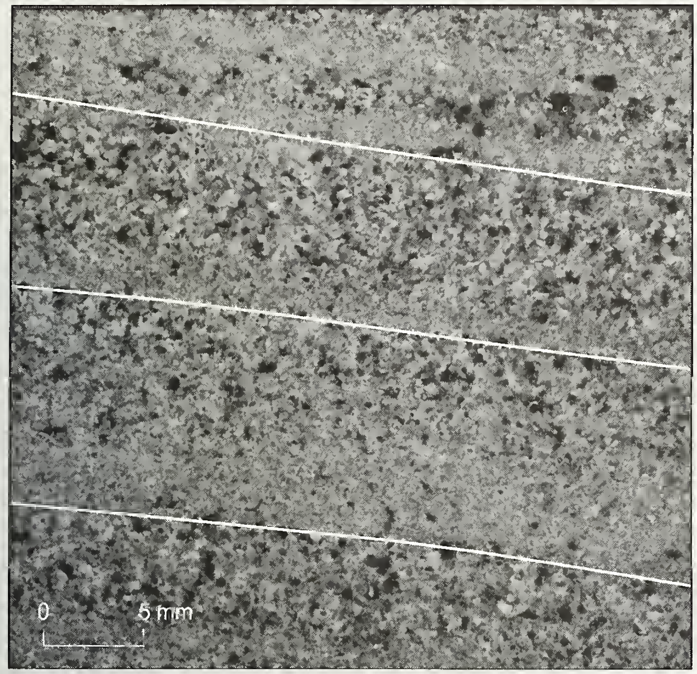


Figure 11 A polished slab of Chesterian limestone from West Virginia showing inverse grading that is characteristic of eolian limestone. This photograph is the Denmar Limestone, a Ste. Genevieve equivalent, from the Mingo section in Randolph County, West Virginia. (Photograph from Al-Tawil 1998.)

Figure 12 Exhumed dune foresets in the Ste. Genevieve Limestone at a road cut on Indiana Route 135 south of Corydon, Harrison County, Indiana.

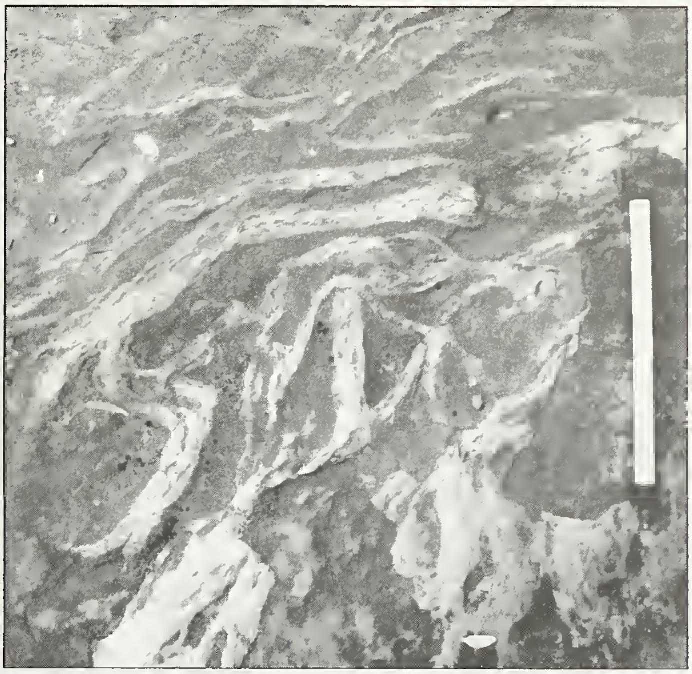


Figure 13 Root traces or rhizoliths on the top of eolian limestone of the Ste. Genevieve. Location is the Mitchell Quarry, Lawrence County, Indiana (outcrop section 64). Pen for scale.

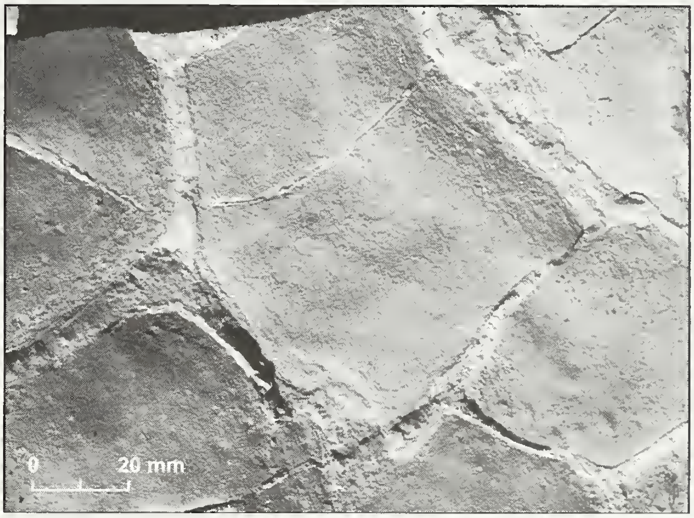


Figure 14 Mud cracks on a bedding surface underlying eolian limestone of the Ste. Genevieve. Location is the Mitchell Quarry, Lawrence County, Indiana (outcrop section 64).

incised valleys during lowstand; even this was largely reworked during the ensuing transgression.

The transgressive systems tract (TST) was deposited as sea level rose from the IFS to the MFS. The TST consists of marine sediments that record progressively deeper water. In most cases, the TST is relatively thin. In the Chesterian of the Illinois Basin, the TST typically is either shale and sandstone (fig. 6) or a thin bed of grainstone or packstone at the base of a limestone interval.

The highstand systems tract (HST) comprises deposits from the MFS upward to the upper sequence boundary. The HST thus records the transition from deep water to shoaling and re-emergence of the shoreline. Where not truncated by erosion, the HST generally is much thicker than the TST and comprises the bulk of most sequences. Chesterian HSTs of the Illinois Basin may consist either of limestone or siliciclastic rocks. Limestone HSTs generally show a shoaling transition from lime mudstone and wackestone at the base to packstone and grainstone at the top. Siliciclastic HSTs typically coarsen upward from shale at the base to sandstone at the top, recording prograding deltas and shorelines.

LOWER CHESTERIAN SEQUENCES

St. Louis Limestone

Although the St. Louis was not studied in detail for this report, it is described here to set the stage for the sequences that overlie it.

Definition and Extent

The St. Louis Limestone was named by Englemann (1847) for St. Louis, Missouri. There is no type section, but Thompson (1986) described a complete reference section at a quarry in the type area. The St. Louis extends throughout the Illinois Basin and onto the flanks of neighboring arches, except where truncated by younger strata. It is as thick as 180 m in the southern part of the Fairfield Basin, thinning to less than 60 m on most of the Western Shelf and to 30 m on the northern part of the Eastern Shelf. The contact with the underlying Salem Limestone is gradational and intertonguing (Lineback 1972, Droste and Carpenter 1990, Sable and Dever 1990).

Lithology

The St. Louis is dominantly composed of fine-grained carbonate rock: lime mudstone, fine-grained skeletal wackestone and packstone, and microgranular dolomite. The most diagnostic lithology of the St. Louis is dense, "sublithographic" limestone that breaks with conchoidal fracture and contains many lenses and stringers of blue-gray to black, vitreous chert. Oolitic limestone is present, but as a minor component, and the oolites (often actually pellets rather than true oolites) are barely visible without a hand lens. Anhydrite and gypsum are widely present in the lower St. Louis and are commercially mined in Martin County, Indiana (McGregor 1954, Saxby and Lamar 1957, McGrain and Helton 1964).

On wireline logs, the St. Louis typically has low spontaneous potential, high-resistivity, low gamma ray, and high-density readings compared with the readings for the enclosing formations. These log responses reflect high density and a lack of porosity and permeability (Bandy 1993). However, the St. Louis contains beds of microsucrosic dolomite that have as much as 25% porosity and moderate permeability and that serve as oil reservoirs (Cluff and Lineback 1981, Seyler and Cluff 1991). A distinctive geophysical log inflection near the middle of the St. Louis in Indiana is called the "X marker." It represents a porous dolomite bed that overlies impermeable, cherty limestone (Droste and Carpenter 1990).

Sandy beds are reported in the upper St. Louis north and west of the type area. Rubey (1952) described a bed of sandstone or sandy, oolitic, cross-bedded limestone as thick as 6 m near the top of the St. Louis in Jersey County, Illinois. The quartz sand is fine- to coarse-grained, the fine grains being angular and the medium to coarse ones being rounded. Conglomeratic limestone, composed of pebble- to boulder-sized limestone clasts in a limestone matrix, also occurs in the upper St. Louis here (Rubey 1952). Thicker sandstone beds are present in the St. Louis in northwestern Missouri (Greene 1945), southeastern Nebraska (Carlson 1979), and southeastern Iowa (Carlson 1979, Sable 1979, Witzke et al. 1990). In Iowa, siltstone and sandstone beds with coarse, rounded, and frosted quartz grains occur in the Croton Member, which is faunally equivalent to the type St. Louis (Witzke et al. 1990).

Facies Pattern and Sediment Source

The presence of fenestral structures, stromatolitic laminations, collapse breccias, and widespread evaporites indicates that the St. Louis was deposited in a restricted, shallow subtidal to supratidal environment similar to the modern Florida Bay (Cluff and Lineback 1981). Cores and mine exposures in Indiana reveal up to eighteen cycles of evaporite deposition in environments interpreted as ranging from shallow lagoons to intertidal flats and sabkhas (Jorgensen and Carr 1972). The distribution of sandstone in the St. Louis suggests, as Carlson (1979) and Sable (1979) proposed, that the Transcontinental Arch was exposed during Meramecian (late Valmeyeran) time. The arch was a broad uplift that extended from central Minnesota to northern Colorado and separated the Illinois Basin from the Williston Basin (fig. 3A). Rounded, frosted quartz grains in the St. Louis likely were derived from the St. Peter Sandstone (Ordovician) on the crest of the arch.

Sequence 1

Sequence 1 comprises the Fredonia Limestone Member and most of the Spar Mountain Sandstone Member of the Ste. Genevieve Limestone (figs. 5 and 15). Sequence 1 is thickest in the southern part of the basin, being 60 to 80 m thick in the Moorman Syncline and reaching a maximum of more than 100 m in Union and Johnson Counties of southern Illinois. The sequence thins to about 15 m on the northern and northwestern edges of the basin, 20 m near the Cincinnati Arch, and 8 to 15 m on the Eastern Shelf.

Lower Sequence Boundary

The lower boundary of Sequence 1 is placed at or near the top of the St. Louis Limestone. This surface exhibits evidence of erosion and subaerial exposure around the margins of the Illinois Basin, but in the basin interior becomes conformable and difficult to identify.

The Ste. Genevieve Limestone overlies the St. Louis with a clearly erosional contact near the Ozark Dome in southwestern Illinois and adjacent Missouri (Weller and Sutton 1940, Spreng 1961, Willman et al. 1975, Thompson 1986). The contact locally truncates bedding of the St. Louis, and oolitic sediment fills fissures in the upper St. Louis. Also, the Ste. Genevieve has a basal chert-pebble conglomerate that contains silicified fossils from units as old as Middle Devonian (Weller and St. Clair 1928). Evidently, large areas of the Ozark Dome were exposed to erosion at that time.

Multiple unconformities near the Ozark Dome complicate placement of the sequence boundary. Different geologists placed it at four different points on the bluff at Alton, Illinois (Collinson et al. 1954). Lensing beds of oolitic, sandy limestone intertongue with fine-grained carbonates in the contact interval.

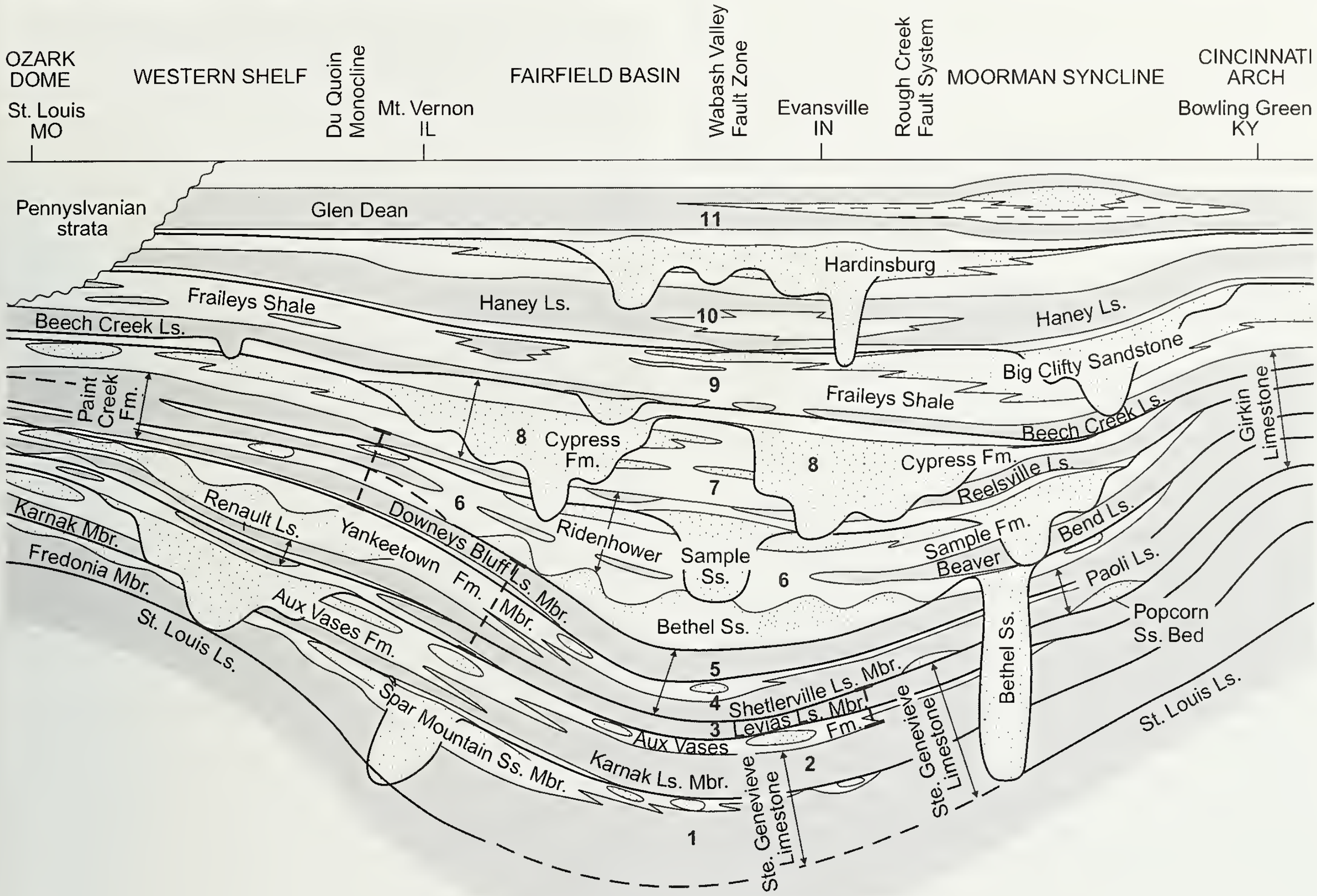


Figure 15 Generalized cross section of lower Chesterian rocks from the Ozark Dome to the Cincinnati Arch.

Moreover, contacts that are erosional at one place on the bluff become conformable when traced laterally. Collinson et al. (1954) noted several layers of breccia or conglomerate at Alton Bluff. Some of these are sedimentary conglomerates of eroded clasts, others are products of collapse after dissolution of anhydrite, and still others are probably pedogenic. Alton Bluff lies close to the Cap au Gres Faulted Flexure, which was active during Mississippian time (Rubey 1952, Nelson and Marshak 1996), so some unconformities here may be products of local tectonic movement.

On the Eastern Shelf, the sequence boundary commonly is an undulose surface within a dolomite or micritic limestone layer overlying the Lost River Chert Bed (Merkely 1991; Hunter et al. 1996; Carl B. Rexroad, personal communication 1996). The Lost River (Elrod 1899) is a bed of silicified limestone that contains large fragments of brachiopods and fenestrate bryozoans; it occurs at or near the top of a laterally extensive unit of skeletal grainstone. Although best known in the eastern part of the Illinois Basin, the Lost River also occurs east of the crest of the Cincinnati Arch in south-central Kentucky and adjacent Tennessee. In that area, also, widespread subaerial erosion, caliche development, and erosion took place directly after deposition of the Lost River Chert (Dever et al. 1990, Sable and Dever 1990, Dever 1999). Recently, Lasemi and Norby (1999) identified what they believe to be the Lost River Chert zone near St. Louis, Missouri. Here, the chert zone occurs a few meters below an abrupt change in lithology and conodont fauna.

Within the deeper areas of the basin, including the Moorman Syncline and the Fairfield Basin, the base of Sequence 1 apparently is conformable, and its placement is problematic. Beds of dark, micritic, and cherty limestone (St. Louis) and light-colored skeletal and oolitic grainstone (Ste. Genevieve) alternate through an interval tens of meters thick, and so placing the formation contact also is highly subjective (Shaver et al. 1986, Drost and Carpenter 1990, Sable and Dever 1990). Cores (Choquette and Steinen 1980) and quarry highwalls show no evidence of unconformities within the boundary interval. On our subsurface cross sections (plates 3 through 8), the base of Sequence 1 was drawn arbitrarily at the lowest prominent ooid bed, as identified from samples, wireline logs, or both. This contact undoubtedly crosses time lines, and so it is depicted as a dashed line.

Thus, our evidence indicates that a drop of sea level near the end of St. Louis deposition exposed the flanking arches of the Illinois Basin, but not the more rapidly subsiding central part of the basin. The sequence boundary, unconformable on the basin's margins, becomes a correlative conformity in the basin's interior.

The base of Sequence 1 coincides closely, if not exactly, with conodont, foraminiferal, and coral zone boundaries (Collinson et al. 1971, Rexroad and Fraunfelter 1977, Maples and Waters 1987, Lasemi and Norby 1999). The St. Louis is in the conodont zone of *Apatognathus scalenus (*now called *Synclydognathus geminus) - Cavusgnathus*. Collinson et al. (1971, p. 382) stated, "The upper boundary of this zone represents the sharpest conodont faunal break in the Mississippian of the Illinois Basin." According to Rodney D. Norby (ISGS, written communication 2000), the time missing at the sequence boundary may be equal to half a conodont zone or less.

Fredonia Member

The Fredonia Limestone Member of the Ste. Genevieve Limestone comprises carbonate strata below the Spar Mountain Sandstone Member (figs. 5 and 15). The Fredonia ranges from less than 8 m thick on the Eastern Shelf to more than 60 m in the Fairfield Basin and 52 to 79 m in the Moorman Syncline. In places on the Western Shelf, the Fredonia is completely truncated by erosion at the base of the Spar Mountain or younger units. The Fredonia is recognized only where the Spar Mountain is present because the Fredonia is similar in lithology to the Karnak Member, which overlies the Spar Mountain.

The Fredonia is composed mostly of oolitic and skeletal grainstone that is nearly white to light yellowish or brownish gray. The distinct oolites are fine- to coarse-grained and generally have light-colored fossil grains as nuclei. Echinoderms, bryozoans, and brachiopods are the dominant bioclasts (as in most Chesterian limestones). Oolitic limestone typically exhibits large-scale cross-bedding (fig. 16) and occurs in units 3 to 12 m thick that are bounded by sharp, undulating surfaces. Oolitic units are separated by thinner (1 to 3 m) intervals of fine-grained packstone, wackestone, lime mudstone, and microgranular dolomite. These beds are darker than the oolitic rocks and are somewhat cherty. Interbeds of gray to greenish gray shale and siltstone, a few centimeters to about 1 m thick, are present locally. In several areas where detailed studies have been conducted, ooid grainstone in the Fredonia forms elongate lenses that have flat bottoms and convex tops and are interpreted as bars (Carr 1973, Choquette and Steinen 1980, Seyler 1986, Bandy 1993, Manley et al. 1993). Lenses are hundreds of meters to several kilometers across and 4 to 8 m thick; they have irregular outlines in map view. Lenses commonly trend north-south to northeast-southwest, although other orientations occur. In one study, cross-bedding indicated bidirectional currents parallel to long axes of lenses (Carr 1973). Bandy (1993) described north-trending oolite bodies having a channel geometry. However, correlating oolite bodies and defining their geometry can be challenging, even in densely drilled areas having good quality logs (Zuppann 1993).

Figure 16 Cross-bedded oolitic grainstone in the Fredonia Member of the Ste. Genevieve Limestone, at the Anna Quarry in Union County, Illinois (outcrop section 5). Staff is graduated in feet.

Spar Mountain Sandstone Member

The Spar Mountain Sandstone was named by Tippie (1944) for a locality in Hardin County, in southeastern Illinois, where lenticular calcareous sandstone or sandy limestone less than 3 m thick lies about 18 to 25 m below the top of the Ste. Genevieve. Willman et al. (1975, p. 142) described the Spar Mountain as erratic in thickness, variable in lithology, and difficult to differentiate from other sandstone bodies in the Ste. Genevieve. The Spar Mountain is often confused with the younger Aux Vases Sandstone. Swann (1963) and later geologists observed that the Aux Vases thickens and apparently merges with the Spar Mountain in western Illinois. Cluff and Lineback (1981) interpreted the Spar Mountain as a lower tongue of the Aux Vases Sandstone, intergrading laterally with the Ste. Genevieve Limestone. To make matters worse, most petroleum geologists call the Spar Mountain the "Rosiclare Sand," but the Rosiclare Sandstone Member formally is part of the younger Aux Vases (Swann 1963).

Using more than 1,500 wireline logs along with cores and outcrop data, Leetaru (1997, 2000) mapped the Spar Mountain Sandstone through a large area of Illinois. These maps show that the unit is thickest and sandiest along a belt that runs north-south along the western margin of the Fairfield Basin (fig. 15). Within this belt, the Spar Mountain fills channels incised as deeply as 24 m into underlying carbonates, cutting into the St. Louis in places. On the Western Shelf, the Spar Mountain in turn is cut out by incised valleys that are filled with the younger Aux Vases Sandstone. Leetaru (2000) interpreted sequence boundaries at both the top and the base of the Spar Mountain and indicated no intertonguing between Spar Mountain and Aux Vases (as proposed by Cluff and Lineback 1981).

Our outcrop and subsurface studies supplement Leetaru's mapping (fig. 15; plates 2 through 4). We found the Spar Mountain thickest near the western edge of the Fairfield Basin, where Leetaru mapped the major sand accumulation. We did not recognize incised valleys, but our cross sections are largely south of the area where Leetaru found them. On our cross sections on the Western Shelf and northern Fairfield Basin, the Spar Mountain is typically 1.5 to 9 m thick and composed of oolitic and skeletal limestone that contains 20% or more detrital quartz silt and sand. Lenses of sandstone are present throughout this area. Interbeds of green and purple shale are widespread, particularly at the base; red or variegated shale and mudstone commonly occur at the top.

Farther southeast (southernmost Illinois and southwestern Indiana), the Spar Mountain is reduced to isolated sandstone lenses or sandy limestone less than 5 m thick. Sandstone is rare in Kentucky and south-central Indiana; nevertheless, the Spar Mountain can be traced all the way to the southeast corner of the basin (plate 1). In these outcrops the Spar Mountain ranges from 1.5 to 5 m thick and consists of calcareous, glauconitic quartz sandstone along with various types of dolomite and limestone that contain floating quartz sand grains. Much of the eastern Spar Mountain is quartz-peloid grainstone that contains sedimentary and petrologic features indicative of eolian sedimentation. Caliche, breccia, and other features of subaerial exposure occur at the top. All of these features are conspicuous on outcrops and in cores but are difficult to recognize in well cuttings and wireline logs (Conner 1987).

Upper Sequence Boundary

The top of Sequence 1 is erosional in central Illinois, where the Spar Mountain fills valleys incised into older units. These valleys run north-south to north-northeast–south-southwest and are most deeply downcut on the north (Leetaru 1997, 2000). Outside of incised valleys, we interpret the top of Sequence 1 as a non-erosional boundary lying at or near the top of the Spar Mountain where pedogenic breccia, caliche, and eolian deposits are evidence of subaerial exposure. Sample logs of some wells in southwestern Illinois indicate red shale or mudstone, which may be a paleosol, at the top of the Spar Mountain. On subsurface cross sections, we placed the sequence boundary at the top of the Spar Mountain. Where the Spar Mountain was not identified, Sequences 1 and 2 are combined.

Our interpretation differs from that of Leetaru (2000), who indicated one sequence boundary at the base and another at the top of the Spar Mountain. Leetaru documented only the lower unconformity, as expressed by incised valleys. He cited Smith and Nelson (1996) as the authority for a sequence boundary at the top of the Spar Mountain, based on paleosols we observed on outcrops south and east of the area that he mapped. Leetaru did not observe unconformities at both top and base of the Spar Mountain in the same area, nor did we. Therefore, we interpret a single sequence boundary, which is at the top of the Spar Mountain in some areas and at the base in others. This interpretation requires that the Spar Mountain be split between two sequences, the thin and lenticular part being in older Sequence 1 and the valley-fill sandstone being in younger Sequence 2.

Facies Pattern and Sediment Source

No lowstand deposits are recognized in Sequence 1, with the possible exception of local basal conglomerates on the Western Shelf. Given the updip shelf position and lack of incised valleys in Sequence 1, preservation of the LST is not to be expected.

Smith (1996) identified nine cyclic packages in Sequence 1 and interpreted them as parasequences (plate 1). Correlating parasequences in the subsurface is nearly impossible; tracing oolite bodies can be problematic even in areas having dense well control (Zuppann 1993). Smith (1996) interpreted the lower four parasequences of Sequence 1, in the Fredonia Member, to be the TST. Parasequences 1 and 2 are thin and confined to the basin interior; parasequences 3 and 4 are thicker and partially onlap the Eastern Shelf (plate 1). Parasequences 5 to 9 overlap the Eastern Shelf and were assigned to the HST.

Oolitic grainstone of the Fredonia accumulated largely as tidal sand bars on a broad shelf similar to the modern Bahama Banks. The prevalent north-south to northeast-southwest orientation of oolite lenses represents tidal currents running parallel to the long axis of the structurally controlled embayment. Some grainstone bodies probably are tidal channels (Bandy 1993). Finer grained carbonates accumulated in lagoons and in deeper water between the oolite shoals (Carr 1973, Choquette and Steinen 1980, Cluff and Lineback 1981, Seyler 1986, Bandy 1993, Manley et al. 1993, Zuppann 1993).

Quartz sand influx (Spar Mountain) began during highstand or regression. Thickness and facies patterns of the Spar Mountain, especially its incised valleys, indicate that the main sediment source lay north of Illinois, as Leetaru (1997, 2000) stated. Probable correlative units occur in southeastern Iowa in more upland settings. The Verdi Member in Iowa contains a typical early Ste. Genevieve (Fredonia) fauna. This mixed carbonate-clastic unit records initial marine transgression followed by regression to subaerial exposure. The overlying Waugh Member, which yields facies and fauna (including a vertebrate fauna) ranging from marginal-marine to freshwater and terrestrial (Witzke et al. 1990), is a likely Spar Mountain equivalent but is more terrestrial than anything in Illinois. The Iowa evidence supports subaerial exposure of the Transcontinental Arch during deposition of Sequence 1, as proposed by Carlson (1979) and Sable (1979).

Sequence 2

Sequence 2 comprises valley-fill sediments of the Spar Mountain Sandstone Member, the Karnak Limestone Member of the Ste. Genevieve Limestone, and the older part of the Aux Vases Formation (figs. 5 and 15). On the Eastern Shelf, Moorman Syncline, and most of the Fairfield Basin, the upper boundary is a non-erosive unconformity near the top of the Aux Vases. An erosional upper boundary occurs in some areas of the northern Fairfield Basin and adjacent parts of the Western Shelf, where incised valleys filled with Aux Vases sandstone cut into Sequence 2.

Sequence 2 is as thick as 45 m in the southern Fairfield Basin and reaches 50 m on the southern part of the Western Shelf in Perry County, Illinois. This general area is also where Sequence 1 is thickest and is well west of the present structural axis of the basin. Sequence 2 thins to 10 to15 m in the Moorman Syncline, on the Eastern Shelf, and on the northern part of the Western Shelf. This sequence is absent on parts of the Western Shelf because of erosion at the base of Sequence 3.

Spar Mountain Valley Fill

The Spar Mountain Sandstone fills channels cut into the Fredonia and St. Louis Limestones in the northern part of the Fairfield Basin (fig. 17). Valley-filling Spar Mountain is fine- to medium-grained quartz arenite that is, on average, coarser than the Aux Vases Sandstone in the same area. The Spar Mountain contains less than 3% feldspar grains, compared with a maximum of 10% in the Aux Vases (Leetaru 1997). Valley-fill sandstone in cores from the Cooks Mills oil field in Coles and Douglas Counties is fine- to medium-grained, angular to subangular, and commonly cross-bedded. It contains lenses of sandy, oolitic limestone and, near the top, a widespread layer of greenish gray to brownish gray, fissile, calcareous shale (Whiting 1959).

Leetaru (2000) stated that Spar Mountain incised valleys trend generally north-south and are most deeply downcut at the northern margin of the Illinois Basin, adjacent to the presumed source of sediment.

Karnak Limestone Member

The Karnak Limestone Member (figs. 5 and 15) is a westward-thinning wedge of limestone between the Spar Mountain and Aux Vases Sandstones. In southeastern Illinois, where the Spar Mountain is lenticular, the Karnak is 18 to 27 m thick and is composed of alternating units of light gray ooid grainstone (typically cross-bedded) and darker gray skeletal packstone, wackestone, and lime mudstone. Interbeds of greenish gray shale and lenses of calcareous siltstone to very fine sandstone are common in the Karnak in southeastern Illinois.

In much of the central and northern Fairfield Basin, as in the subsurface of Indiana, the Karnak is dense, highly resistive limestone 3 to 10 m thick (plates 2 through 5) and is a good marker bed for regional mapping (Bristol and Howard 1976). Sample logs and cores indicate the presence of skeletal packstone and grainstone and lesser amounts of oolitic grainstone, all of which are partially dolomitized. In Coles and Douglas Counties of east-central Illinois, the Karnak is largely dense, sublithographic lime mudstone to finely granular limestone that is partially dolomitized (Whiting 1959).

Westward, the Karnak thins and interfingers in complex fashion with sandstone of the Aux Vases (plate 3). As many as five sandstone-limestone alternations are shown on some logs. The number and thickness of sandstone interbeds increase westward, and the youngest tongues of sandstone extend farthest east—implying the source of sand from the west. The Karnak terminates on the southern part of the Western Shelf (plate 3) because of a combination of facies change and erosion at the base of Sequence 3.

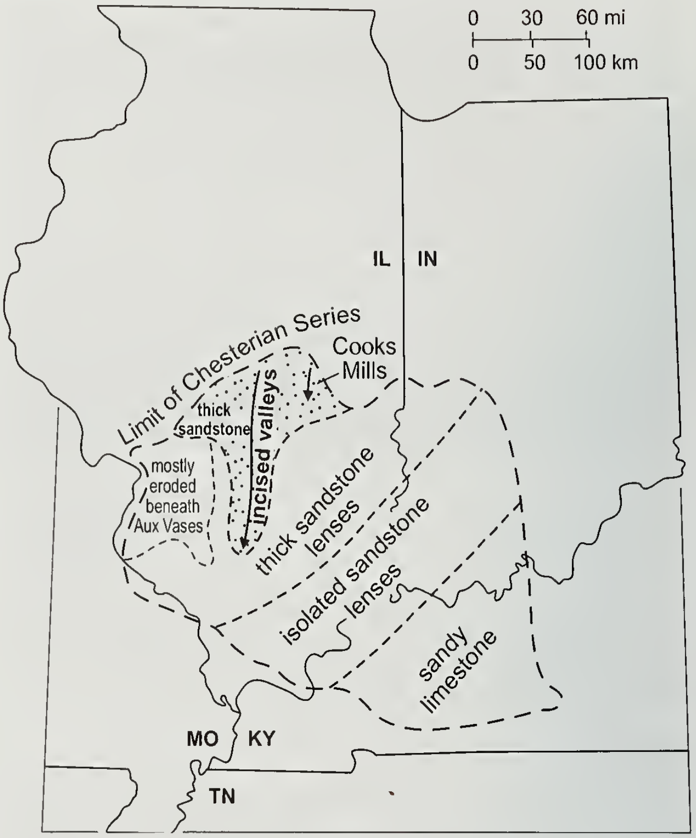


Figure 17 Map showing the generalized facies distribution of the Spar Mountain Sandstone (Sequence 1). Based partly on Leetaru (2000).

Joppa Member (Deleted)

Swann (1963) defined the Joppa Member as a unit of interbedded sandstone, shale, and limestone that lies between the Karnak Member of the Ste. Genevieve Limestone and the Aux Vases Sandstone. Swann proposed that the Joppa could be a member of either the Aux Vases (if sandstone dominated) or the Ste. Genevieve (if limestone dominated). Most subsequent authors placed the Joppa in the Ste. Genevieve only (fig. 4); however, Leetaru (2000) regarded the Joppa as a basal transgressive limestone unit within the Aux Vases Formation.

The type section of the Joppa is now totally covered, and no one has suggested a reference section. Joppa appears to be a convenient, elastic receptacle for rocks that do not clearly fit Ste. Genevieve or Aux Vases. Naming the mixed-lithology zone merely introduces two boundary problems where formerly one existed. For the sake of simplicity, we hereby recommend that the name Joppa Member be dropped from formal usage.

Aux Vases Formation

Nomenclature Named by Keyes (1892), the Aux Vases Formation (or Sandstone) is a unit of mostly sandstone with lesser amounts of siltstone, shale, mudstone, and carbonate rock. Presently the Aux Vases is classified as a formation throughout Illinois (fig. 2). In Indiana, the Aux Vases was formerly a formation, but Droste and Carpenter (1990) reclassified it as a member of the Paoli Limestone. That change in rank reflects a miscorrelation, which we shall address under Sequence 4.

In Kentucky, the Aux Vases is known as the Rosiclare Sandstone Member of the Ste. Genevieve Limestone. The Rosiclare Sandstone (Ulrich and Smith 1905) was correlated by Swann and Atherton (1948) with the Aux Vases; then, Swann (1963) redefined the Rosiclare as a member of the Aux Vases in Illinois. However, the name Rosiclare is unnecessary and redundant with Aux Vases. Moreover, the name causes much confusion. Petroleum geologists have (incorrectly) called the Spar Mountain Sandstone the "Rosiclare Sand" for more than 50 years. We are therefore deleting the Rosiclare Sandstone as a formal unit.

The Aux Vases should be classified as a formation where it is mappable. Where the Aux Vases is too thin or discontinuous for mapping, as in much of Indiana and Kentucky, it may be classified as a member of the Ste. Genevieve. We prefer the form Aux Vases Formation to Aux Vases Sandstone because the unit contains substantial amounts of shale, siltstone, mudstone, and limestone in addition to sandstone.

Lithology The Aux Vases is a sandy unit that is thickest and coarsest in the northwestern part of the basin, becoming thinner and finer grained toward the southeast (fig. 18). Although sandstone is absent in most of Indiana and Kentucky, the Aux Vases can be traced all the way to the southeastern corner of the basin.

Nearly continuous, thick sandstone makes up the Aux Vases northwest of a line that runs roughly from Jackson County to Shelby County, Illinois (fig. 18). The sandstone is thickest in the western part of this area, locally reaching 50 m in Perry and Washington Counties, Illinois (Seyler 1986, Leetaru 2000). The fine- to medium-grained quartz arenite to subarkose is largely massive or cross-bedded. In outcrops along the western edge of this area, cross-bedding indicates paleocurrents toward the south and southeast (Potter et al. 1958, Potter 1963). Ripple and planar lamination, herringbone cross-lamination (fig. 19), flaser bedding, and small-scale channels also are present in outcrops (Leetaru 1997). The sandstone is mostly noncalcareous, but scattered marine bioclasts such as echinoderm fragments are present.

A belt of lenticular sandstone lies southeast of the area of thick sandstone, mainly in southeastern Illinois and bordering counties of Indiana (fig. 18). Petroleum geologists commonly refer to this facies as "basin Aux Vases." The light gray to greenish gray, very fine-grained sandstone is calcareous and glauconitic. Cross-bedding, cross-lamination, ripple lamination, flaser bedding, and mud cracks are widely developed; oolites and calcareous bioclasts are common. Sandstone intergrades laterally with lenses of sandy limestone. Reddish to greenish gray mudstone, shale, and siltstone occur above and below. The sandstone lenses, 5 to 10 m thick, are commonly elliptical in map view with their long axes oriented northeast-southwest. The lenses have flat bases, are convex-upward, and are generally interpreted as tidal sand bars (Seyler 1986, Cole 1990, Leetaru 1997).

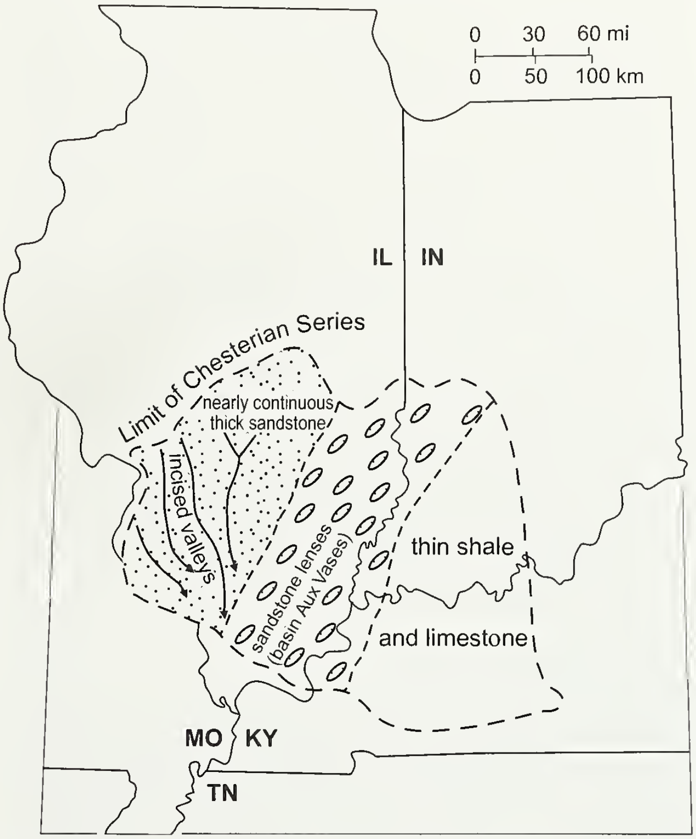


Figure 18 Map showing the generalized facies distribution of the Aux Vases Formation (Sequences 2 and 3), based partly on the work of Seyler (1986) and Leetaru (2000).

Figure 19 Herringbone cross-bedding, a strong indicator of tidal activity, in the Aux Vases Formation at the Cave-in-Rock Quarry, Hardin County, Illinois (outcrop section 15). Scale is a penny.

In the southeastern part of the basin, including most of Kentucky and south-central Indiana, the Aux Vases consists of thin shale and silty to sandy limestone with scattered lenses of calcareous sandstone. The Aux Vases has been traced as a mappable unit as far east as Christian County, Kentucky. Farther east in Kentucky and in southern Indiana, many geologists overlooked the Aux Vases or confused it with older or younger sandy intervals. However, Sable and Dever (1990, p. 62) recognized the Aux Vases as sandy limestone on the flank of the Cincinnati Arch in Kentucky and noted that it contains "micritic crusts and stringers developed during vadose diagenesis." Our work confirms that sandy, peloidal limestone at the position of the Aux Vases extends to the southeastern corner of the basin (plate 1).

Abundant evidence for tidal sedimentation occurs throughout the Aux Vases. Environments ranged from shallow subtidal to supratidal, as shown by flaser and ripple lamination, tidal rhythmites, herringbone cross-lamination, algal mats, dessication cracks, and shallow channel features. Calcareous sandstone and sandy ooid and skeletal limestone intergrade in all proportions (Weimer et al. 1982; Cole 1990; Huff 1993; Leetaru 1997, 2000; Udegbunam et al. 1993).

Upper Sequence Boundary

The upper boundary of Sequence 2 is erosional across much of the Western Shelf (plates 2 through 4). Here the upper part of the Aux Vases Formation, in Sequence 3, fills valleys that cut deeply into Sequence 2 and locally reach the St. Louis Limestone. Other geologists (Weller and St. Clair 1928; Weller and Sutton 1940; Leetaru 1997, 2000) also document the unconformity both on the outcrop and in the subsurface. In places, an angular unconformity is present between the Aux Vases and older units. For example, in eastern Madison County, the Fredonia Limestone is arched and truncated beneath the Aux Vases across the St. Jacobs Dome (plate 2). In Monroe County to the south, the Ste. Genevieve is eroded beneath the Aux Vases on the Waterloo-Dupo Anticline but preserved in an adjacent syncline (Weller and Sutton 1940), showing that some structures on the flank of the Ozark Dome were active during deposition of the Aux Vases. Elsewhere on the Western Shelf, incised valleys of Sequence 3 cut into or completely through Sequence 2, but no angularity is evident. Examples are shown in Jackson County (plate 3) and northern Perry and southern Clinton Counties (plate 4).

In the area of basin Aux Vases, the upper boundary of Sequence 2 is a non-erosive unconformity at the top of the Aux Vases. The contact of the Aux Vases with the overlying Levias Limestone is sharp and undulates with a meter or more of relief in quarry exposures. Relief on the Levias-Aux Vases contact also is evident in the subsurface, for example, at wells 49, 50, and 53 on plate 3. Cores and quarry exposures in Pope and Hardin Counties, Illinois, commonly show conglomerates of shale and siltstone clasts near the base of the Levias. The basal Levias commonly is sandy, and oolitic sediment from the Levias fills cracks in the upper Aux Vases. Features indicative of subaerial exposure and soil formation, including breccia, red and green variegated mudstones, caliche, calcareous rhizocretions, and root casts, are widespread in the upper Aux Vases (Leetaru 1997, Seyler 1998; confirmed by our observations). In cores from the Rural Hill oil field in Hamilton County, Illinois, the upper Aux Vases is composed of fissile green and gray shales that grade upward to blocky, bioturbated red mudstones that contain root marks and desiccation cracks (Weimer et al. 1982). Huff (1993) reported algal-bound, calcareous sandstone in the upper part of the Rosiclare in the Energy oil field, Williamson County, Illinois. In Kentucky, where the Aux Vases generally lacks sandstone, the upper sequence boundary is indicated by micritic crusts and stringers (caliche) in sandy peloidal limestone that is probably of eolian origin (Sable and Dever 1990).

Leetaru (1997, 2000) interpreted sequence boundaries at both the top and base of the Aux Vases in Illinois. Previously, Tippie (1944) reported an unconformity at the base of the Aux Vases in Pope and Hardin Counties, Illinois. In the same area, Leetaru (1997, 2000) described an unconformity at the base of the Aux Vases that was marked by basal conglomerate of limestone pebbles. We have not viewed the relevant cores and outcrops. Assuming observations by Tippie and Leetaru are correct, the basal Aux Vases unconformity in southern Illinois may be (1) a local, shallow incised valley surface at the boundary between Sequences 2 and 3, or (2) the product of local wave or current scour not associated with a drop in sea level. Seyler (1998) described an erosional contact with basal conglomerate in the Zeigler oil field of Franklin County, Illinois, and attributed erosion to storm-wave scour. Our data do not support a basin-wide unconformity at the base of the Aux Vases. The breccia zone or paleosol that we would expect to accompany such a surface is not in evidence.

Facies Pattern and Sediment Source

The oldest deposits of Sequence 2 consist of Spar Mountain Sandstone filling incised valleys near the northern edge of the basin. Although details are lacking, the valley-fill deposits are probably fluvial to estuarine sediments and represent the LSTs to TSTs. Outside of incised valleys, the TST of Sequence 2 is relatively thin, comprising a single parasequence in the lower part of the Karnak Member (Smith 1996). Patchy eolianites and grainstones at the base are overlain by 1 to 10 m of micritic limestone. The maximum flooding surface is placed at a thin, widespread grainstone unit in the Karnak. The remainder of Sequence 2, comprising five parasequences (Smith 1996), is interpreted to be the HST.

As in Sequence 1, transgressive to early highstand parts of Sequence 2 were open-water carbonates deposited far from terrigenous clastic sources. Oolite bars or shoals again alternated with finer grained, more micritic sediments. A broad embayment was swept by strong northeast-southwest tidal currents during deposition of the Karnak Member. Along the margins of the embayment, conditions were somewhat restricted, so finer grained carbonates prevailed.

Aux Vases sand deposition commenced during late highstand or regression. As with the Spar Mountain, the primary sand source lay northwest of the Illinois Basin on the Transcontinental Arch. This sand was delivered by south- and southeast-flowing rivers to a northeast-trending shoreline. Terrestrial sands from the northwest intermixed with open-water carbonates on the southeast. This sand was redistributed by northeast-southwest, longshore tidal currents. Both the thick, fairly continuous sandstone in the northwestern part of the basin and, especially, the lenticular "basin Aux Vases" were reworked in shallow subtidal to intertidal settings. As sea level dropped, siliciclastics prograded toward the southeast. Only a little fine sand and silt, carried by waves, currents, and wind, reached the southeastern corner of the basin late in regression. At final lowstand, all (or nearly all) of the Illinois Basin region lay subaerially exposed, and the northwest corner was deeply eroded. Angular unconformities on active structures of the Western Shelf imply a substantial hiatus in deposition there.

Sequence 3

Sequence 3 contains the valley-fill portion of the Aux Vases Formation, along with the Levias Limestone (figs. 5 and 15). Sequence 3 is the thinnest lower Chesterian sequence in most of the basin, being only 3 to 11 m. Where the Aux Vases fills valleys, Sequence 3 locally thickens to 40 m.

Aux Vases Valley Fills

On the Western Shelf, Aux Vases valleys contain massive and cross-bedded sandstone that is typically 20 to 25 m thick and reaches 40 m in places. The sandstone is light gray, fine- to medium-grained quartz arenite to borderline subarkose, containing a few percent each of detrital chert, feldspar, and mica grains. Echinoderm fragments and other calcareous bioclasts are present and, in places, a basal conglomerate of chert pebbles (Cole 1990; Leetaru 1997, 2000). Potter (1963, p. 68–70) mapped a "thick belt sand body" of the Aux Vases at outcrops in Monroe and Randolph Counties in southwestern Illinois. According to Potter, the western boundary of the "belt" trends north-south and appears to meander. The belt lies on the Ste. Genevieve with an erosional contact, whereas the thin "sheet" sandstone of the Aux Vases, west of the belt, has a conformable lower contact. Cross-bedding in the belt sandstone is strongly unidirectional, indicating a southeast-flowing paleocurrent. Cross-bedding in the thin sheet sandstone is more variable in trend. In the same area Cole (1990) observed scour-and-fill features and southeast-dipping crossbeds in the lower part of the sandstone. The upper part contains herringbone cross-lamination and small, lenticular sandstone bodies that contain echinoderm fragments. At the Aux Vases type section in Missouri, Cole observed herringbone cross-bedding and rhythmic, tidal lamination in the lower part of the sandstone and stromatolites and mud cracks near the top. This succession of features indicates early fluvial deposition gave way to estuarine conditions.

In the subsurface, Aux Vases valley fills are dominantly clean sandstone. Shale breaks and lenses of sandy limestone occur within the sandstone; gray, green, and red shales commonly occur at the top. Some varicolored shales may be paleosols, but most are fissile shales that probably formed on tidal mud flats. A thin limestone directly underlies thick sandstone at the base of the Aux Vases in a number of wells on the southern part of the Western Shelf (plate 4). This sandy, crinoidal limestone contains maroon and purple oolites and grades into overlying sandstone. This limestone may be a basal, transgressive valley-fill deposit of the Aux Vases in Sequence 3.

Levias Limestone Member

Sutton and Weller (1932) named the Levias Limestone for a locality in Crittenden County, Kentucky. Swann (1963) defined the Levias as the lower member of the Renault Limestone in Illinois, but the Levias is the uppermost member of the Ste. Genevieve in western Kentucky (fig. 4). In Indiana, Shaver et al. (1986) assigned all of the Ste. Genevieve above the Spar Mountain to the Levias Member, but Droste and Carpenter (1990, p. 25) recommended abandoning the term Levias. In this report, the Levias is the unit of limestone that overlies the Aux Vases Sandstone and underlies the Shetlerville Limestone. In various parts of the basin, the Levias can be a member of the Ste. Genevieve, Renault, or Paoli Limestone (figs. 5 and 15).

The Levias is largely a white, light gray, and reddish gray, medium to coarse oolitic grainstone with lesser components of skeletal grainstone and packstone. Pink-, red-, or orange-centered hematitic oolites are distinctive but not ubiquitous. Such oolites occur locally in older or younger limestones, but are most common in the Levias. Sedimentary features of the Levias resemble those of the Karnak and Fredonia, and imply a high-energy, tidally dominated setting. Various styles of cross-bedding, ripple lamination, and shallow, steep-sided channels were observed in quarries. Possible paleokarst features suggest episodes of subaerial exposure during Levias deposition.

In southeastern Illinois and adjacent parts of Indiana and Kentucky, the Levias varies from less than 3 to about 11 m thick. It thins to less than 3 m along the Eastern Shelf in Indiana. The Levias either pinches out or grades to sandstone in southwestern Illinois (plates 3 and 4); the overlying Shetlerville Limestone continues westward as a series of lenses.

Upper Sequence Boundary

The upper boundary of Sequence 3 has long been recognized as an unconformity (Weller 1921). The Bryantsville Breccia Bed (not shown) at the top of the Levias indicates subaerial exposure and weathering (Malott 1952, Liebold 1982). The Bryantsville was the first Mississippian paleosol to be identified as such and is the only one to be formally named. The unconformity and associated change in echinoderm fauna led Swann (1963) to place the lower Chesterian series boundary here.

The Bryantsville Breccia Bed ranges from a few centimeters to nearly 4 m thick. Shaver et al. (1986, p. 23) described it thus:

> The breccia fragments of the Bryantsville Breccia Bed are angular to subangular; consist of dense micritic limestone and partly to wholly oolitic limestone; and are bound together by a matrix consisting of calcite, finely divided limestone fragments, oolitic limestone, and, less commonly, chert. The fragments range from 0.01 to 0.4 foot (0.3 to 12.2 cm) in breadth and are commonly

> dark gray to dark blue gray. The binding material, possibly of algal origin and in sinuous subparallel laminae, ranges in color from lighter to darker than the fragments. A zone of color-banded and wavy-laminated cherty or siliceous limestone or of nonsiliceous limestone is found in many exposures of the Bryantsville and in places is its only expression.

Although regionally extensive, the Bryantsville is locally absent or inconspicuous, especially on unweathered exposures, and it rarely can be identified in the subsurface. Other lithologic features provide a guide to the sequence boundary. The Shetlerville (above the boundary) generally is darker, finer grained, and more argillaceous than the Levias. Shetlerville carbonates are mostly medium-gray to brownish gray lime mudstone, skeletal and pelletal wackestone, and packstone. Oolites are smaller than those of the Levias and have dark nuclei. In some areas, especially in Indiana, the Shetlerville is consistently less porous than the Levias, as indicated on wireline logs. The Popcorn Sandstone Bed at the base of the Shetlerville can be recognized in well cuttings and, locally, on wireline logs.

No incised valleys are known at the top of Sequence 3, but, in places, there is considerable relief at the sequence boundary. For example, in Perry and Spencer Counties, Indiana (wells 42 to 49, plate 7), the Levias-Shetlerville contact undulates strongly relative to a persistent bed of microgranular dolomite near the top of the Ste. Genevieve. The Levias and Shetlerville are quite distinct in samples from these wells, and the Bryantsville Breccia was identified in nearby cores and quarries.

The upper boundary of Sequence 3 is marked by basal conglomerate in places on the Western Shelf. Pebbles of Precambrian rhyolite porphyry were reported in basal conglomerate of the Renault in Perry and Ste. Genevieve Counties, Missouri (Weller and St. Clair 1928). The Renault Limestone truncates the Aux Vases and Ste. Genevieve with an angular unconformity, resting directly on the St. Louis in southern Monroe County, Illinois (Weller and Weller 1939). The area of truncation is in line with the southeastern end of the Waterloo-Dupo Anticline. These observations indicate that tectonic uplift took place and that the Precambrian core of the Ozark Dome was exposed during erosion of the sequence boundary.

Facies Pattern and Sediment Source

Lowstand deposits of Sequence 3 are preserved locally in the form of fluvial sediments in the lower part of Aux Vases incised valleys. These sediments are identified by unidirectional cross-bedding and by the absence of marine or tidal indicators. The upper part of Aux Vases valley fill bears bidirectional current indicators and marine bioclasts, which are evidence of transgressive, estuarine conditions. Maximum flooding, to shallow subtidal depth, probably took place early during Levias deposition; the upper Levias comprises the HST. Sequence 3 probably consists of a single parasequence (Smith 1996).

As outlined under Sequence 2, thickness and facies trends of the Aux Vases (including incised valleys) indicate that the Transcontinental Arch was the primary sediment source. The Ozark Dome probably contributed small amounts of siliciclastics to the Western Shelf.

Sequence 4

Sequence 4 is composed of the Shetlerville and Yankeetown Members of the Paoli Limestone in the eastern and central areas of the basin and most, if not all, of the Renault Limestone and Yankeetown Formation on the west (figs. 5 and 15). Equivalent strata within the Girkin Limestone represent sequence 4 on the flank of the Cincinnati Arch. This sequence is 6 to 35 m thick on the Western Shelf, 9 to 20 m in the basin interior, 6 to 15 m on the Eastern Shelf, and about 4 m near the Cincinnati Arch. The upper sequence boundary is non-erosive, except locally on the Western Shelf.

Stratigraphic Nomenclature

The stratigraphy of Sequence 4 and adjacent parts of Sequences 3 and 5 has long been a source of confusion because names, ranks, and definitions of units change at state boundaries (fig. 4).

The Renault Limestone (Weller 1913) was extended from southwestern Illinois into southeastern Illinois, Indiana, and Kentucky using outcrop data. Swann and Atherton (1948), using wireline logs, determined that the upper part of the "Renault" of outcrop mappers in Kentucky includes equivalents of the Yankeetown Formation and Downeys Bluff Limestones, which are younger than the type Renault (figs. 4, 5, and 15). Swann (1963) redefined the Renault Limestone, Yankeetown Formation, and Downeys Bluff Limestone as formations in Illinois; however, geologists in Kentucky continued to use the old definition of Renault. The Renault, Yankeetown, and Downeys Bluff are troublesome formations because they are commonly too thin to map and their boundaries can be gradational.

The Paoli Limestone lies between the Ste. Genevieve Limestone and the Bethel Sandstone in Indiana and the adjacent part of Kentucky. The Paoli was named by Elrod (1899), redefined by Cumings (1922), and again redefined by Droste and Carpenter (1990), who assigned the Aux Vases Sandstone, Renault Limestone, Yankeetown, and Downeys Bluff Limestone as members (fig. 4). Unfortunately, Droste and Carpenter miscorrelated the Aux Vases Sandstone in the subsurface of southwestern Indiana with the Popcorn Sandstone on the outcrop. The Aux Vases actually lies below the Levias Limestone in Sequences 2 and 3, whereas the Popcorn Sandstone Bed is at the base of the Shetlerville Limestone at the base of Sequence 4.

The Girkin Limestone[1] (Sutton and Weller 1932) is mapped on the flank of the Cincinnati Arch in Kentucky. In the area where the name Girkin is used, the interval from the Shetlerville Limestone at the base to the Beech Creek Limestone Member of the Golconda Formation at the top is almost entirely

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[1] Although the U.S. Geological Survey refers to this unit as the Girkin Formation, we prefer to call it the Girkin Limestone, because limestone is the predominant lithology.

limestone. Several sandstone/shale units, the Yankeetown, Bethel, Sample, and Cypress, all pinch out on the flanks of the arch (figs. 20 and 21). These sandstones can be identified as thin shale or sandy limestone beds within the Girkin.

We propose the following clarifications and changes:

1. *The Aux Vases is classified as a formation overlying the Ste. Genevieve Limestone wherever the Aux Vases is mappable: all of Illinois and parts of Missouri, Indiana, and western Kentucky near the Illinois border.* In the eastern part of the basin (more or less the area of Indiana and Kentucky east of U.S. Rt. 41 and the Pennyrile Parkway), where the Aux Vases is too thin and lenticular to map, it becomes a member of the Ste. Genevieve Limestone, and the top of the Ste. Genevieve steps up to the top of the Levias Limestone Member (fig. 4). This change follows current practice in Kentucky.

2. *The Renault Limestone (or Formation) is restricted to southwestern Illinois.* The Renault should be used only in areas where the overlying Yankeetown is mappable as a formation.

3. *The Paoli Limestone is redefined again and extended into southeastern Illinois and western Kentucky.* In areas where the Aux Vases is mapped as a formation, the Paoli comprises the Levias Limestone, Shetlerville Limestone, Yankeetown Limestone, and Downeys Bluff Limestone Members. Where the Aux Vases and Levias are members of the Ste. Genevieve (the eastern part of the basin), the Paoli comprises the Shetlerville, Yankeetown, and Downeys Bluff Members only. Our redefinition of Paoli involves a vertical cutoff. Alternative classifications that would keep the Paoli–Ste. Genevieve contact at the same position throughout the basin were considered. One is to make the base of the Levias the base of the Paoli everywhere, which would create a contact that may not be mappable in the southeast part of the basin and also would change the long-standing definition of the Ste. Genevieve in that area. The other alternative is to make the base of the Paoli the base of the Shetlerville everywhere. This alternative follows current practice at Kentucky and Indiana outcrops, but again creates a problem for the subsurface. The Shetlerville-Levias contact is nearly impossible to identify on wireline logs without a good set of samples. This contact would be within a limestone, rather than at the readily identified contact between limestone (Levias) and sandstone (Aux Vases). The Levias would become a tongue of the Ste. Genevieve, enclosing the Aux Vases Formation in the western part of the basin. A vertical offset of the contact, as we propose, creates a more practical mapping boundary and makes fewer changes to traditional classification.

4. *The Yankeetown is a formation where it is mappable, principally on the Western Shelf and western part of the Fairfield Basin, where thick sandstone bodies are present.* On the east and south, where the Yankeetown is thin and its contact with the Shetlerville ill-defined, the Yankeetown becomes a member of the Paoli Limestone. Conversely, the Paoli Limestone ends where the Yankeetown can be mapped as a formation.

5. *The Downeys Bluff Limestone is the upper member of the Paoli Limestone.* In the western part of the basin, where Paoli is not used, the Downeys Bluff may be classified as a formation (where mappable) or as a member of the Paint Creek Formation. Problems involving use of the term Paint Creek are addressed under Sequence 6.

6. *The usage of Girkin Limestone continues unchanged.*

Shetlerville Member The Shetlerville Member (Weller et al. 1920) is a unit of limestone that locally contains the Popcorn Sandstone Bed at the base.

Popcorn Sandstone Bed The Popcorn Sandstone Bed was named by Swann (1963) for Popcorn Spring in Lawrence County, Indiana. Although thin (less than 4 m) and lenticular, the bed is present at many outcrops and can be identified in wells throughout Indiana, western Kentucky, and southeastern Illinois (plates 3 and 5–7; figs. 20 and 21). The Popcorn Sandstone may be present elsewhere in Illinois also, but is difficult to differentiate from other sandstones.

The Popcorn Bed is composed of sandstone, siltstone, shale, and shaly to sandy limestone. The sandstone generally is similar to the basin Aux Vases: greenish gray, very fine to fine-grained, and calcareous. Siltstone and shale also are mostly greenish gray and calcareous. Limestones have diverse textures, but quartz sand must be noticeable to warrant including limestone in the Popcorn Bed. The lower contact is sharp, irregular, and erosional. Several geologic quadrangle mappers in Kentucky observed a basal conglomerate and scoured lower contact (Sandberg and Bowles 1965, Amos 1977, Johnson 1978). In the subsurface, a good set of samples generally is needed to identify the Popcorn. Locally the sandstone is thick and clean enough to register as a permeable zone on wireline logs. The "Renault sand," from which oil is produced at several fields in southwestern Indiana (Droste and Carpenter 1990, p. 32–33), probably is the Popcorn.

Stratigraphers commonly confuse the Popcorn Sandstone with the Aux Vases. Malott (1952) identified the sandstone at Popcorn Springs as the Aux Vases. Recognizing a question as to correlation, geologic quadrangle mappers in Kentucky referred to the Popcorn as "the Aux Vases Sandstone as used by Malott (1952)." More recently, Droste and Carpenter (1990) correlated the Popcorn Sandstone of Indiana outcrops with the Aux Vases Sandstone in the subsurface of southwestern Indiana. Here is a case where sequence stratigraphy aids regional correlation. Both sandstones are highly lenticular in Indiana and difficult, if not impossible, to trace from well to well using wireline logs. The sandstones appear to be close to the same position, yet are separated by two major unconformities. The Aux Vases Sandstone is in Sequence 2, unconformably below the Levias Limestone in Sequence 3. The Popcorn Sandstone is at the base of Sequence 4 and unconformably overlies the Levias.

Remainder of Shetlerville The Shetlerville Member comprises the lower part of the Paoli Limestone in Indiana, most of western Kentucky, and the basin interior in Illinois. Near the Cincinnati Arch, the Shetlerville becomes part of the

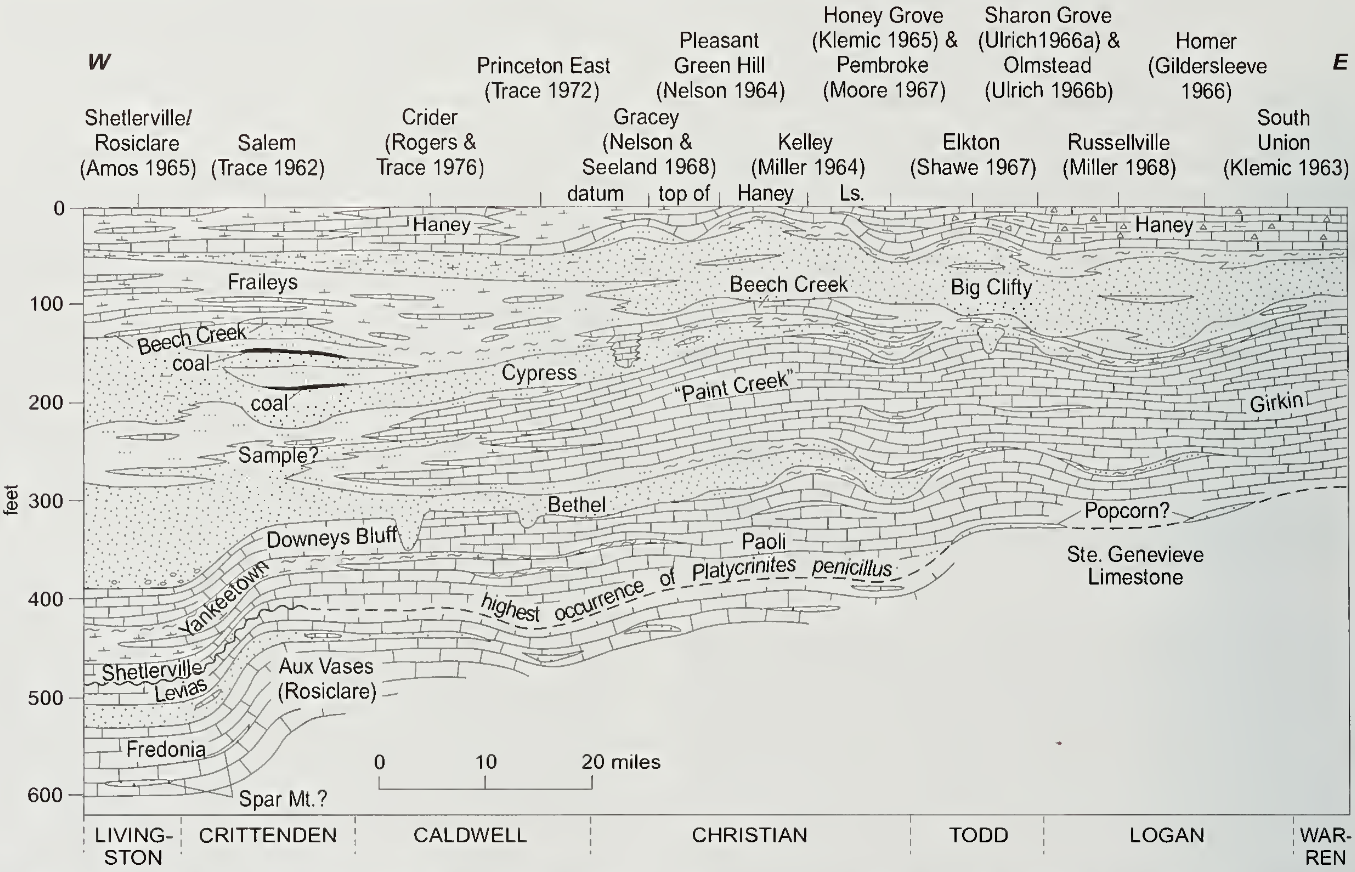

Figure 20 Cross section KY-1, showing lower Chesterian rocks in western Kentucky, based on geologic quadrangle maps. Line of section is on figure 1.

Girkin Limestone. The Shetlerville is equivalent to most of the Renault Limestone on the Western Shelf, although the Renault locally may contain Levias equivalents (figs. 5 and 15).

On the Eastern Shelf in Indiana, the Shetlerville is 6 to 15 m thick and consists of drab gray to brown, relatively dense limestone and dolomite. The limestone is mostly lime mudstone and skeletal wackestone and packstone. The overlying Yankeetown Member is reduced to interbeds and laminae of green to red mudstone near the top of the Shetlerville. Micritic to fine-grained, somewhat cherty limestone also prevails on the portion of the Eastern Shelf in Kentucky. The unit thickens from 3 to 6 m near the Ohio River to 8 to 10 m in Grayson County south of which the Shetlerville becomes part of the Girkin Limestone.

In the Fairfield Basin and Moorman Syncline, the Shetlerville is mostly drab, fine-grained skeletal and oolitic limestone. Interbedded with the limestone is dark gray to olive-gray clay shale that is fissile and highly fossiliferous. Shale interbeds become thicker and more numerous upward and toward the northwest.

Channels 1 to 3 m deep and a few tens of meters wide were observed in the lower Shetlerville at quarries in Hardin County, Illinois. Their filling is ooid and skeletal grainstone, which grades upward to muddy carbonates. Most likely these are tidal channels. Some channels in the Shetlerville cut across the lower sequence boundary and truncate the Bryantsville Breccia—an example of a local unconformity cutting out a regional one.

Renault Limestone

The Renault Limestone on the Western Shelf typically is either a single limestone bed less than 3 m thick or two such beds separated by 3 to 8 m of shale (plates 3 and 4). At outcrops in Monroe and Randolph Counties, Illinois, Walker (1985) described the Renault as lenses of skeletal packstone and lesser amounts of grainstone and wackestone. Some limestone is oolitic, and quartz sand is common. Walker interpreted the limestone lenses as shallow subtidal bars or shoals. In well samples, the limestone is mostly gray, somewhat sandy, sublithographic, dolomitic lime mudstone. Microbreccia and microfractures filled with sparry calcite were observed in large cutting chips. Shale of the Renault is gray to greenish gray, partly silty, calcareous, and fossiliferous. Thin lenses of sandstone occur; this rock is greenish gray, very fine grained, and calcareous. Red or variegated shale was noted on a few logs.

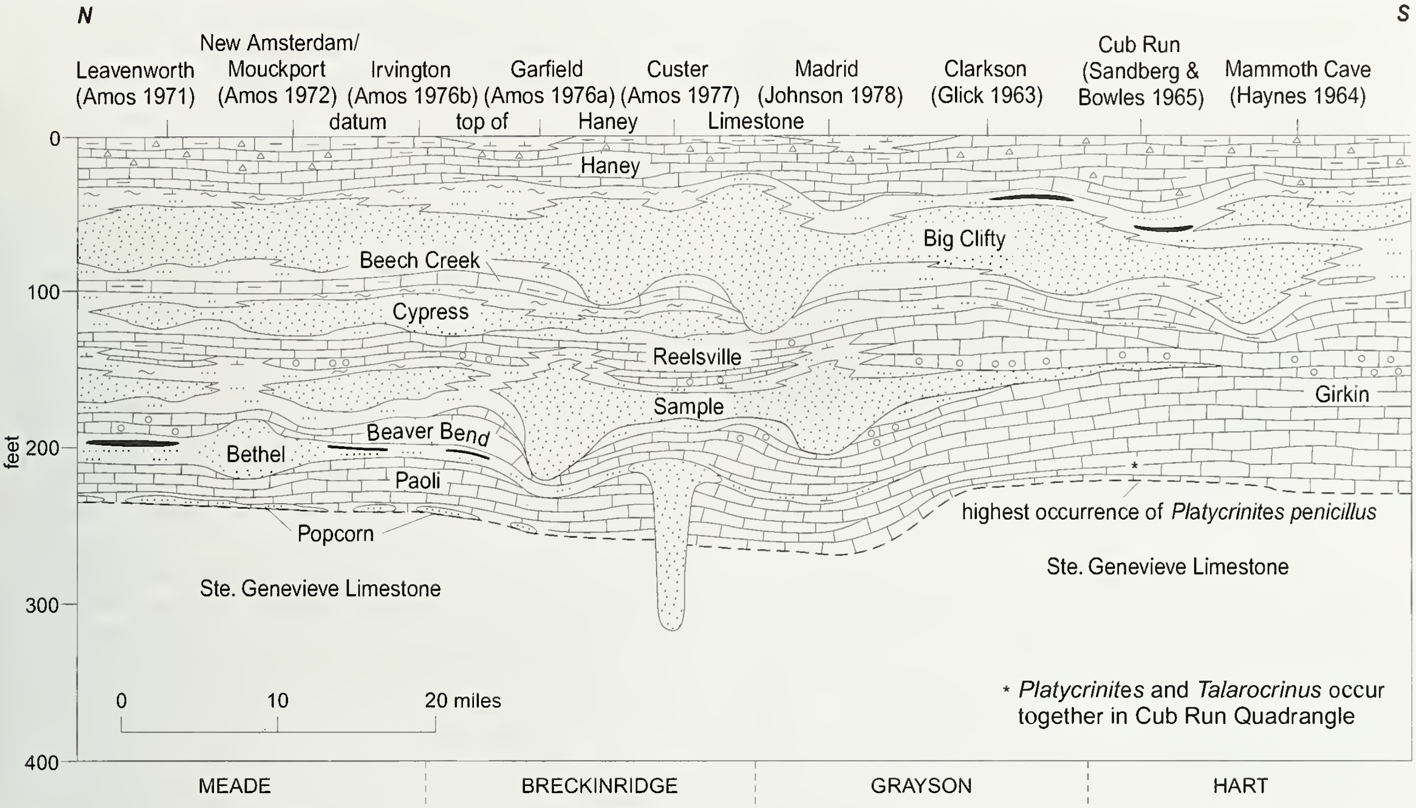

***Figure 21** Cross section KY-2, showing lower Chesterian rocks along the eastern margin of the Illinois Basin in western Kentucky, based on geologic quadrangle maps. Line of section is on figure 1.*

In some outcrops on the Western Shelf, the Renault contains *Talarocrinus* sp. and lacks *Platycrinites penicillus*, indicating that only the Shetlerville Member is represented (Spreng 1961, Thompson 1986). However, some well records (not on cross section) indicate two Renault limestone beds separated by sandstone, overlain in turn by red shale, gray shale, and coal. These strata imply a regression between two transgressions. Hence, the lower limestone bed may be the Levias and the upper bed may be the Shetlerville.

Yankeetown Member or Formation

Like the Spar Mountain and Aux Vases, the Yankeetown Formation is a siliciclastic unit that is thickest and coarsest to the northwest and grades southeastward to limestone and shale (fig. 22). Traced southeastward, the lower beds of the Yankeetown progressively intergrade with limestone of the Shetlerville, the uppermost sandstone beds extending farthest southeast (plates 2, 4, 6, and 7). On the northwest, the Yankeetown is as thick as 30 m and contains large bodies of sandstone. The sandstone forms large lenses that coalesce into a semi-continuous, pinching and swelling sheet (plates 3 and 4). The lower contact appears conformable and is nearly parallel to the top of the Renault, whereas the upper contact is strongly convex. Overlying shale and limestone thicken where the sandstone is thin, and vice versa, suggesting a series of offshore marine bars.

On the flank of the Ozark Dome (the type area), the Yankeetown thins to 6 m or less and is silicified to a quartzitic or chertlike texture (Weller 1913, Weller and St. Clair 1928, Thompson 1986). Describing this rock, Weller and Weller (1939, p. 11) stated, “Weathering, alteration of sandstones, and partial leaching of limestones appear to have progressed to variable depths . . . .” Cores from Madison County, Illinois, show that the upper part of the Yankeetown Sandstone is silicified and brecciated and contains chert nodules and caliche. Silicified sandstone is overlain by as much as 30 feet of red and green variegated shale and mudstone that contains several paleosols. Variegated mudstone occurs above the sandstone throughout the Western Shelf. The log of the Forester core (well 12, plates 4 and 5) from Perry County, Illinois, indicates a “conglomerate of weathered limestone” at the top of the sandstone, overlain by multi-colored shale. In outcrops near Millstadt, St. Clair County, the Yankeetown consists of siltstone to fine sandstone that is altered to a knobby, hummocky chert and overlain by variegated red and green mudstone. Current and linguloid ripples and tidal laminations in some outcrops indicate sediments deposited in shallow tidal settings and later altered as a result of prolonged exposure (Joseph A. Devera, ISGS, written communication 2000).

In southeastern Illinois, the Yankeetown consists of intercalated limestone and shale with isolated lenses of sandstone (fig. 22). The shale is largely fissile clay-shale that is calcareous and very fossiliferous. Colors are dark gray and dark

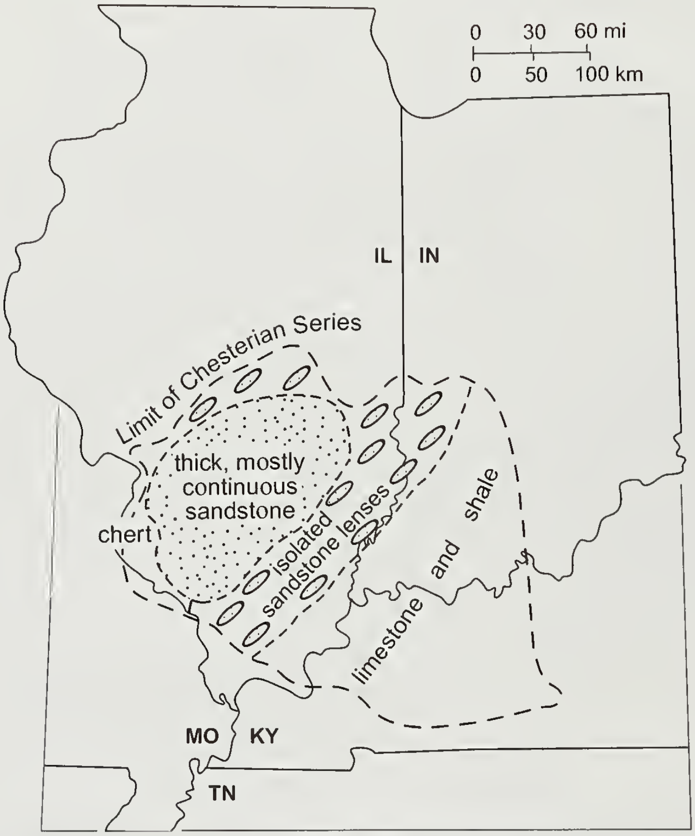

Figure 22 Map showing the generalized facies distribution of the Yankeetown Sandstone (Sequence 4).

greenish gray; red mottling appears in the upper part. Limestone interbeds are light-colored, coarse-grained skeletal and oolitic packstones and grainstones. Calcareous sandstone and siltstone occur as isolated lenses up to about 6 m thick. These rocks contain ooids and marine fossils, and grade laterally to silty limestone. A bed of orange to buff, microcrystalline dolomite is widespread near the top of the Yankeetown in southern Illinois. The uppermost Yankeetown consists of variegated, blocky mudstone that records paleosol development.

In Kentucky, near the border with Illinois, the Yankeetown averages about 12 m thick and is composed of shale and limestone thinly interbedded. Shale is largely greenish gray, less commonly reddish to brownish, and contains marine fossils. The limestone is similar to that of the Shetlerville, but shalier and richly fossiliferous. Small brachiopods of the genera *Composita, Eumetria,* and *Spirifer* are especially abundant, along with *Pentremites* and rugose corals (Trace 1976). The Yankeetown thins eastward in Kentucky, reaching a feather edge in Christian County (fig. 20) and thinning to less than 1 m of green shale near the middle of the Paoli Limestone in Meade, Breckinridge, and Grayson Counties (fig. 21). The uppermost shale layers of the Yankeetown extend farthest southeast.

On the Eastern Shelf in Indiana, the Yankeetown is thin (less than 2 m) and easily overlooked. The gray to green mudstone and siltstone contains nodules and lenses of lime mudstone and wackestone (Droste and Carpenter 1990). Mudstone variegated in red, green, gray, and ochre occurs at the top.

The Yankeetown is the only major sandstone unit in which no incised valleys are known. Thick Yankeetown sandstone bodies on the Western Shelf mostly appear conformable with underlying strata. Lectaru (1997) observed the Yankeetown lying directly on the Aux Vases, with no Renault intervening, at several outcrops in Missouri and southwestern Illinois. Whether the Renault was eroded or never deposited at these sites is not known.

Upper Sequence Boundary

Prolonged subaerial exposure is evident at the top of the Yankeetown throughout the basin and is most obvious on the flank of the Ozark Dome, where the sandstone is altered to a chertlike silcrete. Accompanying the silcrete are variegated mudstones that contain multiple paleosols. In the Fairfield Basin, the Shetlerville-Yankeetown succession records progressive shoaling. Open-marine carbonates at the base are overlain in turn by shallow subtidal (increasing shale content), tidal flat (variegated clay shales and microgranular dolomite), and finally supratidal (variegated mudstone that contains brecciated carbonate nodules) deposits. The irregular, commonly scoured contact of the Yankeetown with the overlying Downeys Bluff Limestone is the upper boundary of Sequence 4. Correlation of quarry sections and cores in Hardin and Pope Counties, Illinois, reveals several meters of erosional relief at this contact. The Downeys Bluff completely truncates the Yankeetown Member in places.

The sequence boundary locally may lie within the lower Downeys Bluff Limestone. For example, at the Hardin County Materials No. 2 Quarry (quarry highwall outcrop 14, plate 1), the basal 2 m of the Downeys Bluff is sandy, peloidal grainstone that contains graded lamination, low-angle cross-bedding, and other strong indicators of wind-blown deposition. Caliche occurs near the top of this unit, which is sharply truncated and overlain by cross-bedded (high-angle cross-bedding) grainstone and packstone. Hence, the lower Downeys Bluff appears to be subaerially deposited dune sand, whereas the remainder of the unit is marine.

Facies Pattern and Sediment Source

No incised valleys or lowstand sediments are known in Sequence 4. The Popcorn Sandstone Bed and lower limestone portion of the Shetlerville Member represent the TST. The upper part of the Shetlerville and the Yankeetown, making up the bulk of Sequence 4, are the HST. Smith (1996) identified two parasequences in the TST and four in the HST.

The Popcorn Bed may represent sand reworked from the Levias and Aux Vases, mixed with sand carried eastward from the Transcontinental Arch by marine currents or the wind. As Walker (1985) indicated, the Renault Limestone on the Western Shelf probably represents shallow subtidal bars and shoals deposited by strong waves and currents. The lower Shetlerville in the Fairfield Basin records quieter, but not necessarily deeper waters. Ooid-filled channels in the lower Shetlerville probably were created by tide- or storm-generated currents.

Thick coalescing lenses of sandstone in the Yankeetown on the eastern part of the Western Shelf and western Fairfield Basin appear to be large offshore marine bars or tidal sand ridges. These lenses seem to be analogous to better-documented examples in the Ste. Genevieve and Aux Vases below and Cypress above. More mapping of Yankeetown sand bodies is needed to test the hypothesis of the tidal sand ridge.

As in Sequences 1 and 2, terrigenous clastics in the HST of Sequence 4 prograded southeastward across the Illinois Basin from the Transcontinental Arch. This sequence is the last in which the Transcontinental Arch was a major source area.

Sequence 5

Sequence 5 is a thin sequence that includes the Downeys Bluff Limestone and, in places, the lower part of the Bethel Formation and equivalent rocks in the Girkin Limestone (figs. 5 and 15). Sequence 5 is 1.5 to 10 m thick on the Western Shelf, up to 20 m thick in the eastern Fairfield Basin, 7 m thick near the Cincinnati Arch, and less than 3 m thick on the northern part of the Eastern Shelf.

Downeys Bluff Limestone Member

The Downeys Bluff Limestone is virtually continuous and an excellent subsurface marker bed in Illinois, where its thickness varies from as much as 15 m in southeastern Illinois to as little as 1.5 m on the Eastern and Western Shelves. White to light gray or buff, coarse-grained crinoidal and oolitic grainstone are the dominant rock types. Pink, orange, or red silicified echinoderm fragments are diagnostic of the Downeys Bluff in much of Illinois, but are most abundant on the Western Shelf, where the unit is thin. In southeastern Illinois, the bright-colored grains are sparse and occur mostly in the upper part of the limestone. In Kentucky and Indiana off the Eastern Shelf, the Downeys Bluff is largely light gray crinoidal and oolitic grainstone, but the lower part tends to be darker, more micritic, and dolomitic. On the Eastern Shelf in Indiana, more micritic lithofacies are present: skeletal packstone, wackestone, and dolomitic lime mudstone. Microgranular dolomite and dolomitic limestone make up much of the Downeys Bluff in Perry and Spencer Counties, Indiana.

Where the Downeys Bluff is thick, its lower part commonly contains quartz-peloid grainstone of probable eolian origin. This lithology is found in many subsurface sample logs as well as in quarries and outcrops. Quartz-peloid grainstone also occurs at the top of the Downeys Bluff in surface sections near the Cincinnati Arch (plate 1). Shale interbeds, some of which are traceable for many kilometers on well logs, occur near the basin center. Some shales are dark gray to greenish gray and calcareous; others are variegated and mottled.

Red, green, and variegated shale or mudstone are common at the top of the Downeys Bluff. This unit tends to be a fissile marine shale in basinal areas and a blocky to massive paleosol on the shelves. In Livingston County, Kentucky, near the axis of the Moorman Syncline, Amos (1967) reported as much as 8 m of greenish gray, calcareous shale between the limestone and the Bethel Sandstone. A soil regolith is present at the same position near the southeast margin of the basin (fig. 23). On the Western Shelf, the log from the Forester core (well 12, plate 4) in Perry County, Illinois, records a "conglomerate of weathered limestone pebbles and boulders with interstitial red shale" at the top of the Downeys Bluff.

Figure 23 A soil regolith in the Paoli Limestone in a road cut near Park City in Barren County, Kentucky (outcrop section 33).

Bethel Sandstone

The Bethel Sandstone (Butts 1917) is a thick sandstone unit in much of the Illinois Basin, but on the Eastern and Western Shelves it thins markedly and becomes mostly shale and mudstone. The name Mooretown Formation has been used by many geologists for the shaly facies of the Bethel on the Eastern Shelf. Because equivalence of Bethel and Mooretown is generally accepted and the name Bethel has priority, Bethel should be retained and Mooretown suppressed.

Like many other Chesterian siliciclastic formations, the Bethel is divided between two sequences. The older part of the Bethel is in Sequence 5, and the younger part, including thick valley-fill sandstones, belongs to Sequence 6.

On the Eastern Shelf, the Bethel is largely shale that is dark gray to olive and greenish gray, locally mottled with red. In places, the shale contains marine fossils and lenses of micritic limestone. Lenses of fine- to medium-grained sandstone, containing fossil plant stems and leaves, occur within the shale. Near the top of the Bethel, claystone containing stigmarian root casts is overlain by a widespread bed of shaly coal as thick as 45 cm. Red and green mottled mudstone occurs locally instead of coal. On the flank of the Cincinnati Arch, from Logan to Hardin Counties, Kentucky, the Bethel is reduced to 1 to 3 m of sandy limestone and shale within the Girkin Limestone. This interval, overlooked by many geologic quadrangle mappers, can be identified in large road cuts and quarries. Laminated, silicified, micritic crusts and stringers (caliche) and other evidence of subaerial exposure occur in this interval, as reported by Dever et al. (1979).

The Bethel likewise thins onto the Western Shelf and loses most of its sandstone. On the southeastern part of the shelf in Perry County, Illinois (plates 3 and 4), the Bethel consists of calcareous shale that contains abundant bryozoans and other marine fossils and lenses of calcareous sandstone. Farther north and west, the Bethel thins to less than 5 m and changes to red and green variegated, fissile shale and maroon or variegated, blocky, slickensided mudstone (plates 2, 3, and 4).

In the Fairfield Basin and western part of the Moorman Syncline, only a thin interval of shale, siltstone, and mudstone at the base of the Bethel is interpreted as part of Sequence 5. Through much of this region, these beds were scoured away prior to deposition of sandstone of the upper Bethel, which is part of Sequence 6.

Upper Sequence Boundary

Through most of the Fairfield Basin and western Moorman Syncline, the top of Sequence 5 is at the base of the Bethel Sandstone. This erosional contact is marked by lag deposits of chert, limestone, and shale pebbles. No valley incision is documented beneath the Bethel in the Fairfield Basin, but a remarkably deep Bethel channel crosses western Kentucky (details are presented in Sequence 6). The upper boundary of Sequence 5 on the Eastern and Western Shelves is placed at the top of paleosols near the top of the Bethel Formation. The paleosol is an underclay (claystone underlying coal) in places; elsewhere, it is a maroon or variegated claystone. Variegated mudstone that locally overlies the Downeys Bluff in the Fairfield Basin probably is a paleosol also, but in most places this mudstone was eroded prior to Bethel deposition.

Facies Pattern and Sediment Source

Like many Chesterian sequences, Sequence 5 lacks known lowstand sediments. The lower part of the Downeys Bluff Limestone is assigned to the TST, whereas the upper Downeys Bluff and Bethel portion of the sequence represent the HST. Smith (1996) identified four parasequences, of which only one was traced out of the basin interior onto the Eastern and Western Shelves.

During deposition of Sequence 5, the Fairfield Basin subsided more rapidly than the Eastern and Western Shelves, but otherwise the region was quiet tectonically. Ocean waters never were deep anywhere in the basin. Even at maximum flooding, oolitic and crinoidal grainstones accumulated under energetic, shallow subtidal conditions. Bethel sediments on the shelves probably were deposited in shallow, subtidal conditions during highstand. Portions of the shelves were exposed, and the wind formed dunes of carbonate sand. Late in Sequence 5 deposition, as sea level dropped, widespread tidal mud flats and marshes developed, and finally paleosols formed.

The Transcontinental Arch no longer was a major source of sediment to the Illinois Basin. The source of the thin, lenticular sands in Sequence 5 is not obvious, but the presence of medium-grained sand on the Eastern Shelf suggests an eastern source. Following deposition of Sequence 5, most Chesterian siliciclastics came from northeastern sources.

Sequence 6

Sequence 6 comprises most of the Bethel Sandstone (including valleys fills) along with the Beaver Bend Limestone and the older part of the Sample Sandstone (figs. 5 and 15). Equivalent units include parts of the Paint Creek Formation in southwestern Illinois, the Ridenhower Formation in southern Illinois, and the Girkin Limestone in Kentucky. Sequence 6 thickens from as little as 7 m on the flank of the Cincinnati Arch to 25 m on the northern part of the Eastern Shelf in Indiana. In the central Fairfield Basin the sequence is commonly 30 to 40 m thick, but it thins rapidly toward the west and north. Thickness on the Western Shelf is not accurately known because of uncertainty about the upper boundary but is probably less than 15 m in most places.

Stratigraphic Nomenclature

Facies changes and early miscorrelations, made before subsurface data became widely available, resulted in a confusing array of unit names being applied to Sequence 6 and adjacent sequences (fig. 4).

The situation on the Eastern Shelf is fairly straightforward. The Bethel Sandstone, Beaver Bend Limestone, Sample Sandstone, Reelsville Limestone, and Cypress Formation are relatively tabular, lithically distinct, and have been mapped at 1:24,000 scale across several counties of Indiana and Kentucky. These units can be traced downdip in the subsurface from the Eastern Shelf into the eastern Fairfield Basin (plates 6 and 7).

In the central Fairfield Basin, the Beaver Bend and Reelsville Limestones are thin, discontinuous, and difficult to map. The Ridenhower Shale is equivalent to the Beaver Bend, Sample, and Reelsville together (fig. 4). On the Western Shelf, the Paint Creek Formation (Weller 1913) is equivalent to Downeys Bluff Limestone, Bethel Sandstone, and Ridenhower Shale of southern and central Illinois.

The name Paint Creek Shale was used by geologic quadrangle mappers in Crittenden, Livingston, and Caldwell Counties, Kentucky, for strata that are called the Ridenhower Formation in Illinois. Farther east, this interval changes to limestone, which the mappers called Paint Creek Limestone. This usage of Paint Creek conflicts with that of the type area, where older rocks are included in the Paint Creek.

We propose the following changes in this report:

1. ***The Paint Creek Formation is restricted to the Western Shelf*** and should not be used in Kentucky. Limestone is the principal lithology; mudstone, shale, siltstone, and sandstone are subordinate. The Downeys Bluff Limestone, Bethel, and Ridenhower Members are recognized in some areas. Strata previously called "Paint Creek Limestone" in Kentucky are here referred to as Beaver Bend and Reelsville Limestones, undifferentiated.

2. ***The Ridenhower Formation is restricted to areas where shale dominates,*** and the constituent Beaver Bend, Sample, and Reelsville units are not mappable at the scale required for a formation. These areas include southern and southeastern Illinois and the adjacent part of Kentucky where the name "Paint Creek Shale" previously was used. The Beaver Bend, Sample, and Reelsville may be classified as members of the Ridenhower in this area.

3. ***The Beaver Bend, Sample, and Reelsville are extended into Illinois at formation rank*** where these units are mappable.

Bethel Sandstone (Younger Part)

The Bethel Sandstone is thick and semi-continuous in southeastern Illinois, southwestern Indiana, and the adjacent part of western Kentucky (fig. 24). This thick Bethel is believed to belong to Sequence 6. In places, the thick Bethel appears sheetlike, but more commonly it forms a series of coalescing lenses that have flat bases and convex tops (plates 4 and 7). Isopach mapping in Indiana (Sullivan 1972) indicates that the long axes of the lenses, like those of many Chesterian sandstones, trend northeast-southwest to north-northeast–south-southwest.

The Bethel of Sequence 6 is white to light gray, very fine- to medium-grained quartz arenite. Commonly it contains calcareous marine bioclasts and is cemented by calcite. In many wells, the upper part of the Bethel grades to sandy limestone, which may grade in turn to sand-free limestone of the Beaver Bend. On the outcrop, the Bethel exhibits herringbone cross-lamination, flaser bedding, and other features indicative of tidal processes.

Also in Sequence 6 is the fill of a deeply incised Bethel paleochannel in western Kentucky. The deepest of all Chesterian incised valleys, this slightly sinuous channel extends southwest from Harrison County, Indiana, to Caldwell County, Kentucky, a distance of more than 160 km (Reynolds and Vincent 1967, Sedimentation Seminar 1969). It is 0.8 to 1.2 km wide, steep-sided, and as deep as 75 m, locally cutting into the St. Louis Limestone. Near its southwestern end, the Bethel channel bifurcates several times, suggesting distributaries of a delta (fig. 24). The lower part of the valley fill is dominantly sandstone that exhibits unidirectional, southwest-dipping planar and trough cross-bedding. The sandstone is mostly fine- to medium-grained, but locally contains coarse sand and small quartz granules. It is quartz arenite that contains scattered marine bioclasts and has quartz and calcite cement. Lens-shaped bodies of limestone as thick as 12 m occur in the upper part of the channel fill. The limestone is largely medium to coarse skeletal and crinoidal grainstone that is sandy and contains coal clasts (Sedimentation Seminar 1969).

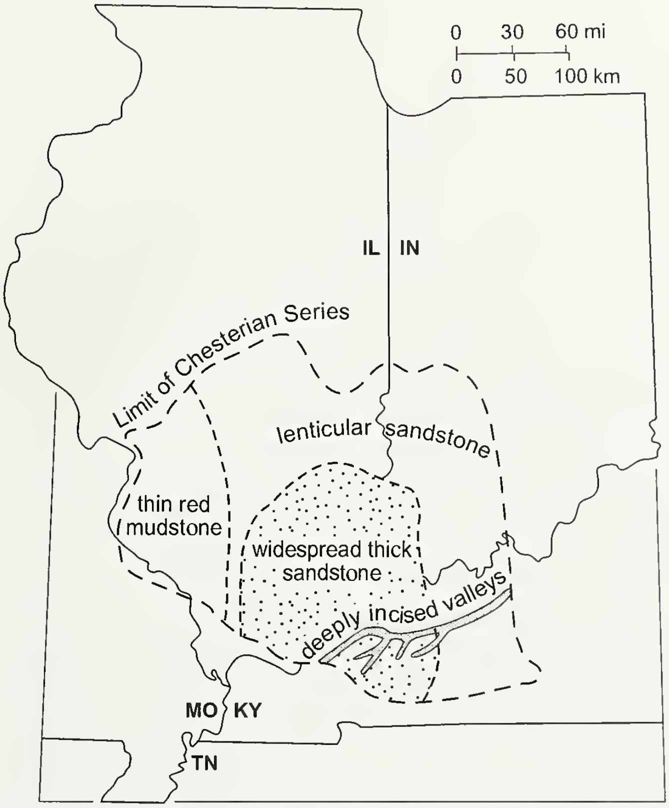

***Figure 24** Map showing the generalized facies of the Bethel Sandstone (Sequences 5 and 6).*

Beaver Bend Limestone

The Beaver Bend Limestone is a continuous, nearly tabular unit on the Eastern Shelf in Indiana (plates 6 and 7). Light-colored oolitic and crinoidal grainstone, packstone, and wackestone are the usual lithologies. The sharp but conformable contact to the Bethel in this area evidently reflects a rapid transgression. The Beaver Bend also is mapped in Meade, Breckinridge, and Grayson Counties, Kentucky. It thickens from 1 to 8 m near the Ohio River to 3 to 15 m on the south, where it becomes part of the Girkin Limestone (fig. 21). As described on geologic quadrangle maps, the Beaver Bend is largely micritic to fine-grained, yellowish gray to yellowish brown limestone. Oolitic limestone is common near the top of the unit; the ooids have dark nuclei. The Beaver Bend contains chert nodules, calcite-filled vugs, and thin interbeds of greenish gray shale. Common fossils include spiriferid and productid brachiopods, blastoids of *Pentremites* sp., the crinoids *Agassizocrinus* sp. and *Talarocrinus* sp., and the coral *Lithodrumus veryi* Greene.

In the western Moorman Syncline, the Beaver Bend (mapped as part of the "Paint Creek Limestone") consists of dark brownish gray, micritic and dolomitic limestone at the base, grading upward through crinoidal packstone and grainstone to oolitic grainstone at the top. In southeastern Illinois (eastern part, plate 3; northern part, plate 5), the Beaver Bend directly overlies the Bethel Sandstone with a gradational contact (not shown). Limestone occurs mainly above the thickest parts of convex-upward Bethel sand ridges and is absent between the ridges. Dark gray calcareous shale fills the swales between ridges. Evidently, carbonate developed on the shoals at the crests of sand ridges, while mud filled the deeper intervening swales.

In the central part of the Fairfield Basin (plates 2, 3, and 5), the Beaver Bend is typically thicker and more persistent than the younger Reelsville Limestone. This situation partially reflects erosion of the Reelsville in incised valleys filled with the Cypress Formation (Sequence 8). Few Cypress paleovalleys reach the Beaver Bend in the central basin. Where the Bethel

Sandstone is thin, as in Franklin County, Illinois (plate 3), the Beaver Bend comprises a thin lower limestone and a thin, sandy upper limestone, separated by 18 m or more of dark olive-gray clay shale. These strata are equivalent to the Ridenhower Formation at its type section in Johnson County, Illinois. In other areas, the Ridenhower contains Sample and Reelsville equivalents.

On the Western Shelf, the Beaver Bend is part of the upper limestone member of the Paint Creek Formation, overlying variegated mudstone of the Bethel Member. No details from this area are available.

Sample Sandstone (Older Part)

The Sample Sandstone (or Formation), like several other Chesterian sandstone units, is divided between two sequences. The older part of the Sample belongs to Sequence 6, and the younger part, consisting mainly of valley fills, is in Sequence 7. The formation is thickest in the south-central and southeastern part of the basin (fig. 25). Toward the north and west, the Sample is dominantly shale and can be difficult to identify.

The Sample is best known from outcrops and shallow subsurface data on the Eastern Shelf of Indiana and Kentucky. Here it is 3 to 15 m thick and composed of shale, siltstone, sandstone, and mudstone. The lower part commonly is dark gray to greenish gray shale, which contains marine fossils, particularly *Agassizocrinus* sp. and *Talarocrinus* sp. Sandstone is very fine- to medium-grained quartz arenite that is thin- to thick-bedded and contains shale clasts, carbonized plant remains, and casts of brachiopods. Variegated mudstone overlies sandstone near the top of the Sample in many places on the Eastern Shelf in both Kentucky and Indiana.

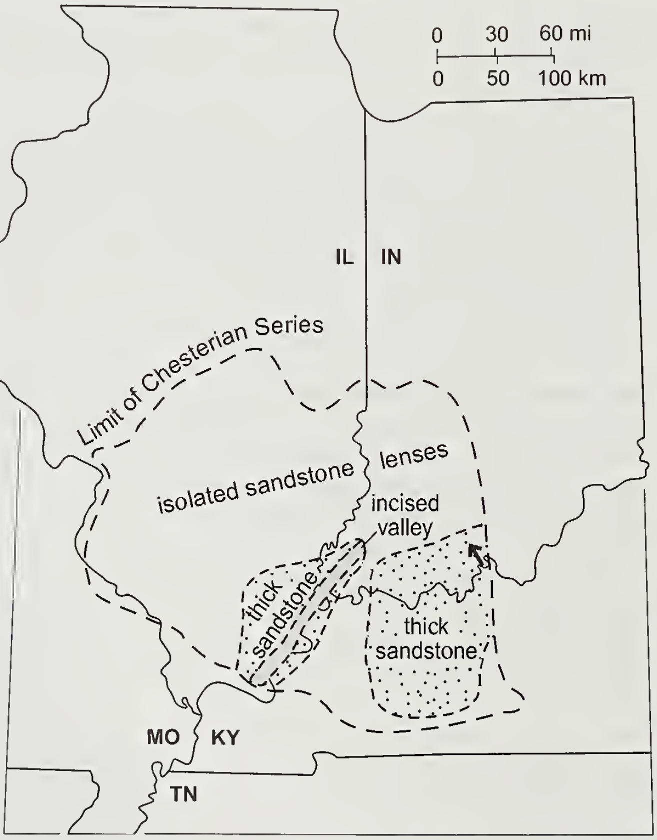

Figure 25 Map showing the generalized facies of the Sample Sandstone (Sequences 6 and 7). Arrow represents trend of incised valleys at Cape Sandy and Temple Quarries in southern Indiana.

A consistent succession of facies was found in a study of the Sample Formation at large quarry and road cut exposures in southern Indiana (Ambers and Robinson 1992). The lower Sample is dark gray shale that contains marine fossils, including spiriferid, compositid, and productid brachiopods, bryozoans, myalinid bivalves, and the trace fossil *Conostichus broadheadi*, which is attributed to burrowing sea anemones. Lenses of sandstone that contain marine bioclasts occur locally at the base of the shale. The shale coarsens upward to siltstone and/or sandstone that displays ripple and cross-lamination, tidal bundles, and herringbone cross-bedding. The sandstone at one quarry defined bars with long axes running north-south and lying about 30 m apart. Above the sandstone is blocky, slickensided mudstone that is variegated in olive, green, purple, and gray (fig. 26). Root casts and local flint clay and carbonate caliches (fig. 27) define the mudstone as a paleosol (Ambers and Robinson 1992).

The Reelsville Limestone directly overlies the paleosol in some places. Elsewhere, the uppermost Sample strata above the paleosol are siltstone and sandstone that contain abundant evidence of tidal influence. Also, at two quarries in Crawford County, Ambers and Robinson (1992) observed incised valleys that cut down from the top of the Reelsville. The upper tidal strata and the valley-fill strata are described in Sequence 7.

We traced the Sample Formation into southeastern Illinois, where it is a fairly tabular sandstone about 12 m thick (plate 5). In southern Gallatin and northern Hardin Counties, the Sample Sandstone thickens to more than 30 m, filling valleys that entirely cut out the Beaver Bend. The valley-fill phase is in Sequence 7. In the central Fairfield Basin north of White County (northern plate 5, eastern plate 2), the Sample consists of 3 to 9 m of shale with isolated sandstone lenses. Several sample logs indicate variegated shale or mudstone (paleosol?)

Figure 26 Paleosol composed of variegated mudstone in the Sample Formation at the Mitchell Quarry in Lawrence County, Indiana (outcrop section 64). Reelsville Limestone is at top of view.

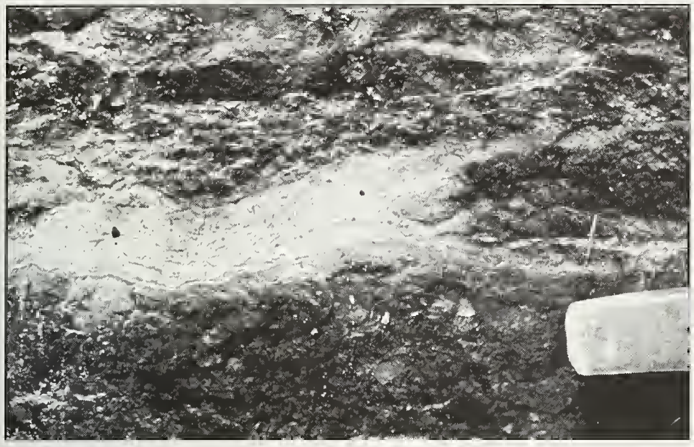

Figure 27 Caliche in siltstone in the Sample Formation in a road cut northwest of Bowling Green, Warren County, Kentucky (outcrop section 29).

in the lower part of the Sample in this area. The sequence boundary accordingly was drawn at the top of the variegated shale.

In the western part of the Fairfield Basin and along the eastern edge of the Western Shelf (plate 4 and western part of plate 3), the Sample Formation appears to average 9 to 12 m thick and is mostly shale and siltstone. Sandstone occurs as lenticular to sheetlike bodies that are generally less than 6 m thick. The sandstone is fine grained, shaly, partly calcareous, and may be burrowed. No evidence was observed for downcutting at the base of sandstone bodies. Variegated shale or mudstone occurs in the upper Sample (above the sandstone, where present) in a few wells. This shale probably marks the top of Sequence 6.

The Sample has not been identified at outcrops or in the subsurface on the western part of the Western Shelf. In the Madison County cores (plate 2), the Cypress Formation cuts out the Sample. The Sample may occur as a thin shale or mudstone break within the upper limestone member of the Paint Creek Formation south of Madison County. The Sample is missing due to valley-cutting at the base of the Cypress Formation (Sequence 8) in much of south-central and southwestern Illinois.

Ridenhower Formation

The Ridenhower Formation (or Shale) is composed predominantly of shale and lies between the Bethel and Cypress Sandstones in parts of southern and southeastern Illinois and neighboring parts of Kentucky. The Ridenhower is equivalent to the Beaver Bend Limestone, Sample Formation, and Reelsville Limestone in the eastern part of the basin. In places, these units can be identified within the Ridenhower and classified as members.

The Ridenhower is highly variable in thickness, ranging from a few meters to more than 25 m. Abrupt local variations in thickness result from both compaction over lenses of Bethel Sandstone and erosion at the base of the Cypress. The principal lithology is well-laminated clay-shale that is dark greenish gray and dark gray. Planar, wavy, and ripple laminations of light gray siltstone are common. Some shale is calcareous, and the bedding planes crowded with fenestrate bryozoans, brachiopods, and other marine fossils.

One to three beds of limestone, typically thinner than 1.5 m, are present in many areas. The limestone is dark gray to reddish gray wackestone to packstone composed of large fragments of echinoderms, brachiopods, and other fossils in a very shaly to sandy, micritic matrix. Limestone beds grade laterally to calcareous shale and sandstone that contain marine fossils. The thickness and number of limestone interbeds in the Ridenhower increase westward across southern Illinois. Where limestone becomes the dominant lithology, the name Paint Creek Formation is used rather than Ridenhower.

Siltstone and thin-bedded, shaly sandstone intergrade with clay shales of the Ridenhower in southeastern Illinois and western Kentucky. Much of the sandy strata appear to represent facies gradation between the Sample Sandstone and Ridenhower. In some areas, however, the Ridenhower (as mapped) may contain shaly equivalents of the upper Bethel and lower Cypress Formations.

Upper Sequence Boundary

In areas where the lower part of the Sample Formation is conformable to older units, the upper boundary of Sequence 6 is at the top of the paleosol in the upper part of the Sample. Generally this part is a red and green, variegated mudstone, overlain by either the Reelsville Limestone or a thin interval of shale and heterolithic facies below the Reelsville. This contact generally is sharp and locally exhibits scouring.

In several areas on the Eastern Shelf and eastern part of the basin interior, the upper Sample Sandstone fills valleys that cut as deeply as the Downeys Bluff Limestone. These valleys and their filling are described in the section on Sequence 7.

Facies Pattern and Sediment Source

Sequence 6 is one of the few Chesterian sequences that has a clearly defined LST: the fluvial sandstone filling the lower part of the deeply incised Bethel paleovalley in Kentucky. This coarse, poorly sorted sandstone has large-scale, unidirectional, southwest-facing cross-beds. Remarkably, this paleovalley crossed a shelf area rather than the Fairfield Basin, where subsidence was greatest. Flanking out-of-channel Bethel sediments are only a few meters thick along much of the length of the channel. This channel must have been a trunk stream that became deeply entrenched in carbonate rock. The resistant substrate would have hindered lateral widening of the valley.

Tectonic movements along northeast-trending faults that cross the Moorman Syncline may have influenced channel incision. Portions of the paleovalley are remarkably linear and run parallel to mapped faults, as in the Constantine Quadrangle (Sable 1964). Tectonism possibly accounts also for the unusual depth of this paleovalley. Uplift during incision might have forced the valley to downcut more deeply, an example of antecedent drainage.

The remainder of the Bethel Formation, together with the lower fine-grained part of the Beaver Bend Limestone, comprise the TST. The MFS for Sequence 5 is probably at the base of the skeletal wackestone unit in the lower part of the Beaver Bend Limestone on the Eastern Shelf (Kissling 1967). In the western part of the basin, the MFS is tentatively placed near the base of the Ridenhower Shale or in the lower part of the Paint Creek Formation above the Bethel Member. A scarcity of core and outcrop data hinders sequence interpretation of the Paint Creek. The upper part of the Beaver Bend is a highstand facies that typically consists of skeletal wackestone grading upward to skeletal grainstone or packstone. In the Fairfield Basin, the Beaver Bend either pinched out on tidal sand ridges of the Bethel, or was removed by subsequent incision, or changed facies into quartz sandstone of the West Baden clastic belt. Overlying fossiliferous shale and heterolithic strata of the Sample Formation represent regressive facies.

The southwest-flowing Bethel paleovalley implies a northeastern source for Bethel sediment. Source areas for the Sample are less well marked, but this unit generally is thickest and sandiest on the eastern side of the basin, implying an eastern or northeastern source.

Sequence 7

Sequence 7 contains the valley-fill phase of the Sample Sandstone, all of the Reelsville Limestone, and the oldest (pre-valley fill) part of the Cypress Formation (fig. 5). The sequence is 20 to 45 m thick in the basin interior and 15 to 27 m in the Moorman Syncline and on the Eastern Shelf. Sequence 7 pinches out near the Cincinnati Arch and is missing on much of the Western Shelf because of erosion beneath Sequence 8.

Sample Sandstone (Uppermost Part and Valley Fill)

An interval of sandstone and siltstone a few centimeters to several meters thick locally overlies the paleosol near the top of the Sample Formation. This interval contains marine body fossils, oolites, tidal rhythmites, and herringbone cross-lamination. These features, evidence of marine transgression, place the uppermost part of the Sample in Sequence 7.

The Sample Formation also fills valleys incised into older strata in Indiana and eastern Illinois (fig. 25). We observed Sample valley fills at the Cape Sandy and Temple Quarries in Crawford County, Indiana, where Ambers and Robinson (1992) documented them earlier. Channels here strike N 30°W and cut down as much as 14 m from the paleosol near the top of the Sample, removing the lower marine part of the Sample and, in places, nearly all of the Beaver Bend as well (fig. 7). The sandstone filling the channels is a clean quartz arenite that contains marine body fossils and trace fossils (*Cruziana* ichnofacies). These channels are among the best examples of Chesterian incised valleys in the Illinois Basin. Other Sample paleovalleys are defined by well data in western Warrick and Vanderburgh Counties, Indiana (plate 7), and Knox and Pike Counties, Illinois (plate 6). Note that variegated mudstone (paleosol) is absent in the upper Sample within paleovalleys.

This study shows that much of the sandstone previously mapped as Bethel in southeastern Illinois actually is the valley-fill phase of the Sample Sandstone (plate 5). In central White County, the Sample Formation is a thin shale, bracketed by Beaver Bend Limestone below and Reelsville Limestone above. Southward, the Sample thickens and becomes mostly sandstone; logs indicate that the sandstone fines upward, which is consistent with a channel or valley fill. South of well 5 (plate 5) the Sample truncates the Beaver Bend and cuts into the Bethel (fig. 28). The core of well 1 shows the Sample, with basal conglomerate, resting directly on the Downeys Bluff Limestone.

Outcrop and core studies in Hardin and Pope Counties, Illinois, confirm that the Sample fills deep paleovalleys. In this area, the Sample is a fining-upward sandstone that commonly is thicker than 30 m. The upper part is very fine-grained, thin-bedded, and commonly burrowed. The lower part is fine- to medium-grained and contains scattered coarse sand grains and quartz granules (previously ascribed to the Bethel). The lower sandstone generally shows unidirectional cross-bedding in sets up to several feet thick. A basal conglomerate of shale, siltstone and limestone clasts, and fossil plant stems commonly is developed. This contact truncates underlying strata, showing as much as 3 m of local erosional relief (fig. 26). In contrast, the underlying Bethel Sandstone is very fine to fine quartz arenite interlaminated with greenish gray shale. Its herringbone cross-bedding and flaser bedding are indicative of tidal activity. Preserved thickness varies from 0 to about 6 m.

A cross section based on outcrops and cores in Johnson, Massac, and Pope Counties, Illinois (fig. 29), shows the valley-fill phase of the Sample (Sequence 7) deeply incised into the Bethel on the east. Westward, the Sample becomes thinner and less deeply downcut. The valley-fill phase of the Cypress (Sequence 8) gradually cuts downward toward the west and removes the Reelsville Formation.

Two sandstone/limestone couplets, both interpreted as Sample Formation, are present in eastern Saline and Gallatin Counties, Illinois (near the east end of plate 3). These couplets are designated Subsequences 7a and 7b. Examples of sandstone fining upward (valley fill?) and coarsening upward (prograding?) are shown for both subsequences. The extent and significance of the subsequences are unclear, particularly because much of Subsequence 7b is truncated by Sequence 8. This complex area requires further study.

Reelsville Limestone

In Indiana, the Reelsville is typically a single bench of limestone, 1 to 10 m thick. Light gray oolitic and skeletal grainstone and packstone make up most of the unit. In some places, two benches of limestone are separated by a meter or so of marine shale (Ambers and Robinson 1992). The Reelsville becomes lenticular in western Indiana; distinguishing the Reelsville from the Beaver Bend is difficult in the area of the West Baden clastic belt (plates 6 and 7).

The Reelsville varies from 1.5 to 18 m thick on the Eastern Shelf in Kentucky but, in most places, is 3 to 12 m. The

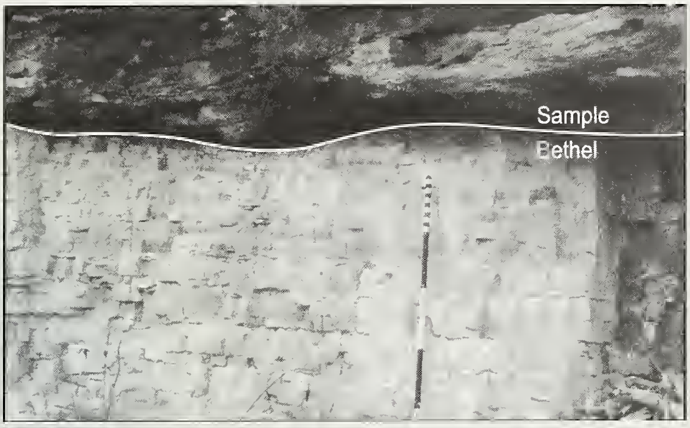

Figure 28 Outcrop showing the contact between the Sample Sandstone in Sequence 7 and the Bethel Sandstone in Sequence 6 at Roper's Landing, Pope County, Illinois. The Sample is coarser grained and more thickly bedded than the Bethel. Previously, both sandstones in this area were identified as Bethel. Staff is graduated in feet and inches.

Reelsville tends to thicken where the Sample is thin, and vice versa. The limestone is mostly light gray to light olive-gray, weathering reddish gray in places. Characteristic fossils include large, abundant fragments of *Agassizocrinus*, along with *Talarocrinus* sp., *Pentremites* sp., *Girtyella* sp., *Composita* sp., productid brachiopods, and horn corals. Much of the limestone is crinoidal wackestone to grainstone that contains thin micritic interbeds and occasional laminae and partings of greenish gray shale. Both the upper and lower parts of the Reelsville are oolitic, and the lower part is commonly sandy.

The Reelsville is a thin but persistent limestone unit in Illinois near the Indiana border (plates 2 and 5). Generally it is a single limestone bed less than 3 m thick, but, in places, two thin limestone layers are separated by a meter or two of shale. Lithologic details are few, being based solely on well cuttings. In the Fluorspar District of southeastern Illinois, where the Sample fills deep incised valleys, the Reelsville Limestone becomes sporadic. One or two thin beds of limestone are found within a thick (commonly 12 to 25 m) succession of shale, the Ridenhower Formation. This dark greenish gray to dark gray, calcareous clay and shale contains marine fossils and intertongues with the upper part of the Sample Sandstone. The limestone is dark, very argillaceous, and sandy crinoidal or skeletal packstone and wackestone; beds rarely are thicker than 2 m.

The Reelsville is absent or not identifiable in large areas of the central Fairfield Basin in Illinois, where the Cypress Formation fills deeply downcut paleovalleys (plates 2 and 3). On the southern part of the Western Shelf, the Reelsville probably occurs as part of the upper limestone member of the Paint Creek Formation. Northward on the shelf, as in Clinton County (plate 2), the Paint Creek limestones grade laterally to Ridenhower shales, and the Reelsville cannot be identified. The Cypress Formation truncates the entire Ridenhower in Madison County (plate 2).

Cypress Formation (Older Part)

Nomenclature The Cypress Sandstone or Formation was named by Englemann (1863) for Cypress Creek in Johnson County, Illinois. Malott (1919) named the Elwren Formation for a locality in Monroe County, Indiana. Later subsurface

Figure 29 Cross section illustrating variation in Sequences 6 and 7 in southernmost Illinois, based on outcrop and core data. Datum is the top of the Downeys Bluff Limestone. Sequences are numbered, and their boundaries are indicated by bold lines.

work confirmed that the Elwren is entirely correlative with the Cypress; however, the name Elwren is still used on the outcrop in Indiana. The use of two names for the same unit is confusing and contrary to the North American Stratigraphic Code (NACSN 1983). Because the name Cypress has priority, we are abandoning the name Elwren.

Lithology The Cypress Formation is divided among three sequences. As interpreted here, the oldest part of the Cypress is in Sequence 7, the bulk of the Cypress is in Sequence 8, and the youngest or uppermost part is in Sequence 9 (figs. 5 and 15).

On the Eastern Shelf, nearly the entire Cypress belongs to Sequence 7. It is largely shale in this area, with lenses of sandstone in the lower part and persistent red and green variegated mudstone in the upper part (fig. 30; plates 6 and 7). Shales are dark gray, olive-gray, and greenish gray, locally mottled with reddish gray. Some shale contains laminae and lenses of light gray sandstone and siltstone. Sandstone is very fine- to fine-grained quartz arenite that is mostly laminated to thin-bedded. Small channels eroded into the Reelsville Limestone are locally present, as in Todd County, Kentucky (Shawe 1967).

Ambers and Petzold (1992) interpreted the Cypress in southern Indiana as a prograding, subtidal to supratidal succession. Dark gray shale and cross-bedded, lenticular sandstone in the lower Cypress commonly contain marine fossils. These rocks are overlain by fissile, variegated shale interpreted as tidal mud flat or lagoon deposits. Next is bedded, micritic dolostone that probably formed on supratidal mud flats. The upper Cypress is maroon, blocky mudstone that has mud cracks, root traces, and other features of paleosol formation (fig. 30).

The Cypress is 6 to 18 m thick on the Eastern Shelf in Indiana, generally thinning toward the east. In Kentucky it thins southward from 17 m near the Ohio River to less than 1 m south of Hart and Edmonson Counties (fig. 21). Approaching the Cincinnati Arch, the Cypress grades to calcareous shale that contains lenses of limestone. On the flank of the arch near Bowling Green, large road cuts show that the Cypress consists of 10 to 50 cm of soft, calcareous shale overlying argillaceous, nodular limestone that shows abundant evidence of subaerial exposure. Although geologic quadrangle mappers did not identify the Cypress in this area, the lithology and position directly beneath the Beech Creek Limestone leave no doubt as to the correlation.

The Western Shelf is more or less a mirror image of the Eastern Shelf. The Cypress thins dramatically and becomes mostly shale, containing thick variegated mudstones in the upper part. In the Fairfield Basin, only scattered erosional remnants of the lower Cypress belong to Sequence 7 (plates 3 and 5). These strata consist of shale and sandstone that conformably overlie the Reelsville Limestone and commonly coarsen upward. Variegated shale or mudstone locally marks the sequence boundary. This variegated mudstone lies 6 to 12 m below more widespread paleosols near the top of the Cypress, in Sequence 8. Well 56 on plate 6 exemplifies a well that shows both paleosols.

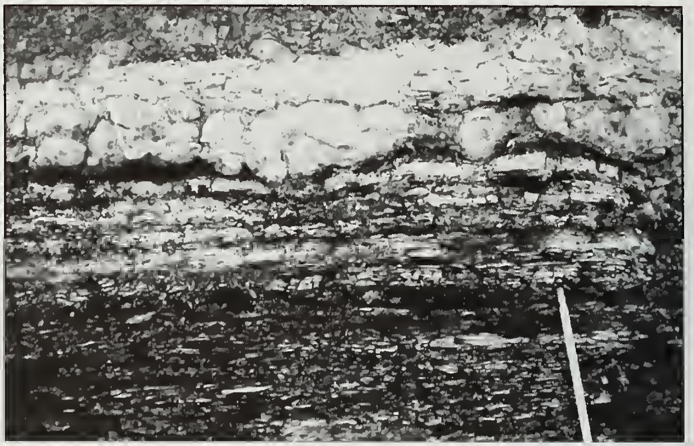

Figure 30 A paleosol consisting of large dolomite nodules in blocky red mudstone, in the upper part of the Cypress Formation at the Sulphur Interchange, Crawford County, Indiana (outcrop section 53). Pencil for scale.

In part of southeastern Illinois, Sequence 7 may actually consist of two sequences. These are designated Subsequences 7a and 7b and are best shown in White and Edwards Counties (plate 5) and Saline County (plate 3). In these areas, Subsequence 7a includes the upper Sample, Reelsville, and 6 to 18 m of the Cypress. The part of the Cypress in 7a coarsens upward from shale at the base to sandstone at the top and is capped by variegated mudstone. Subsequence 7b is up to 21 m thick and consists mainly of sandstone with shale interbeds, coarsening upward in some wells, and again capped by multi-colored mudstone or shale. Locally there is a thin limestone at the base of 7b. Subsequence 7b appears to fill incised valleys in wells 34 to 36 (plate 5) and in wells 48 and 49 (plate 3).

Upper Sequence Boundary

Sequence 7 is bounded at the top by paleosol(s) on the Eastern and Western Shelves. Variegated mudstones in the upper Cypress on the outcrop in Indiana are paleosols (Ambers and Petzold 1992); multiple paleosols are shown in cores from southern Illinois. Where more than one paleosol is observed, the upper one is designated as the sequence boundary. In the Fairfield Basin and western Moorman Syncline, the upper boundary of Sequence 7 is erosional and exhibits several tens of meters of relief. Sequence 7 is completely truncated by this unconformity in places. Thick sandstone of the Cypress Formation (Sequence 8) overlies the unconformity. The sequence boundary may coincide with a conodont zone boundary between the Reelsville and the Beech Creek Limestones (Collinson et al. 1962).

Facies Pattern and Sediment Source

Incised valleys of the Sample Formation may contain an LST, but none can be identified using available data. The TST comprises most (if not all) Sample valley-fill deposits, along with the lower part of the Reelsville Limestone. The rest of Sequence 7 represents the HST. Smith (1996) identified three parasequences: one in the upper Sample, the second including the Reelsville and lower Cypress, and the third in the middle Cypress. The two lower parasequences are equivalent to Subsequence 7a of this report, whereas the upper parasequence equals Subsequence 7b.

The distribution of Sample incised valleys is poorly known because only short segments of valleys have been mapped. Valleys are known to exist in south-central and southwestern Indiana, far southeastern Illinois, and adjoining parts of Kentucky. The Sample changes to shale and pinches out toward the Cincinnati Arch and also toward the northwestern part of the basin. A northeastern source area and southwestward sediment transport, as for the Bethel before and Cypress after, are most plausible.

The Reelsville Limestone is best developed in the southeastern and possibly the northwestern parts of the basin. The Reelsville becomes lenticular and sandy, intergrading with shale (Ridenhower) in the southern Fairfield Basin. Hence, considerable silt and clay were being delivered to the central basin even during the highstand of Sequence 7. The source areas were again probably to the northeast, as were those operating during the deposition of the Cypress Formation.

Sequence 8

Sequence 8 is entirely in one formation, the Cypress, and consists largely of valley-fill deposits (figs. 5 and 15). This sequence is well developed throughout much of the Fairfield Basin and western Moorman Syncline and extends partially onto the Eastern and Western Shelves. The thickness locally exceeds 60 m in southern Illinois but, on the inner shelves, this sequence is represented by only a few meters of mudstone paleosols.

Our Sequences 8 and 9 correspond to Sequence 7 of Smith (1996). Working mainly from outcrops, Smith did not recognize the widespread unconformity within his Sequence 7. This unconformity occurs within an interval of shales that rarely crops out and is not exposed in quarries, but subsurface data, particularly cores, demonstrate its presence.

Valley Fills

Sequence 8 is composed dominantly of sandstone that fills two clastic belts, or incised valley systems, within the Fairfield Basin. The eastern belt, which Sullivan (1972) named the West Baden clastic belt, runs south-southwest from the northern limit of Chesterian rocks in west-central Indiana to the southern limit in Massac County, Illinois (fig. 31). The belt is 20 to 50 km wide and bifurcates toward the north, suggesting two tributaries that fed a trunk stream. The West Baden trend parallels the Wabash Valley Fault System and follows the Dixon Springs Graben closely, implying tectonic control of valley cutting (Cole and Nelson 1995). The western belt of thick Cypress runs north-south through the subsurface in Illinois from Jasper and Cumberland Counties, emerging at the outcrop in the Cypress type area of Union and Johnson Counties (Cole and Nelson 1995). Whitaker (1992) identified incised valleys in the western belt of the Cypress and depicted (in a poster paper) their erosional base as a sequence boundary.

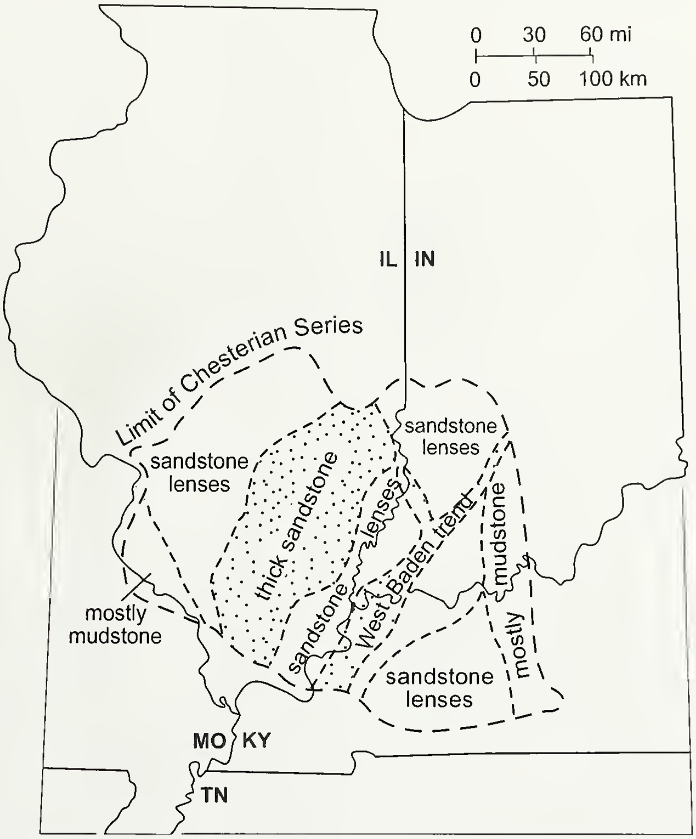

Figure 31 ***Map showing generalized facies distribution of the Cypress Formation (Sequences 7, 8, and 9).***

In both belts the Cypress Formation is incised deeply into underlying strata. In Madison County, Illinois, the Cypress cuts into the Downeys Bluff Limestone, removing all of Sequences 6 and 7 (west end of plate 2). Local erosional relief is typically 10 to 15 m and, in eastern Perry County, Illinois, reaches 55 m (wells 7 to 10, plate 3). Examples of such valleys appear on all of the subsurface cross sections, especially the western part of plate 6, the central and eastern parts of plate 2, the central part of plate 3, and the southern part of plate 4.

The valley fill is predominantly white to light gray quartz arenite that is well-sorted, very fine- to fine-grained (rarely medium-grained), and composed of subrounded to angular grains. Feldspar, mica, and dark opaque minerals constitute (at most) a few percent of the rock. Sand-size echinoderm, brachiopod, and bryozoan fragments are common in well samples but are leached out of most surface exposures (Cole and Nelson 1995). Dark gray to greenish gray shale and siltstone occur as partings, laminae, and interbeds. On most geophysical logs the valley-fill sandstone shows either a clean "blocky" or upward-fining profile (figs. 32 and 33).

Cross-bedding is the prevalent sedimentary structure in Cypress valley-fill sandstone. Planar lamination, ripple lamination with clay drapes, flaser bedding, and scour-and-fill structures also are common. Load casts and slumped lamination

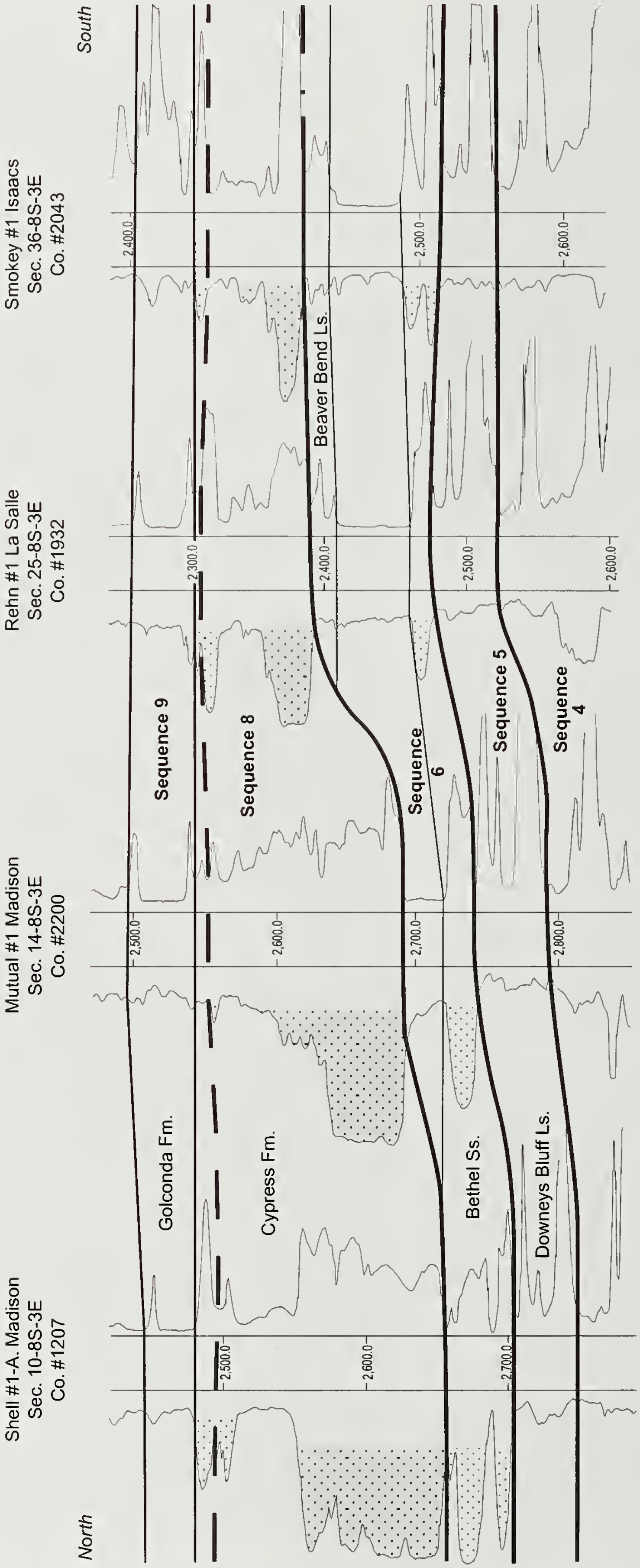

Figure 32 Geophysical log cross section in Williamson County, Illinois, illustrating an incised valley in the Cypress Formation (Sequence 8). Length of section is about 4 miles. Depth is measured in feet.

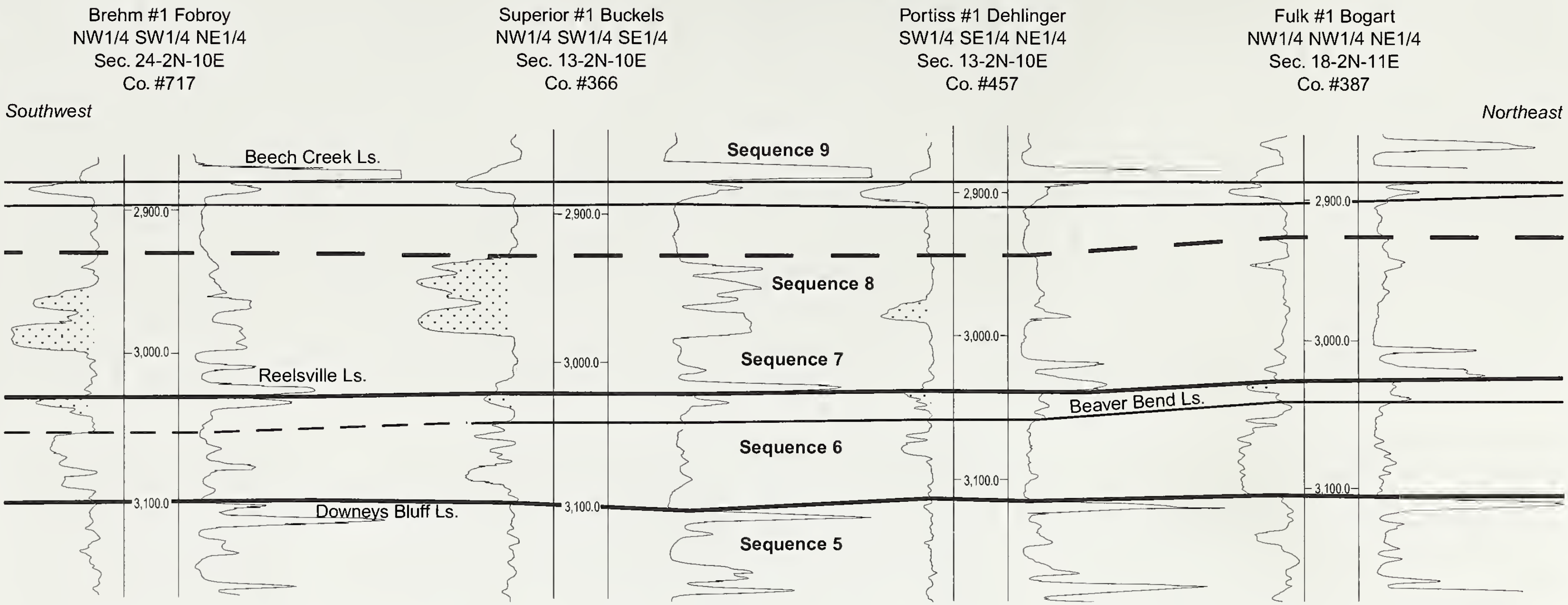

Figure 33 ***Geophysical log cross section in Richland County, Illinois, illustrating an incised valley in the Cypress Formation (Sequence 8). Length of section is roughly 1 mile. Depth is measured in feet.***

occur in shaly intervals. Many sandstones exhibit contorted laminations that likely reflect dewatering of soft sediment. At a large road cut in Union County, Illinois (Interstate 57, 1.5 km south of the Anna interchange), the lower Cypress appears to be composed of stacked, imbricate sand bars.

A thin limestone bed occurs at the base of thick Cypress valley-fill sandstone in many wells in southern Illinois. Unfortunately, no cores or outcrops revealed contact relationships of this limestone. Drill cuttings, wireline logs, and float blocks on the outcrop indicate a coarse, sandy, dark-colored skeletal wackestone less than 1.5 m thick. The limestone possibly represented erosional remnants of Sequence 7, which were more resistant than enclosing shale. An alternative interpretation is that the limestone is a basal transgressive deposit of Sequence 8. The limestone could be analogous to limestone at the base of Aux Vases valley fills (Sequence 3) on the Western Shelf. This interpretation raises the possibility that the lower boundary of Sequence 8 is a marine ravinement surface rather than a surface of subaerial erosion.

Two short cross sections using geophysical logs illustrate incised valleys of Sequence 8. A section in Williamson County, Illinois (fig. 32), shows valley-fill sandstone truncating Sequence 6 as deeply as the Bethel Sandstone. Sequence 7 is totally cut out. Note the blocky to fining-upward character of the sandstone that fills the valley. In the Richland County, Illinois, section (fig. 33), the valley is less deeply downcut, only partially removing Sequence 7. Observe that on this section, the valley-filling sandstone is partitioned by thick shale intervals. This partitioning may reflect reworking by marine tidal currents, the originally massive estuarine sand being redeposited as a series of lenses separated by mud.

Contrary to Cole and Nelson (1995), we find that the lower sandstone of the Cypress is not a lateral facies of limestone in the Paint Creek Formation. In Section IL-2 (plate 3), which parallels a cross section used by Cole and Nelson (1995) but uses additional control points, the lower sandstone of the Cypress clearly truncates the Paint Creek in western Perry County. Another section by Cole and Nelson (1995, their plate 1) suggested intertonguing of lower Cypress and Paint Creek in western Union County. The key well on that section is the Union County core. A sandy shale in this core, which Cole and Nelson interpreted as a lower tongue of the Cypress, we now consider to be probably the Sample Sandstone.

Shaly Strata and Paleosols

The upper part of Sequence 8 in the central basin is composed of shaly, heterolithic strata that are capped by paleosols. Coal and carbonaceous shale with plant fossils occur widely in the upper Cypress Formation in southeastern Illinois and the adjacent part of Kentucky (Trace and Amos 1984, Cole and Nelson 1995). These rocks immediately overlie thick sandstone valley fills in most cases. Analogous deposits are common in other ancient and modern valley-fill sequences. They probably record salt marshes that developed during drowning of estuaries (transgression) following the backfilling of the incised valleys (Zaitlin et al. 1994a, 1994b; Nichol et al. 1996).

Overlying the coaly zone in the upper Cypress is a heterolithic facies, containing lenses of sandstone that range up to 6 m thick. The heterolithic rocks contain ripple and flaser bedding, tidal rhythmites, and brackish water to marine trace fossils and body fossils (Cole and Nelson 1995). Sandstone lenses in the upper Cypress are elliptical in map view and mostly oriented northeast-southwest. These lenses, which are major hydrocarbon reservoirs, are interpreted as offshore marine bars or, more specifically, as tidal sand ridges (Grube 1992, Whitaker and Finley 1992, Cole and Nelson 1995, Xu and Huff 1995).

The uppermost part of Sequence 8 is composed of blocky mudstones that are paleosols. Cores in southeastern Illinois show as many as five paleosols in succession through an interval more than 10 m thick. Each typically fines upward from siltstone or shaly sandstone at the base to claystone at the top. Claystones are greenish to olive-gray, some with red and purple mottling, blocky, and slickensided. They contain root casts, breccia, siderite pellets, veinlets, and other evidence of repeated dessication and soil formation. Similar lithologies occur in samples from many petroleum test holes, but logs of these wells rarely are detailed enough to distinguish more than one paleosol.

Cypress reservoirs in oil fields on the Western Shelf are divisible into three or four sandstone units that are separated by laterally persistent shale. In some cases, the shales are red or variegated (Grube 1992, Whitaker and Finley 1992). Grube and Frankie (1999) report variegated mudstone and, locally, coal at two distinct horizons in the Richview Field of Washington County, Illinois. One paleosol directly overlies their sandstone A, which is the thick lower valley-fill sandstone of Sequence 8 in the present study. The second paleosol occurs between their sandstones C and D, the latter being a thin sandstone immediately below the Beech Creek Limestone. Where more than one paleosol can be identified in the upper Cypress, we placed the sequence boundary at the top of the uppermost. Whether multiple paleosols reflect autogenic processes or eustatic events is unclear.

West Baden Clastic Belt

Sullivan (1972) gave the name West Baden clastic belt to a linear tract in Indiana where the Bethel, Sample, and Cypress Sandstones appear to merge into a single unit. As mapped by Sullivan, the clastic belt is slightly sinuous and trends S 35°W from the outcrop in Owen County to the Ohio River in Vanderburgh County. Toward the southwest the belt widens from about 3 km to more than 10 km and thickens from about 40 m to more than 65 m. A narrower "tributary" belt enters the main belt from the northwest at an acute angle. Additional areas of stacked sandstone occupy irregularly shaped areas west of the main sublinear belt. Outcrop and borehole data from Illinois and western Kentucky show that the West Baden clastic belt continues southwesterly across the Fluorspar District to the edge of the Mississippi Embayment in Massac County, Illinois (figs. 24, 25, and 31). Cross sections (plates 6 and 7) illustrate the complexity of the West Baden clastic belt. Its borders probably are far more irregular than Sullivan (1972) showed

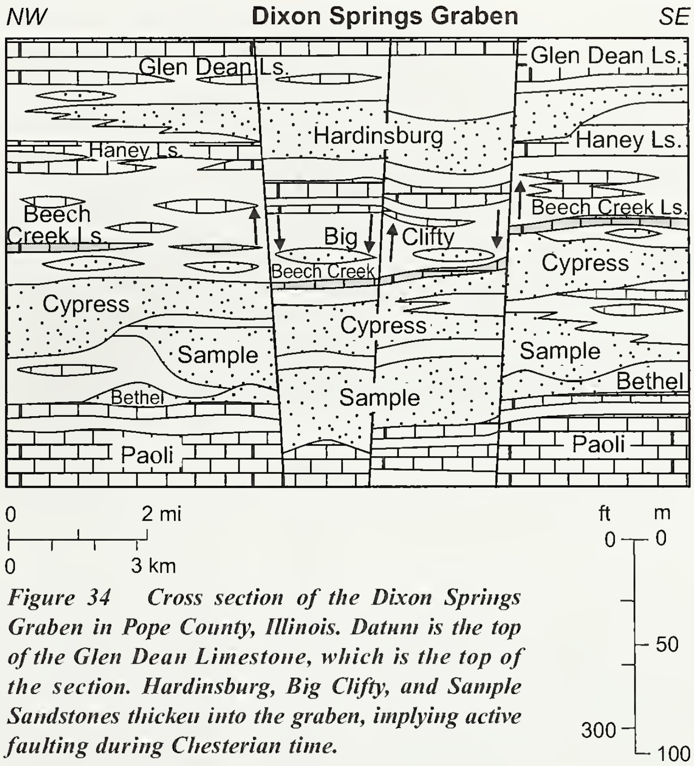

Figure 34 Cross section of the Dixon Springs Graben in Pope County, Illinois. Datum is the top of the Glen Dean Limestone, which is the top of the section. Hardinsburg, Big Clifty, and Sample Sandstones thicken into the graben, implying active faulting during Chesterian time.

them. There are "islands" within the clastic belt where the Reelsville or Beaver Bend Limestone are preserved. In some places, only two of the three sandstones are present, the third being entirely eroded by the next younger sandstone. Wherever good data are available, sequence boundaries can be traced through the West Baden clastic belt.

The linear segment of the clastic belt from Pike to Vanderburgh Counties, Indiana, runs parallel to the eastern margin of the Wabash Valley Fault System (fig. 31). Farther southwest, the clastic belt follows the Dixon Springs Graben along the northwestern margin of the Illinois-Kentucky Fluorspar District (fig. 34). Note that not only the West Baden, but also the Big Clifty (Sequence 10) and Hardinsburg (Sequence 11) incised valleys line up with the Dixon Springs Graben. Although major movements in the Wabash Valley and Fluorspar District were post-Pennsylvanian, Nelson (1996) documented recurrent faulting during the Mississippian also.

As Sullivan (1972) recognized, the West Baden clastic belt is the product of multiple events of erosion and deposition. We interpret the clastic belt as three (locally, more) sets of incised valleys that became "stacked" because of faulting during sedimentation.

Upper Sequence Boundary

The upper boundary of Sequence 8 is defined by paleosols in most of the basin. Where several paleosols are present, the uppermost is presumed to represent the sequence boundary. Locally, channels or incised valleys filled with either limestone or sandstone of Sequence 9 truncate the paleosols. These channels are described under Sequence 9.

Facies Pattern and Sediment Source

No lowstand deposits were identified in Sequence 8. Sedimentary features of thick Cypress sandstones are more consistent with estuarine or shallow subtidal environments than with fluvial ones (Cole and Nelson 1995). Accordingly, we interpret Cypress valley fills as TST to early HST deposits. Extensive tidal reworking of lowstand fluvial deposits during transgression seems probable. In places, limestone at the bottom of the valley fill may represent a transgressive lag. Mudstone paleosols, coaly layers, and heterolithic beds of the upper Cypress represent late phases of the HST, but the maximum flooding surface cannot be identified with precision, and no parasequences can be defined.

The two major "clastic belts" of thick Cypress Formation trend north-south to north-northeast across the Fairfield Basin. No direct evidence (paleocurrents or trends in grain size or maturity) has been found to indicate the direction of transport. Southward transport is assumed on the basis of regional paleogeography and known southward transport in older and younger units (Cole and Nelson 1995).

The Cypress clastic belts are comparable with paleovalleys eroded into the sub-Pennsylvanian surface in the Illinois Basin (Bristol and Howard 1971). Sub-Pennsylvanian valleys trend northeast-southwest, exhibit paleoflow to the southwest, and are as wide as 35 km and as deep as 137 m. Cypress paleovalleys may be even wider, but not as deep; however, Cypress valleys have been mapped with much less detail and accuracy than sub-Pennsylvanian valleys. Lower Pennsylvanian sandstones in the central Appalachian Basin occupy clastic belts as wide as 90 km that trend subparallel to the basin axis. These belts are interpreted as "braidplains" developed as part of a "recurring bedload fluvial trunk system" (Greb and Chesnut 1996). Major sandstones of the Caseyville Formation (Lower Pennsylvanian) in the Illinois Basin have similar characteristics and lend themselves to the same interpretation (Nelson 1989).

Sequence 9

Sequence 9 includes the uppermost part of the Cypress Formation, the Beech Creek Limestone, and nearly all of the Fraileys Shale and Big Clifty Sandstone (figs. 5 and 15). This sequence normally ranges from 18 to 37 m thick, thinning slightly across the Eastern and Western Shelves. Valley fills in the Cypress locally add 20 m to the base of the sequence.

Uppermost Cypress

Incised valleys filled with sandstone locally cut down from just below the Beech Creek Limestone. A cross section (fig. 34) shows a clean valley-filling sandstone that thickens from near zero to 21 m in a lateral distance of 1 km. The Cypress below the infilled valley in this section is unusual, being almost entirely shale with a limestone bed near the middle.

Outside of such incised valleys, uppermost Cypress strata overlying the paleosols are placed in Sequence 9. These rocks consist of a few meters of shale, siltstone, and sandstone that display strong marine indicators, such as ripple

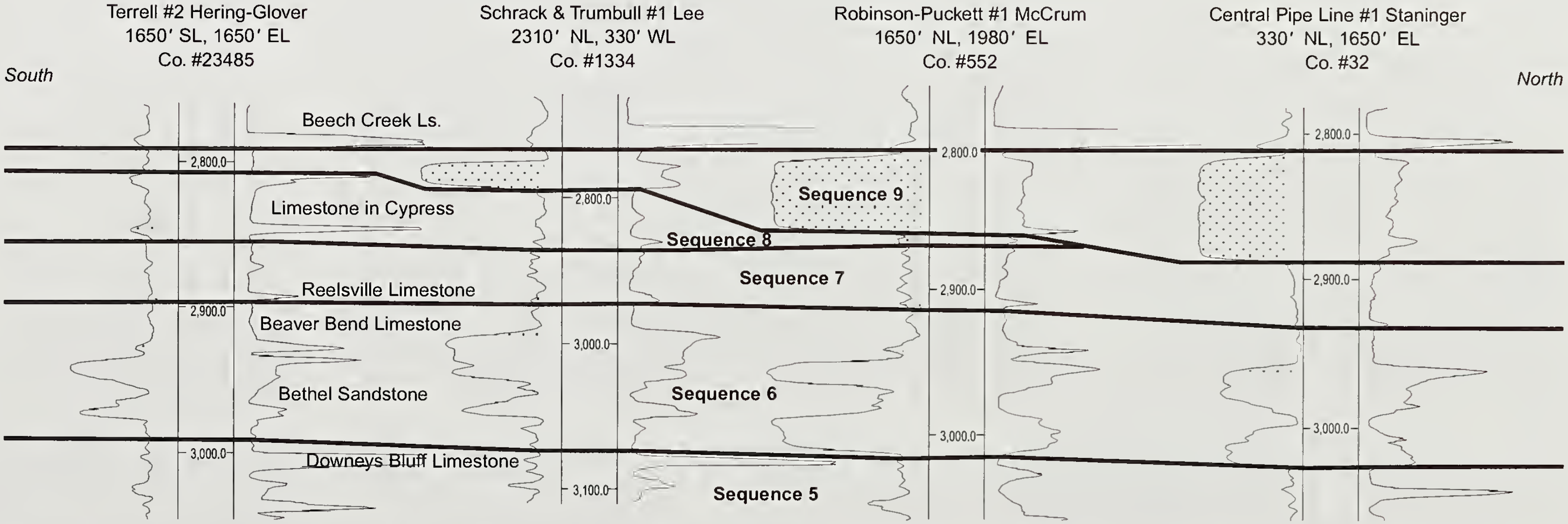

Figure 35 **Geophysical log cross section in Edwards County, Illinois, illustrating an incised valley in the upper Cypress Formation (Sequence 9). Datum is the base of the Beech Creek Limestone. All four wells are in Section 31, T1N, R14W, and the section is approximately 3,000 feet (1 km) long. Depth is measured in feet.**

and flaser laminations, clay drapes, marine trace fossils and body fossils, and tidal rhythmites. Lenses of greenish gray, calcareous, glauconitic sandstone at the top of the Cypress grade into the overlying Beech Creek Limestone.

Golconda Formation

The Golconda Formation (Butts 1917) has been treated differently by stratigraphers in the three states (fig. 4). In Kentucky, the Golconda consistently has been called a formation containing the Beech Creek Limestone, Fraileys Shale, Big Clifty Sandstone, and Haney Limestone Members. In Illinois, Swann (1963) elevated the Golconda to a group and elevated members to formations. In Indiana, the name Golconda is not used, and the Beech Creek, Big Clifty, and Haney have been called formations.

In this report, the Golconda is a formation throughout the basin, and it contains the Beech Creek Limestone, Fraileys Shale, Big Clifty Sandstone, Indian Springs, and Haney Limestone Members. This classification is adopted (1) to avoid designating as formations units that are commonly too thin to map or have gradational lateral and vertical boundaries, and (2) to maintain the Mammoth Cave and Pope Groups as larger units useful for regional synthesis.

Beech Creek Limestone

The Beech Creek Limestone (informally called the "Barlow lime" by petroleum geologists) is one of the most widespread, most reliable marker beds in the Illinois Basin. The Beech Creek is thinnest (less than 3 m) in the southern Fairfield Basin, thickening to 4 to 12 m northward and onto the Eastern and Western Shelves. Increased water depth and siliciclastic input along the basin axis may have inhibited limestone deposition.

On the Eastern Shelf, dark brown or brownish gray skeletal wackestone and packstone is the most common lithology. Some limestone is pelletal, and small dark-centered oolites are common. Coarse crinoidal grainstone occurs at the top of the limestone. The big productid brachiopods *Inflatia inflata* ("*Productus inflatus*" in older reports) and *Diaphragmus cestriensis* are abundant in eastern outcrops, along with large rugose corals and the crinoid *Agassizocrinus* sp. These fossils aid in identifying the Beech Creek where it is part of the Girkin Limestone on the flank of the Cincinnati Arch (Amos 1977).

Harris (1992) described the Beech Creek in southern Indiana as having a transgressive lag deposit of sandy oolitic limestone and shale-pebble conglomerate, overlain by skeletal and pelletal limestone that probably acccumulated below wave base. The upper Beech Creek comprises coarser and grainier limestones that record shoaling and higher wave and current energy (fig. 36). Harris thereby interpreted the Beech Creek as a single transgressive-regressive cycle. Wireline logs and sample studies used in our Indiana cross sections confirm an upward-coarsening profile. Argillaceous, silty or sandy lime mudstone and wackestone in the lower part changes to coarse packstone and grainstone in the upper part. The thin basal transgressive zone observed by Harris generally is too thin to register on logs.

Figure 36 Cross-bedded skeletal grainstone in the upper part of the Beech Creek Limestone at the Sulphur Interchange, Crawford County, Indiana (outcrop section 53). Pen for scale is 15 cm long.

Cores and sample logs in the southern Fairfield Basin mostly show a single upward-fining interval, grading from skeletal packstone (or grainstone) at the base to shaly skeletal wackestone. Sandstone lenses and interbeds may occur near the base. The lower contact is sharp and commonly scoured; shale rip-up clasts occur near the base of the limestone. Less commonly, the Beech Creek coarsens upward from shaly lime mudstone and wackestone to coarse crinoidal packstone and grainstone at the top.

On the Western Shelf, the Beech Creek is thicker and has a lithologic succession similar to that on the Eastern Shelf. Cores in Madison County, Illinois, show 2 to 7 m of interbedded limestone (skeletal packstone) and green, fossiliferous shale in the lower Beech Creek. Shaly strata grade upward to shale-free lime mudstone and wackestone, which in turn grade to skeletal packstone and grainstone in the upper Beech Creek. The uppermost Beech Creek contains breccia clasts and is overlain by blocky, variegated claystone. This area is the only one where we observed a paleosol directly overlying the Beech Creek.

The Beech Creek fills channels scoured as much as 15 m into the Cypress Formation. Several examples appear on our cross sections; a good one is at well 8 on plate 3. Called "false Barlow," these features were interpreted as infilled tidal channels by Cluff and Lasemi (1980). Sample studies show that the false Barlow tends to be sandy at the base, grading upward through silty and argillaceous lime mudstone and wackestone in the middle to coarse packstone at the top. This succession implies upward shoaling, but false Barlow is more micritic and contains more clay and silt than does normal Beech Creek. It is unusually fine sediment for a tidal channel. Cluff and Lasemi proposed that the channels were cut late during Cypress deposition and that carbonates in the lower parts of the channels were contemporaneous with upper Cypress shale and sandstone. We propose, alternatively, that "false Barlow" channels may have been eroded during a lowstand and filled upon transgression.

Big Clifty Sandstone and Fraileys Shale

The Big Clifty Sandstone and Fraileys Shale are lateral facies, the Big Clifty being developed on the eastern side of the basin and the Fraileys on the western side. Sandstone and shale intergrade laterally through a transition zone tens of kilometers wide near the eastern border of Illinois. The Big Clifty is thickest (up to 36 m), coarsest, and sandiest in Hart and Hardin Counties, Kentucky, where it fills channels scoured into or through the Beech Creek Limestone (fig. 37). These channels are part of Sequence 10 and are discussed there. Elsewhere in Kentucky and southern Indiana, sandstone bodies in the Big Clifty are elongate lenses that are oriented mostly northeast-southwest to east-northeast–west-southwest (fig. 38). These sandstone bodies probably are tidal sand ridges (Treworgy 1988, Droste and Keller 1995). The Big Clifty in southwestern Indiana shows an overall regressional (shoaling) trend and apparently was deposited as tidally influenced shoreline and deltaic sediments (Horowitz and Kelly 1987, Keller 1988, Horowitz 1992).

The uppermost sandstone tongue of the Big Clifty extends farthest west into the Fraileys Shale. Thin calcareous sandstone or siltstone lenses are common in southeastern Illinois; siltstone or silty shale occurs near the top of the Fraileys as far as Washington County on the Western Shelf. The pattern of the youngest sandstone tongues extending farthest from the source mirrors the pattern for the older Aux Vases and Yankeetown Sandstones.

The Fraileys Shale reaches 30 m thick in parts of Livingston and Crittenden Counties, Kentucky; elsewhere, Fraileys Shale is typically 12 to 24 m thick. The lower part is typically dark gray to black, fissile clay-shale that contains siderite nodules. Upward the shale becomes greenish to olive-gray and is somewhat silty, calcareous, and fossiliferous. Echinoderms are diverse and abundant, and wing plates of *Pterotocrinus capitalis* are characteristic. Limestone interbeds are common and become more so toward the north and west (plates 2 and 3). The limestone is mostly coarse to very coarse, crinoidal and skeletal wackestone and packstone, along with lesser amounts of ooid and skeletal grainstone. Alternating shale-limestone packages, observed both on well logs and on the outcrop (fig. 39), may represent parasequences.

Local "buildups" of coarse, highly fossiliferous limestone up to 10 m thick occur in the middle part of the Fraileys in southern Illinois, both in subsurface and on the outcrop. Their depositional setting is uncertain, but high-energy conditions are strongly implied. A thin but widely traceable bed of buff, micritic dolomite or dolomitic limestone occurs near the top of the Fraileys. This bed is commonly silty and grades to calcareous siltstone; locally, the bed contains coarse skeletal wackestone or packstone.

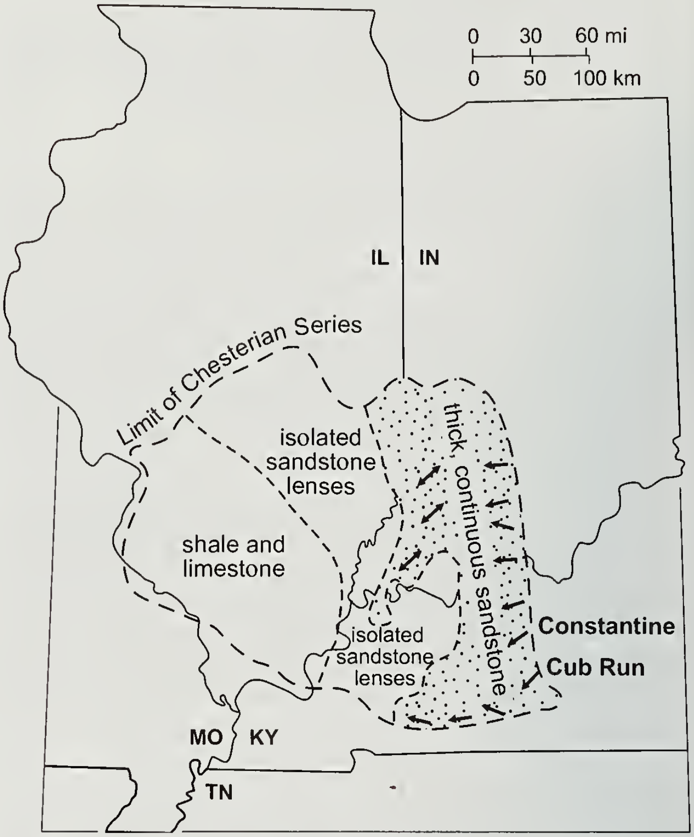

Figure 37 Map showing generalized facies distribution of the Big Clifty Sandstone-Fraileys Shale interval (Sequences 9 and 10). Arrows represent paleocurrent trends. Channels in Constantine and Cub Run Quadrangles, Kentucky, are labeled.

Near the top of the Fraileys-Big Clifty is a nearly basin-wide interval of red, green, and gray variegated shale and mudstone. The mudstone contains abundant evidence of exposure, including blocky structure, slickensides, sideritic veinlets and granules, root traces, and pedogenic breccias and carbonate nodules. Previous researchers (Horowitz and Kelly 1987, Treworgy 1988, Horowitz 1992) identified the mudstone as containing paleosols or exposure surfaces. This mudstone is probably the most widespread Chesterian variegated paleosol in the Illinois Basin. The only large area where this unit is absent is in Hart and Hardin Counties, Kentucky, where the Big Clifty fills incised valleys.

Upper Sequence Boundary

The top of Sequence 9 is placed at the top of the variegated mudstone in the upper Fraileys or Big Clifty, except near the southeastern corner of the basin, where the Big Clifty Sandstone is interpreted as a valley-fill deposit. Here, the sequence boundary is positioned at the base of the valley fill.

Facies Pattern and Sediment Source

Sequence 9 probably lacks lowstand deposits, although remnants could be preserved in sand-filled incised valleys of the upper Cypress. Transgressive deposits include upper Cypress valley fills, uppermost Cypress heterolithic beds, and the lower part of the Beech Creek Limestone (including the false Barlow channnel fills). The MFS is marked by micritic, subtidal limestone of the Beech Creek, directly

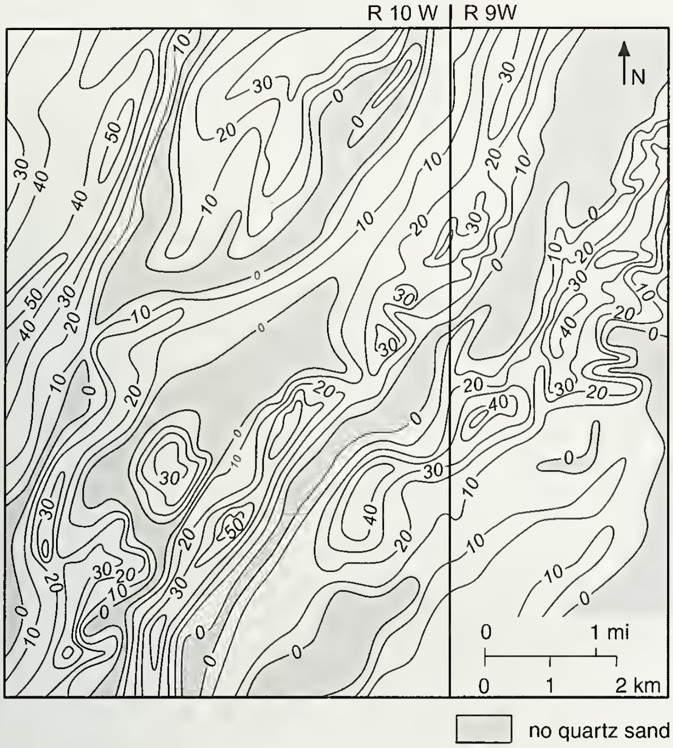

Figure 38 Map showing net sandstone thickness in the Big Clifty Sandstone in part of Gibson County, Indiana (modified from Specht 1985). Contour interval is 10 feet (3 m).

overlying the thin basal transgressive portion. The upper Beech Creek, Fraileys, and Big Clifty make up the HST.

Smith (1996) identified five parasequences in Sequence 9. The upper Cypress represents one, the Beech Creek another, and in the Fraileys-Big Clifty interval three more. Among these, the lower two are clearly defined, and the upper three are more inferential.

Thickness trends of the Fraileys-Big Clifty signify that subsidence rates were nearly uniform across the entire basin. The Fraileys-Big Clifty thickens somewhat in the Wabash Valley and Fluorspar District and also at the easternmost outcrops in Kentucky, where the Big Clifty fills incised valleys. Sand was brought into the southeast corner of the basin by southwesterly flowing channels and then redistributed by northeast-southwest tidal currents. The source area for the Big Clifty is discussed under Sequence 10.

Figure 39 Thin, alternating shale-limestone packages that may be parasequences in the Fraileys Shale at the Sulphur Interchange, Crawford County, Indiana (outcrop section 53). Limestone beds have sharp lower contacts and grade upward to shale. Staff is graduated.

Sequence 10

Sequence 10 comprises valley fills of the Big Clifty Sandstone, along with the marine portion of the Indian Springs Member, all of the Haney Limestone, and the older portion of the Hardinsburg Formation (figs. 5 and 15). This sequence ranges up to 50 m thick in the Fairfield Basin and Moorman Syncline, thinning to about 30 m on the Eastern Shelf and 18 m near the Cincinnati Arch.

Big Clifty Valley Fills

In Hardin and Hart Counties, Kentucky, the Big Clifty Sandstone thickens to as much as 36 m and fills channels that locally cut through the Beech Creek Limestone (fig. 37). Channel sandstones are coarsest at the base and fine upward and are capped by coal or carbonaceous shale, rather than the variegated mudstone found elsewhere. Cross-bedding in two well-defined channel segments in the Cub Run and Constantine quadrangles (fig. 37) indicates that paleocurrents flowed toward the southwest (Sable 1964, Sandberg and Bowles 1965).

Indian Springs Member

The Indian Springs Shale Member denotes a few meters of shaley strata that overlie the Big Clifty Sandstone in Indiana. Specifically, the member includes a lower mottled or variegated mudstone and an upper marine shale and limestone (Shaver et al.1986, Horowitz and Kelly 1987). Thus, the Indian Springs comprises the paleosol at the top of Sequence 9 and the transgressive sediments of Sequence 10. Literature on the Indian Springs focuses on the upper marine part, which is highly fossiliferous. The dark gray to black, fossiliferous shale contains lenticular interbeds of coarsely bioclastic limestone that bear diverse marine invertebrates and fishes. "Black corroded pebbles of phosphatized limestone and a phosphatized and corroded fauna of low density and diversity" at the base of the upper Indian Springs (Horowitz and Kelly 1987, p. 389) may be a transgressive lag deposit. The contact of the Indian Springs to the overlying Haney Limestone is locally a minor disconformity, but more commonly is gradational or intertonguing. Subsurface data from our study show that the Indian Springs is widespread throughout the basin and is not confined to Indiana.

We recommend that the name Indian Springs Member be restricted to the fossiliferous marine beds. The variegated mudstone below represents different rock types, environments, and sequences. The variegated mudstone might merit naming as a separate member, although we do not do so here.

Haney Limestone

The Haney is a limestone unit with interbeds of calcareous, fossiliferous shale. Isopach maps by Swann (1964), Vincent (1975), Willman et al. (1975), and Droste and Keller (1995), together with our cross sections, show that the Haney thickens from less than 5 m along the northern and northeastern margins of the basin to more than 30 m in Jackson County, southwestern Illinois. The Haney thins slightly near the eastern, southern, and western margins of the basin.

Skeletal packstone and grainstone are the most common lithofacies, followed by ooid grainstone and packstone, skeletal wackestone, lime mudstone, and microgranular dolomite. The Haney contains a rich and diverse marine fauna, among which large specimens of *Archimedes* and many species of crinoids and blastoids are most prominent. The shaly beds often contain delicately preserved fossils such as articulated crinoids and lacy fenestrate bryozoans. Shale interbeds are numerous; some persist for many kilometers, whereas others are lenticular. The Haney is shaliest in a belt that trends southwest from Pike County, Indiana (plate 6), into the Illinois-Kentucky Fluorspar District. Most of the shale occurs in the middle to upper Haney (Vincent 1975, Treworgy 1988). The belt of shaly Haney corresponds closely to the West Baden clastic belt below and the thickest Hardinsburg sandstone above; the belt follows the persistently active Wabash Valley and Fluorspar District Fault Systems.

Red and green variegated, fissile shale to blocky mudstone are common at the top of the Haney in southeastern Illinois. Overlying the mudstone are thin beds of red to brown, sublithographic to oolitic, sandy limestone and dolomite. Atherton (1948) first described these rocks, which are missing in many areas because of pre-Hardinsburg erosion. These rocks may represent intertidal to supratidal mud flats that developed during a minor lowstand that did not induce valley cutting.

Hardinsburg Formation (Older Part)

The older part of the Hardinsburg is in Sequence 10 and consists of shale and siltstone with lenses of sandstone and a little limestone. These beds conformably overlie the Haney Limestone. The Hardinsburg is thickest in western Indiana, eastern Illinois, and the adjacent part of Kentucky (fig. 40). The Hardinsburg thins to less than 6 m on the Eastern Shelf in Indiana and Kentucky and on parts of the Western Shelf in Illinois (Potter 1962, 1963; Swann 1964; Willman et al. 1975; Droste and Keller 1995).

Shale and siltstone of the lower Hardinsburg are medium to dark gray, greenish gray, and olive-gray. Green colors and reddish mottling become more common toward the basin margins. Some green shales are calcareous and contain marine fossils. Sandstone is rare at the basin edges, becoming thick and abundant toward the center. Sandstone is white to light gray, very fine- to fine-grained quartz arenite, some of which is calcareous and contains marine fossils such as brachiopods and bryozoans. Sandstone commonly forms lenses that are convex upward and probably marine bars. Marine fossils and lenses of limestone occur in sandstone lenses on the shelves.

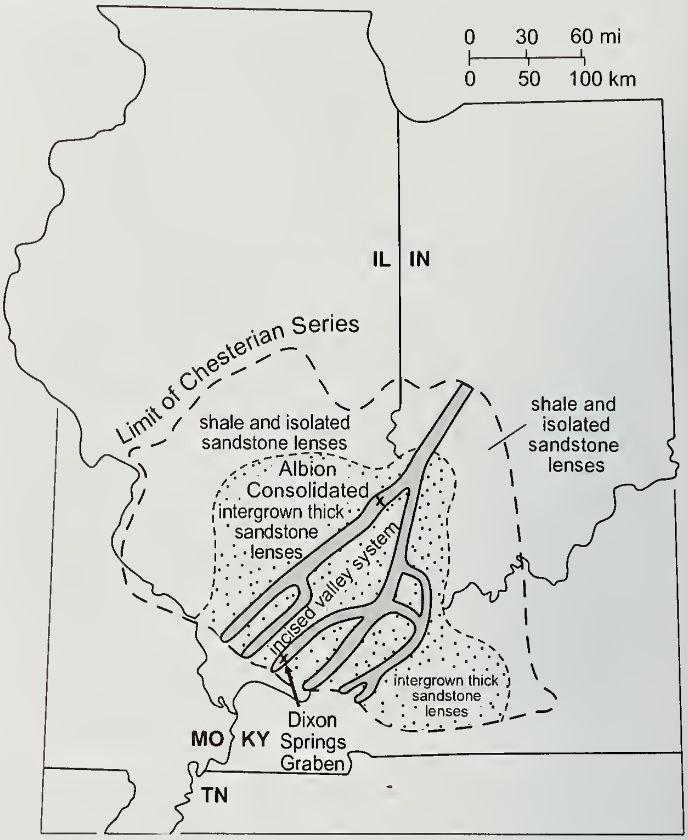

Figure 40 Map showing generalized facies of the Hardinsburg Formation (Sequences 10 and 11). Based partly on Potter (1962, 1963) and Potter et al. (1958).

Upper Sequence Boundary

Outside of incised valleys, the top of Sequence 10 is in the upper part of the Hardinsburg Formation. The boundary is marked by red or variegated, blocky mudstone on the shelves, and by rooted underclay, coal, and carbonaceous shale in the basin interior. Some well records indicate two or three variegated or carbonaceous zones in the middle to upper part of the Hardinsburg. These zones could represent either eustatic events or autocyclic processes, such as delta shifting. As in similar cases, we drew the sequence boundary at the uppermost paleosol. Locally the top of Sequence 10 is an erosional contact at the base of incised valleys in the Hardinsburg. Some of these sandstone-filled paleovalleys cut as deeply as the Beech Creek Limestone. Conodont, coral, and foraminiferal biostratigraphic zone boundaries between the Haney and Glen Dean Limestones may coincide with the sequence boundary (Collinson et al. 1962, Maples and Waters 1987).

Facies Pattern and Sediment Source

Unidirectional cross-bedding reported in Big Clifty valley-fill sandstone implies fluvial origin and lowstand deposition. The remainder of the Big Clifty, the marine portion of the Indian

Springs Member, and the lower Haney Limestone constitute a transgressive package. The MFS appears to be in the lower part of the Haney, leaving the upper Haney and Hardinsburg in the HST. The TST of Sequence 8 is considered to be a single parasequence, whereas up to 6 parasequences are found in the HST (Smith 1996).

Incised valleys of the Big Clifty enter the Illinois Basin farther southeast than any other Chesterian sandstone. Lithofacies and paleocurrent mapping (Potter et al. 1958, Sable and Dever 1990) indicate a general westward transport of sand across the Cincinnati Arch from the area of the southern Appalachian Mountains. East of the Cincinnati Arch, the only siliciclastic unit of similar age to the Big Clifty is the Hartselle Sandstone. The Hartselle extends from northern Alabama through eastern Tennessee to south-central Kentucky, thinning and grading to shale farther north in Kentucky. Although some geologists have correlated the Hartselle with the Hardinsburg Formation, conodont and foraminiferal (Horowitz et al. 1979) and crinoid (Driese et al. 1994) zonation support correlation to the Big Clifty. If this correlation is correct, the Hartselle and Big Clifty Sandstones must have had a common source in what is now the southern Appalachian Mountains.

Sequence 11

Sequence 11, the youngest sequence considered here, consists of the younger part of the Hardinsburg Formation, the Glen Dean Limestone, and the older part of the Tar Springs Formation (figs. 5 and 15). The Tar Springs was not studied in detail, and the upper boundary of this sequence was not defined for this report.

Hardinsburg Formation (Younger Part)

The younger part of the Hardinsburg includes valley-fill sediments that are dominantly sandstone along with thin shale and siltstone that overlie valley fills. Hardinsburg paleovalleys occur in southwestern Indiana, southeastern Illinois, and the adjacent part of Kentucky. Paleovalleys are straight to slightly curved and trend north-northeast to northeast, defining a southwestward-branching system (fig. 40). The paleovalleys range from less than 1 km to several kilometers wide and can be traced tens of kilometers along strike. Some are more than 50 m deep, cutting almost to the Beech Creek Limestone. Examples are shown on plate 2 in Lawrence County, Illinois; plate 5 in Edwards County, Illinois; plate 6 in Knox County, Indiana; and plate 7 in Vanderburgh County, Indiana.

The valley fill is almost entirely sandstone, as described previously (Potter 1962, 1963; Treworgy 1988; Droste and Keller 1995). The white to light gray, very fine- to medium-grained quartz arenite contains occasional partings, laminae, and thin interbeds of dark gray, silty shale, and commonly exhibits an overall upward-fining trend. Cross-bedding trends indicate paleocurrents flowing toward the southwest (Potter et al. 1958). A conglomerate of shale, coal, and limestone clasts commonly is developed at the base.

A short cross section from southeastern Illinois illustrates a Hardinsburg incised valley (fig. 41). This steep-sided paleovalley exhibits 50 m of erosional relief, cutting out all of Sequence 10. Notice that the valley-fill sandstone does not intergrade laterally with the Haney Limestone. In the second well from the right, thick limestone occurs at the base of the channel, below the normal position of the Haney. This limestone might be a block of Haney Limestone that slumped into the channel. Other examples of deeply incised Hardinsburg channels were illustrated by Potter et al. (1958) and Treworgy (1988).

Shale, siltstone, thin sandstone, coal, and mudstone overlie the valley fills. Shale and siltstone are mostly gray to greenish gray; sandstone is mostly very fine-grained, lenticular, and ripple-marked. Coal beds are typically a few centimeters thick, but, in Kentucky, they reach 60 cm. Coals overlie gray mudstones that contain stigmarian root casts. The uppermost Hardinsburg commonly consists of 1 to 3 m of dark gray, fissile clay-shale.

Hardinsburg channels were discussed by Potter (1963) and Swann (1964) who interpreted thick Hardinsburg sand bodies as distributary-channel fills and distributary-mouth bars on a bird's-foot delta. According to their model, siliciclastics below the valley fills represent prodelta and delta-front sediments. The southwest-branching channel pattern shown on figure 39 certainly lends itself toward a system of deltaic distributaries. However, the lower Hardinsburg lacks the usual upward-coarsening profile of a prograding delta. Lower Hardinsburg sandstone lenses have the geometry of offshore tidal bars rather than of deltaic sands. Also, it is difficult to explain how distributary channels could erode as much as 50 m below the base of the parent delta.

Droste and Keller (1995) proposed that Hardinsburg channels were scoured by marine currents and filled with quartz sand during deposition of the Haney Limestone. They explicitly rejected origin either by fluvial backfilling or distributary action, maintaining that marine sedimentation prevailed throughout deposition of the Beech Creek through Glen Dean interval. Obviously, they were unaware of the basin-wide paleosol at the top of the Big Clifty (base of Sequence 8). If Hardinsburg paleochannels formed during Haney deposition, the Haney and Hardinsburg should intergrade laterally. Detailed cross sections such as figure 40 do not show intergrading. Moreover, submarine channels of the type envisioned by Droste and Keller lack modern analogues, as indicated by Sedimentation Seminar (1969) with reference to Bethel paleochannels.

Further evidence that Hardinsburg channels are lowstand valleys is found along Brownfield Bluff in Pope County, Illinois, where coal stringers as thick as 5 cm and several meters long occur near the base of sandstone-filled channels. The lower Hardinsburg, Haney, and Fraileys contain no coal, so the coal stringers cannot be reworked from these rocks. The only plausible source is mats of peat that were torn out of swamps flanking the channel. Thin coal beds do occur in the upper Hardinsburg near Brownfield Bluff outside of the channels.

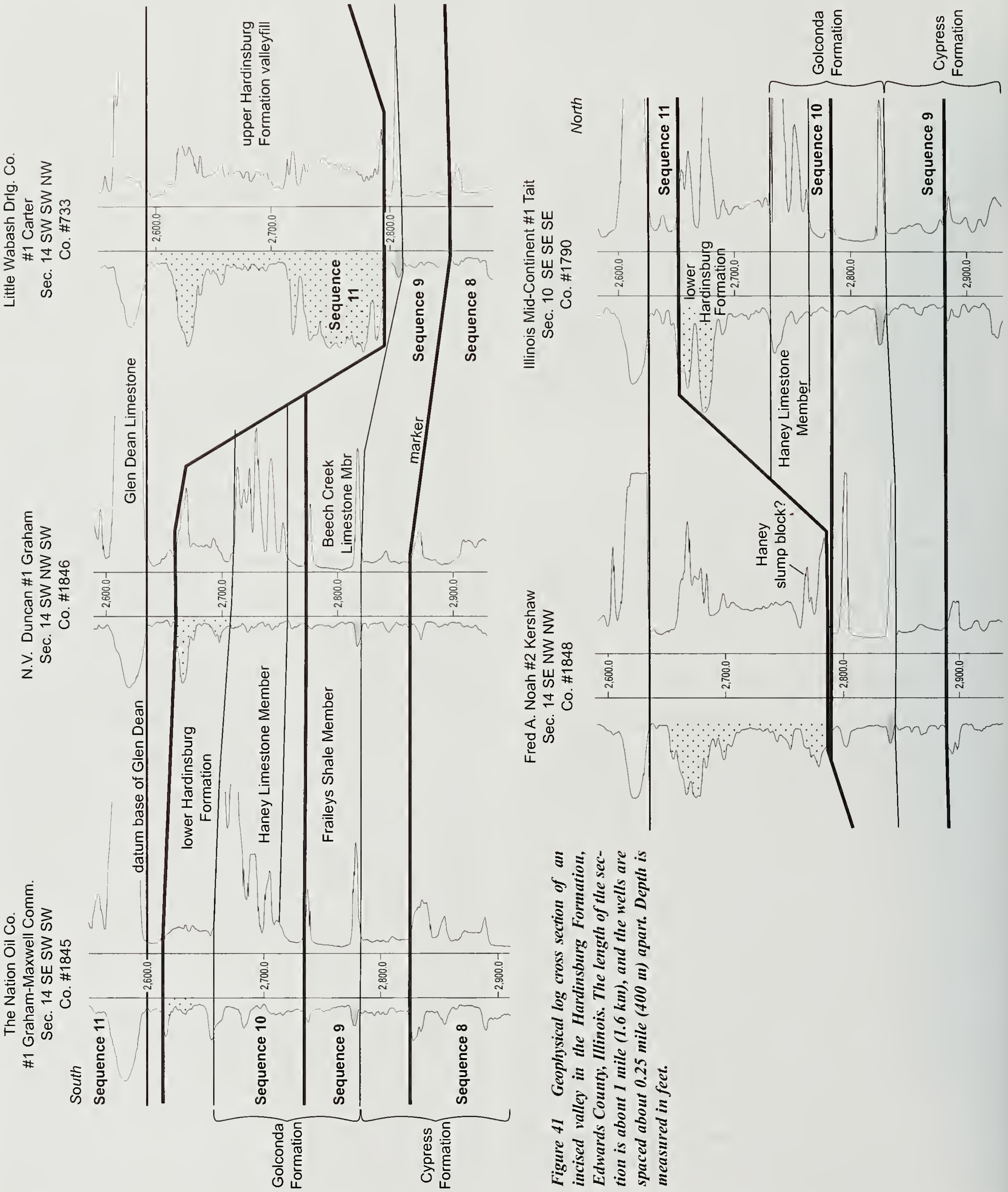

Figure 41 Geophysical log cross section of an incised valley in the Hardinsburg Formation, Edwards County, Illinois. The length of the section is about 1 mile (1.6 km), and the wells are spaced about 0.25 mile (400 m) apart. Depth is measured in feet.

Structural control of Hardinburg paleovalleys is evident. The Hardinsburg doubles in thickness in the Dixon Springs Graben in southern Illinois (fig. 34). Note that the thick Hardinsburg in the graben is not incised into the Haney. Thickening, therefore, must reflect greater subsidence in the graben during Haney deposition. Note also that there are two cycles of valley-filling sandstone capped by rooted underclay and coal. This graben may preserve sediments that were eroded or not deposited elsewhere. Another major Hardinsburg paleochannel that runs through southwestern Indiana also is parallel to the east margin of the Wabash Valley Fault System (fig. 40; plates 6 and 7). This paleovalley is directly above the West Baden clastic belt (plate 7). Such stacking of channels is highly evocative of tectonic control.

The Hardinsburg-Glen Dean contact is conformable; silty, non-calcareous shale commonly grades upward to calcareous shale with marine fossils and nodules or interbeds of limestone. In some places the contact is sharp with limestone overlying upper Hardinsburg shale on a planar or gently undulating surface.

Glen Dean Limestone

The Glen Dean Limestone extends throughout the Illinois Basin, thickening from as little as 1.5 m near its northern limit to 39 m in northwestern Todd County, Kentucky. Over most of the basin, the Glen Dean varies in irregular fashion from 6 to 24 m thick. Most thickness variation seems to reflect erosion of the upper Glen Dean beneath the Tar Springs Formation.

The Glen Dean includes a lower (unnamed) limestone member that is found practically basin-wide and commonly is 5 to 10 m thick. This limestone is similar to the Haney: crinoid-bryozoan wackestone and packstone; oolitic grainstone is common (especially at the top), and beds of microgranular dolomite and lime mudstone occur. Calcareous shale with limestone lenses underlie the lower limestone in many places, but this shale is generally mapped as part of the Hardinsburg. The upper Glen Dean consists of shale that is dark gray to olive-gray and greenish gray; fissile and calcareous; and contains lenses and thin interbeds of limestone. Echinoderms, bryozoans, and brachiopods are abundant. In the southern part of the basin, an upper oolitic, sandy limestone unit 3 to 6 m thick is commonly present.

Sandstone and sandy shale occur in the Glen Dean in western Kentucky, as shown on stratigraphic columns of geologic quadrangle maps. These rocks occupy a belt 50 to 65 km wide running southwest from Breckinridge and Grayson Counties to Christian County. Sandstone follows the central axis of the belt, grading laterally to siltstone and shale. Where best developed, the sandstone caps an upward-coarsening sequence in the middle part of the Glen Dean. Sandstone is calcareous and contains a marine fauna. Overlapping the sandstone is a discontinuous limestone that is gray to reddish gray, sandy, oolitic, and coarsely crinoidal. Some geologic quadrangle mappers interpreted the sandstone as part of the Tar Springs that filled channels eroded into the Glen Dean. However, the fact that limestone overlies the sandstone, the upward-coarsening interval, the marine fauna, and the lateral gradation to shale all imply that the sandstone represents a clastic belt within the middle Glen Dean.

The Glen Dean-Tar Springs contact is erosional in many places. This contact locally has 10 m or more of erosional relief. A gradational, intertonguing contact between the Tar Springs and Glen Dean occurs at many outcrops in southern Illinois (especially in Pope and Johnson Counties). In these outcrops, oolitic and crinoidal grainstone of the upper Glen Dean becomes sandy and interbedded with calcareous sandstone through an interval of 3 m or more. Cross-bedding, current ripple, and small scour-and-fill features imply well-agitated, shallow water.

Tar Springs Formation

The Tar Springs is a basin-wide unit of sandstone, siltstone, and shale. It is 23 m to 45 m thick across much of the basin, thinning somewhat near the northwest and southeast corners. We did not examine the Tar Springs in detail for this study; the following remarks are general.

The Tar Springs appears to be basically similar to the Sample, Cypress, and Hardinsburg Formations. The older part of the Tar Springs conformably overlies the Glen Dean; the younger part unconformably overlies Sequence 11. Younger strata consist largely of valley-fill sandstone, which probably was reworked in an estuarine or shallow marine environment. These valley-fill deposits are overlain by and flanked by shales, rooted underclays, and thin coal beds at or near the top of the Tar Springs.

Upper Sequence Boundary

We did not systematically define the upper boundary of Sequence 11. Our subsurface cross sections indicate that numerous incised valleys, filled with Tar Springs Sandstone, eroded partially through the Glen Dean Limestone. In many other places, the upper Tar Springs contains one or more coal beds that rest on rooted underclays. Such underclays are likely candidates for a non-erosional sequence boundary outside of the incised valleys.

Facies Pattern and Sediment Source

The lower part of Hardinsburg valley-fill deposits probably contains lowstand fluvial sediments, although none were specifically identified during this study. Remaining valley-fill rocks, along with the lower part of the Glen Dean, represent the TST; the rest of the Glen Dean and lower Tar Springs constitute the HST. Three parasequences were identified by Smith (1996). The oldest comprises the Hardinsburg and lower limestone of the Glen Dean. The second is in the middle Glen Dean, best shown by an upward-coarsening sandstone and shale unit in Kentucky. The upper limestone of the Glen Dean represents the third parasequence.

The south-southwestward course of Hardinsburg incised valleys implies that the sediment source lay northeast of the Illinois Basin. The clastic interval of the Glen Dean also apparently had a source to the northeast.

DISCUSSION

Basin Geometry and Deposition

Sequence analysis provides a picture of how the geometry and depositional patterns of the Illinois Basin area changed through early Chesterian time. As mentioned in the Introduction, this region was a shallow marine platform or ramp during the Chesterian, and at times it was an embayment. During lowstands, most or all of the region became a nearly flat coastal plain.

The simplified cross section (fig. 15), which runs perpendicular to what is now the basin axis, illustrates the changes well. Sequences that are nearly uniform in thickness, such as 2, 3 and 5, accumulated when the region was a uniformly subsiding platform. Other sequences thicken toward one side or the other, or toward the middle, signifying that areas of faster tectonic subsidence changed through time (table 1).

Sequences vary considerably in thickness (fig. 15). Ignoring incised valleys, Sequences 1 and 2 are relatively thick; Sequences 3, 4, and 5 are thin; Sequences 6 and 7 are thick; Sequence 8 is thin; and Sequences 9 through 11 are thick. Inferring subsidence rates from sequence thicknesses is questionable, because we do not know how much time any sequence represents or whether the sequences were of similar or variable durations. The depth and extent of incised valleys in a sequence may roughly correspond to the magnitude of sea-level drop during lowstand. Deep valleys (as in the Bethel, Sequence 6) imply larger drops in sea level, whereas widespread valley complexes (as in Sequences 8 and 11) suggest lowstands of long duration.

Tidal currents played a large role in early Chesterian sedimentation. Their best expression is in the swarms of elongate, parallel bars or ridges of either carbonate or quartz sand (figs. 42 and 43). Tidal bars, which are important targets for petroleum exploration, are best developed in the thicker sequences. Sand ridges are 8 to 10 m high, requiring a water depth of at least 10 m. Modern tidal sand ridges of similar dimensions form mostly under macrotidal (tidal range more than 4 m) conditions (Off 1963, Dalrymple et al. 1990). Tidal rhythmites, such as those common in Lower Chesterian siliciclastics, form today in mesotidal (range 2 to 4 m) or macrotidal settings (Kvale 1996). Funnel-shaped estuaries and embayments, such as the Illinois Basin during early Chesterian time, amplify tidal range and currents (Klein 1977). Thus, the Illinois Basin probably was in a mesotidal to macrotidal setting.

The bird's-foot–type fluvially dominated deltas envisioned by Swann (1963) are not in evidence in lower Chesterian strata. Small-scale, upward-coarsening successions are found locally in most siliciclastic units and suggest prograding deltas. However, tidal- and wind-driven (including storm) currents seem to have prevailed in shaping early Chesterian deltas (Treworgy 1988, Harris and Fraunfelter 1993).

Source Areas

The Transcontinental Arch was the primary source for siliciclastics in the St. Louis Limestone and Sequences 1 through 4 (Aux Vases through Yankeetown). The arch shed sediment off both its southeastern and northwestern flanks during this time. Northwest of the arch, tongues of late Meramecian to early Chesterian sandstone extend into the Williston Basin and adjacent shelves. These sandstone units include the Darwin Sandstone in Wyoming (Lageson et al. 1979) and the Kibbey Sandstone in the Williston Basin (Smith and Gilmour 1979).

Table 1 Comparison of basin geometry, relative thickness, and overall lithology of sequences.

Sequence no.	Basin geometry	Thickness	Lithology
1	Platform, slightly downwarped in southern Illinois	Thick	Carbonate, clastics to west
2	Nearly level platform	Thick	Carbonate, clastics to west
3	Nearly level platform	Thin	Limestone, clastics to west
4	Platform, downwarped on Western Shelf	Thin	Limestone, clastics to west
5	Nearly level platform	Thin	Limestone, clastics at top
6	Embayment with axis along Wabash Valley	Thick	Clastics central, limestone on shelves
7	Embayment with axis along Wabash Valley	Thick	Clastics, thin limestone at base
8	Embayment with axis along Wabash Valley	Thin	Sand in basin, shale on shelves
9	Platform, slightly downwarped along southeast margin	Thick	Mostly shale, sandstone east, limestone at base
10	Embayment with axis along Wabash Valley	Thick	Limestone, upper shale
11	Nearly level platform	Thick	Sandstone in basin, shale and limestone at top and on shelves

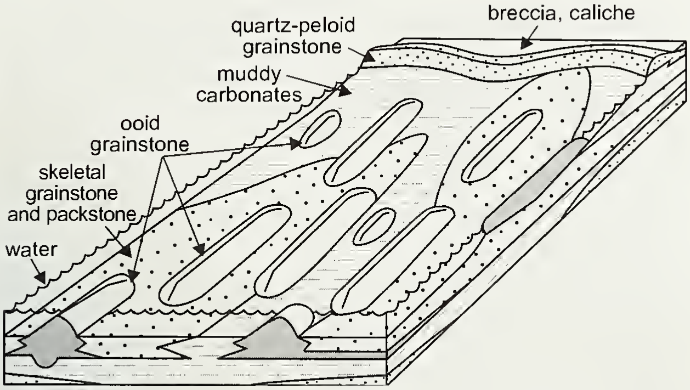

Figure 42 Interpretive block diagram of carbonate depositional environments in Sequences 1 through 5.

Younger Chesterian strata northwest of the arch generally lack sandstone.

After Sequence 4 (Yankeetown), most siliciclastics entered the Illinois Basin from the northeast (mainly in Indiana) and were transported southwestward. Evidence to define a source area more precisely is not available. Older Paleozoic quartz sandstones on the southeastern part of the Canadian Shield may have supplied much of the sediment. Some also may have come from northern parts of the Acadian and Alleghenian orogenic belts, as in the New England region of the United States and Quebec, Canada. Because Mississippian rocks are absent in the relevant areas, it is not possible to define Chesterian tectonic uplifts in possible northeastern source areas.

Effects of Local Tectonic Activity

Numerous areas in the Illinois Basin area were tectonically active during early Chesterian sedimentation. Active structures included both regional features, such as arches (Treworgy 1988), and local folds and fault zones. The influence of regional features such as the Cincinnati Arch and Ozark Dome is apparent on all of the cross sections in this report. In general, features that are now structural highs rose either steadily or intermittently during Chesterian time. In some cases, however, features that are now highs were temporarily downwarped, or vice versa. Notice, for example, that Sequence 4 (containing the Yankeetown) is thickest on part of the Western Shelf, and Sequence 9 (containing the Big Clifty) is thickest on part of the Eastern Shelf.

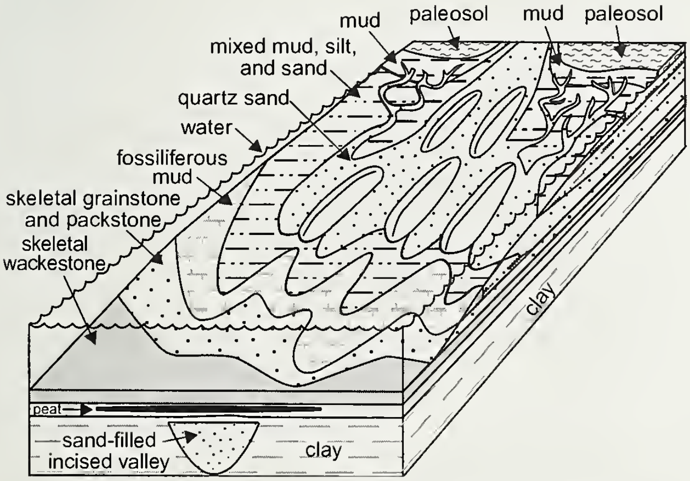

Figure 43 Interpretive block diagram of clastic depositional environments in Sequences 6 through 11.

Angular unconformities are reported on the Waterloo-Dupo Anticline in Monroe County, Illinois. This anticline on the flank of the Ozark Dome trends north-northwest. It has a gentle northeastern flank and a steep southwestern flank that is faulted. The Aux Vases Sandstone (Sequence 3) truncates Sequences 1 and 2 with an angular unconformity on the anticline (Weller and Sutton 1940). The Renault Limestone (Sequence 4) in turn truncates the Aux Vases near the crest of the fold (Weller and Weller 1939).

Farther north in Madison County, Illinois, the Aux Vases truncates Sequences 1 and 2 with angular unconformity on the St. Jacobs Dome (plate 2). Previously interpreted as a product of compaction over a Precambrian high (Nelson 1995a), the St. Jacobs structure may instead be a drape fold overlying an uplifted basement fault block.

A structural low developed in the Wabash Valley during deposition of Sequence 6 and persisted at least through Sequence 11. The low is reflected by linear trends of incised valleys and thick sandstone bodies that trend about N 30°E through southwestern Indiana and adjacent parts of Kentucky and Illinois (figs. 24, 25, 31, and 40). Effects of the low are most pronounced on the West Baden clastic belt (Sullivan 1972) and incised valleys of Hardinsburg Formation in Sequence 11 (Potter 1963). The Big Clifty Sandstone (Sequence 9) was affected to a lesser degree. All of these sandstones "stack up" in Vandenburgh County, Indiana (plate 7).

The Wabash Valley low, as outlined by paleovalley and sandstone trends, follows or parallels present-day tectonic features. The northern part of the low lies immediately east of and parallel to the Wabash Valley Fault System (fig. 3B). On the southwest, the low follows the Dixon Springs Graben, which is part of a fault complex inherited from Cambrian rifting (Nelson 1991, Kolata and Nelson 1991). Fault control here is more pronounced than in the Wabash Valley. Incised valley cutting of Sample and Cypress Sandstones (Sequences 7 and 8) is near a maximum within the graben. The Big Clifty Sandstone also is thicker in the graben than in surrounding areas (fig. 34). The Hardinsburg Sandstone thickens abruptly from about 20 m to 25 m outside the graben to more than 50 m within, which is nearly a maximum for the Hardinsburg. Note that the unusually thick Hardinsburg in the graben is *not* incised into the underlying Haney Limestone. Thus, the graben floor must have sunk to accommodate the extra thickness of Hardinsburg.

Other fault zones in the region probably influenced Chesterian deposition. For instance, the deeply incised Bethel paleochannel parallels a fault zone for 8 km in the Constantine Quadrangle, Breckinridge County, Kentucky (Sable 1964).

Correlation to Eastern Kentucky

Geologists have noticed striking similarities in Chesterian rocks of the Illinois Basin and eastern Kentucky for many decades. The rocks and fossils are so similar that in many cases Illinois Basin names are used for rock units in eastern Kentucky (Butts 1922, McFarlan and Walker 1956, Dever 1980). Even Ettensohn et al. (1984), who made wholesale revisions to eastern Kentucky lithostratigraphic nomenclature, retained the St. Louis and Ste. Genevieve Limestones (as members of their new Slade Formation).

The same geologists also recognized numerous regional unconformities in the Chesterian rocks of eastern Kentucky. Some unconformities represent incised valleys, but more commonly they are identified by zones of carbonate breccia, caliche, paleosols, and other features of subaerial exposure. Al-Tawil (1998) conducted the first comprehensive sequence stratigraphic analysis of lower Chesterian rocks in eastern Kentucky. For the interval equivalent to the Ste. Genevieve Limestone through the Glen Dean Limestone, Al-Tawil defined eleven sequences—the same number we recognize in the Illinois Basin (fig. 44).

Some key points of correlation between the two regions are as follows:

- The St. Louis in eastern Kentucky is dark, micritic, cherty limestone that contains the colonial corals *Acrocyathus proliferus* and *A. floriformis*, which are guide fossils to the St. Louis in Missouri and Illinois (Butts 1922; McFarlan and Walker 1956; Dever 1980, 1999; Dever et al. 1990). The St. Louis also has the same conodont fauna (Ettensohn et al. 1984) and a prominent regional unconformity at the top.
- The Ste. Genevieve in both regions is cross-bedded oolitic grainstone with interbeds of micritic limestone, bears the same index fossils such as *Platycrinites penicillus,* and contains multiple exposure surfaces, most notably the Bryantsville Breccia at the top (Butts 1922, McFarlan and Walker 1956, Dever 1980, Ettensohn et al. 1984).
- The Warix Run Member of eastern Kentucky is a sandy, peloidal packstone with a caliche at the top (Ettensohn et al. 1984). Such a lithology is commonly ascribed to eolian environments and is common in the Downeys Bluff Limestone, a likely partial equivalent in the Illinois Basin.
- The Cave Branch Bed in eastern Kentucky is a thin but widespread interval of red and green variegated shale and mudstone containing thin lenses of limestone. The lithology and fossils of enclosing limestones indicate that the Cave Branch is probably equivalent to either the Sample Sandstone (Dever 1980) or the Bethel Sandstone (Ettensohn et al. 1984) of the Illinois Basin.
- The Maddox Branch Member in eastern Kentucky, another widespread shale unit, probably is correlative to the Hartselle Sandstone of south-central Kentucky, Tennessee, and Alabama. For many years, the Maddox Branch-Hartselle was correlated with the Hardinsburg Formation in the Illinois Basin. Recently acquired evidence from crinoids (Burdick and Strimple 1982) and microfossils (Sable and Dever 1990), however, indicate that this unit is equivalent to the Big Clifty Sandstone. A regionally traceable surface of subaerial exposure is at the base of the Hartselle (Driese et al. 1994).

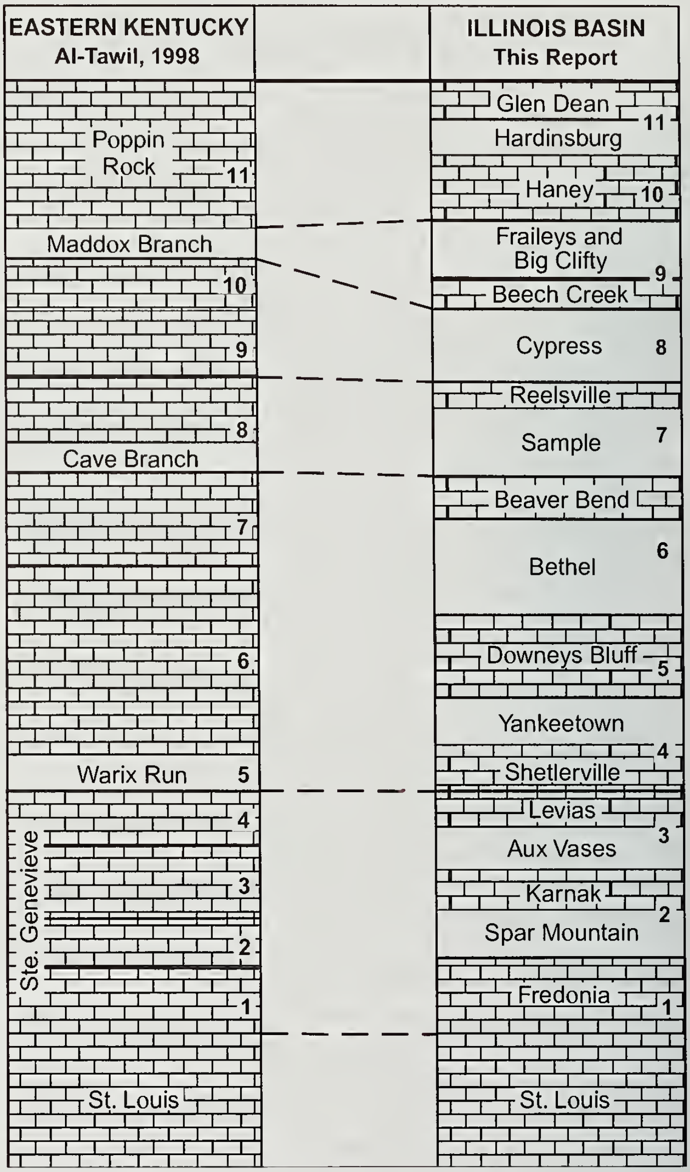

***Figure 44** Sequence correlation from eastern Kentucky (Al-Tawil 1998) to the Illinois Basin (this report). Unit names for eastern Kentucky are from Ettensohn et al. (1984). Not to scale. Numbers represent sequences.*

Comparing Al-Tawil's (1998) sequences to ours, a close, but not exact, correspondence is found. Aside from possible miscorrelations, other factors may explain the discrepancies.

The lower Chesterian succession is substantially thinner (maximum 100 m) in eastern Kentucky than in the Illinois Basin, and gaps in deposition are greater in the eastern section. Because subsidence was slower and the Appalachian Basin was shallower, a given interval (such as the Ste. Genevieve) may contain more unconformities in eastern Kentucky than in the Illinois Basin. Conversely, two or more unconformities that are distinct in the Illinois Basin may be merged in the Appalachian Basin. For example, the Cypress Formation, which straddles three sequences in Illinois, is not identified in eastern Kentucky, and its unconformities could be superimposed. Allowing for such differences, most of Al-Tawil's sequences are good matches for ours, and this close correlation is further evidence for global (eustatic) rather than local control of Chesterian unconformities (fig. 44).

Duration of Sequences

The Ste. Genevieve through Glen Dean interval is correlated with the upper Visean Stage (middle of V3b to V3c) of Europe on the basis of conodont and foraminiferal zonation (Baxter and Brenckle 1982). Faunal zonation is tied to absolute ages through data from Australia, where volcanic rocks (radiometrically dated) are interbedded with fossiliferous marine sedimentary rocks (Roberts et al. 1995). Applying these data yields an interval of 3 to 5 million years for Ste. Genevieve through Glen Dean deposition. Dividing eleven sequences into 3 to 5 million years gives an average sequence length of 273 to 455 thousand years (k.y.) with a large margin of uncertainty in both faunal and radiometric dates. These values compare well to estimated durations of 235 to 393 k.y. for major Pennsylvanian cyclothems in the Midcontinent (Heckel 1986) and are similar to the long-term Milankovitch eccentricity cycle of 414 k.y. (Berger 1988) and in the range of fourth-order sequences 100 to 500 k.y. long (Weber et al. 1995). Extrapolating further, the average duration of Smith's (1996) 45 parasequences is roughly 67 k.y., which corresponds to the fifth-order sequences of Weber et al. (1995).

Climatic Change

Evaporites in the St. Louis Limestone imply a relatively arid climate; abundant oolites, dolomite, and eolian sediments in the lower Chesterian also are consistent with arid to semi-arid conditions. Caliche, pedogenic breccia, and red slickensided mudstone, as seen in most sequences, also signify semi-arid conditions with wet-dry seasonality (Ettensohn et al. 1988, Witzke et al. 1990, Ambers and Petzold 1992). Decreased abundance of oolites upward through the Chesterian, appearance of thin coal and gleyed underclays, and possibly the overall upward increase in siliciclastics, are evidence that the climate became wetter through time.

Origin of Sequences

Lower Chesterian sequences are traceable across the Illinois Basin, and at least some of them continue into adjacent regions (Al-Tawil 1998). Sequences clearly reflect alternating episodes of deposition in shallow marine to nearshore environments and subaerial exposure, erosion, and weathering. Therefore, sequences are products of regional or possibly global changes in relative sea level. The sequences cannot be explained by local or autogenic mechanisms involving lateral shifting of deposition or by localized tectonic movements.

Swann (1964) suggested that "rhythmic" Chesterian sediments reflected cyclic climate changes under relatively static sea level. In his model, siliciclastics were deposited mainly during arid periods, and carbonates were deposited during humid periods when dense vegetation in source areas retarded erosion. Droste and Horowitz (1990) proposed an alternate scenario: carbonates forming during dry periods and siliciclastics in wet times. Cecil (1990) considered climate change to have been the primary control on Pennsylvanian cyclicity. Aside from the fact that Chesterian paleoclimate indicators do not support such radical shifts in climate, models based on climate change do not account for basin-wide paleosols, deeply incised valleys, or the extent of marine flooding needed to deposit offshore carbonates across the platform. Climatic changes may well have influenced Chesterian sedimentation, but sea-level changes are required to explain the sequences.

Tectonic models have been invoked by numerous authors to explain Pennsylvanian cyclothems in Illinois and the Midcontinent. Udden (1912) invoked intermittent or episodic basin subsidence, whereas Weller (1930) favored alternating uplift and downwarp associated with the Alleghenian orogeny. Although such models were plausible in their time, they conflict with modern concepts of crustal response to tectonic loading and isostacy. Under current thinking (e.g., Quinlan and Beaumont 1984), collisional tectonics result in "thrust loading" at continental margins. As thrust sheets stack up, their combined weight depresses the continental margins. Through a combination of crustal flexure and isostatic compensation, intracratonic arches and domes rise and intra-cratonic basins subside in response to thrust loading. According to this mechanism, maximum subsidence in basins such as the Illinois Basin should have coincided with maximum uplift on adjacent arches and shelves. The Chesterian sequence record, however, indicates that basin and shelves rose and fell in concert (relative to sea level). Another difficulty with a tectonic hypothesis of sequences is that the Chesterian predates significant onshore thrusting in the Alleghenian and Ouachita orogenic belts.

Glacially induced eustacy, as introduced by Wanless and Shepard (1936) for Pennsylvanian cyclothems, remains the preferred hypothesis for Chesterian sequences. Sea-level changes in response to glacial events during the Pleistocene are intuitive and amply documented. Glacial deposits in Mississippian rocks from other parts of the world provide the link to eustacy in North America (Crowell 1978, Hambrey and Harland 1981, Caputo and Crowell 1985, Veevers and Powell 1987, Ross and Ross 1988, Frakes et al. 1992). As shown herein, the duration of Chesterian sequences agrees well with fourth-order eustatic sea-level fluctuations. Parasequences, shorter in duration, may reflect fifth-order eustatic events, although some are probably products of autocyclic processes (Smith and Read 1999, 2000).

The depth of valley incision provides a measure of the relative change in sea level for each sequence. Sequences 1 through 5 are bounded by paleosols in most of the basin, with only localized valley incision. Amplitude of sea-level change for Sequences 1 through 5 is estimated at 20 to 30 m. For Sequences 6 through 11, amplitude increased to 25 to 95 m, the greatest being in Sequence 6 (Smith and Read 2000).

Figure 45 shows sea-level changes inferred in this study.

Oil and Gas

The lion's share of oil and gas production in the Illinois Basin has come from Chesterian rocks. Howard (1991) credited the Ste. Genevieve Limestone with 18% of cumulative basin-wide hydrocarbon production, and Chesterian sandstones other than the Spar Mountain and Aux Vases were credited with 60%. Aux Vases production was not specified, but is substantial. Production breakdowns for most individual formations are not available because in many fields the output is commingled. Maps by Howard (1991) indicate that the Hardinsburg and older sandstones produce in many more fields than the Tar Springs and younger Chesterian sandstones.

Ooid and quartz sand ridges probably are the leading reservoir rock types in the lower Chesterian. Nearly all Ste. Genevieve oil occurs in "McClosky" oolite sand bodies (Carr 1973, Choquette and Steinen 1980, Seyler and Cluff 1991). Ooid reservoirs are encased in shale and tight micritic carbonate rocks, which provide good lateral and top seals. Aux Vases reservoirs are largely tidal sand bars of quartz sand, sealed by shaly tidal-flat facies (Seyler 1986; Leetaru 1991, 1993, 1997; Huff 1993). The Cypress Formation, probably the most prolific siliciclastic reservoir unit, also produces from anticlinal closures of massive valley-fill sandstones and from lenticular sandstone bodies that are interpreted as tidal sand ridges. Most of these occur in the upper part of Sequence 8 above the thick valley-fill sandstones (Grube 1992, Whitaker and Finley 1992, Xu and Huff 1995, Cole and Nelson 1995). Tidal sand bars occur in the transgressive to highstand part of a sequence and are best developed where the sequence is thickest.

Some incised valley-fill sandstones support large oil and gas fields. Most production from the Spar Mountain is in incised valleys (Leetaru 1997). The largest gas field in the Bethel Sandstone is the Midland Field in Muhlenberg County, Kentucky. The reservoir at Midland is sandstone filling the deeply incised Bethel paleovalley. The lower sandstone member of the Cypress Formation is the main reservoir for the giant Lawrence County and Louden oil fields in Illinois. The lower sandstone here is interpreted as valley fill of Sequence 8, but is reworked into tidal sand ridges. Most large incised valley sandstones, however, yield only water. Such sandstones lack effective lateral seals except where structural closure exists. The Spar Mountain and Bethel valleys are relatively narrow and are cut into carbonate rocks that are mostly impermeable.

Other settings that support oil production include tidal channels in the Aux Vases (Seyler 1986, Leetaru 1997), basal transgressive sandstones such as the Popcorn ("Renault") in southwestern Indiana, and possibly sandstones of longshore bar, deltaic, and eolian origin.

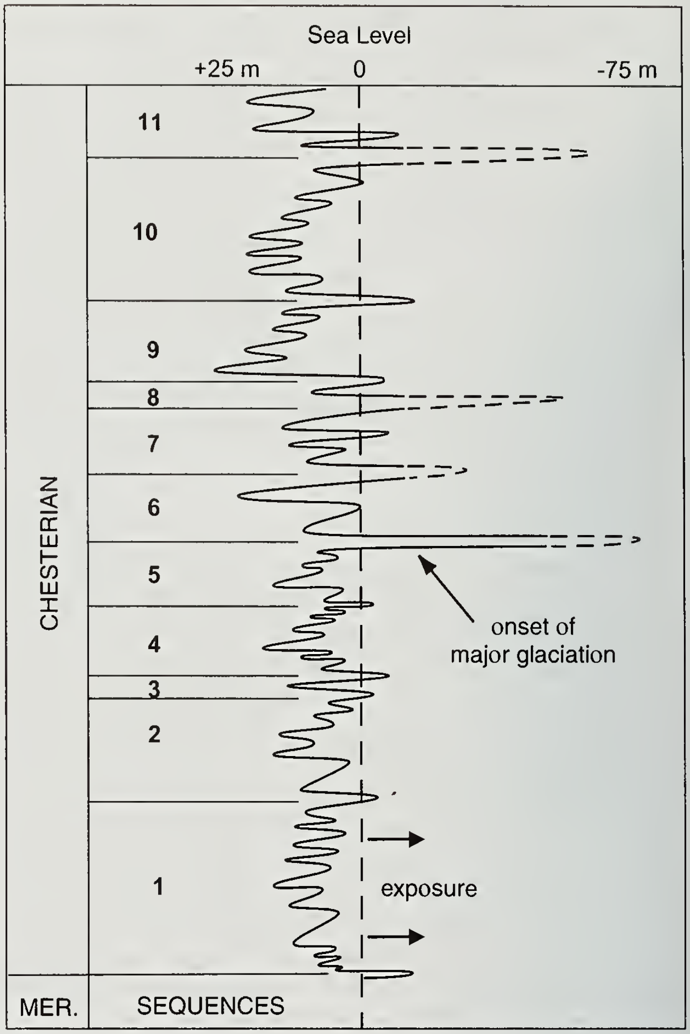

Figure 45 Hypothesized sea-level curve for the study interval based on interpreted water depths for different rock types and depth of incision associated with each sequence boundary. The onset of major glaciation is marked by an abrupt increase from 20- to 30-m sea-level changes of Sequences 1 through 5 up to 95 m for Sequence 6.

CONCLUSIONS

Eleven depositional sequences are identified in lower Chesterian strata from the Ste. Genevieve through Glen Dean Limestones. The sequences are bounded by unconformities that are basin-wide (or nearly so) and attributed to eustatic fluctuations of sea level.

Two types of unconformities bind Chesterian sequences. Erosional unconformities define valleys incised by rivers during lowstand and backfilled during the next transgression. Non-erosional unconformities are defined by paleosols.

The LSTs are uncommon, taking the form of fluvial sediments in the basal parts of some valley fills. Overlying transgressive sequence tracts are generally thin and comprise most valley fills and the lower parts of overlying limestones.

Highstand systems tracts comprise the middle and upper parts of limestones and the overlying upward-shoaling, prograding siliciclastics.

Parasequences are present; Smith (1996) identified 45 total and 1 to 9 per sequence. Regional correlation of parasequences is tentative, and some apparent parasequences may reflect autocyclic rather than eustatic events.

The Illinois Basin area was a cratonic ramp, not an enclosed basin during the late Mississippian. During deposition of some sequences, the tectonic subsidence rate was nearly uniform across the region. During deposition of others, one area or another was downwarped more strongly, yielding thicker sediment packages. The most persistent downwarp or depocenter, from Sequence 6 through 11, paralleled the east side of the Wabash Valley Fault System and followed the Dixon Springs Graben.

The Transcontinental Arch was the principal source of terrigenous clastics during deposition of the St. Louis Limestone and Chesterian Sequences 1 through 4. The primary source during deposition of Sequences 5 through 11 (except the Big Clifty Sandstone) was the southeastern Canadian Shield or in the northern Appalachian Mountains. The Big Clifty Sandstone was derived from a southern Appalachian source.

Lower Chesterian rocks have yielded about three-fourths of the oil and gas produced in this basin. Both highstand oolite and quartzose sand ridges and valley-fill sands are highly productive in structural and combination structural-stratigraphic traps. All four giant oil fields—Salem, Louden, Clay City, and New Harmony—exemplify such conditions. These four fields together account for approximately one-third of all of the oil produced in Illinois (David Morse, ISGS, written communication 2000).

Sequence stratigraphy provides a useful model for understanding the correlation, depositional patterns, and rock-body geometry of Chesterian rocks.

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APPENDIXES

APPENDIX 1

Measured Sections and Cores Used on Outcrop Cross Sections (Plate 1) Updated August 28, 2000

All sections described by Smith, unless indicated otherwise. Note that many numbered columns appear in more than one cross section.

ILLINOIS

Cores are stored at the Illinois State Geological Survey (ISGS) in Champaign.

1. Core, Madison County Coal Corp., hole 6, 375′ SL, 1660′ WL, Sec. 26, T4N, R8W, Madison County. Core C-141 logged by Smith and Nelson. *This is well 2 on Section IL-1 (Appendix 2).*
2. Core, Madison County Coal Corp., hole 5, 175′ SL, 84′ EL, Sec. 3, T3N, R8W, Madison County. Core no. C-140 logged by Smith and Nelson.
3. Core, Madison County Coal Corp., hole 4, center of N½ of Sec. 9, T3N, R8W, Madison County. Core C-146 logged by Smith and Nelson.
4. Core, ISGS borehole CB-2, SE¼ SE¼ SE¼, Sec. 6, T11S, R2W, Union County. Core C-13619 logged by Smith and Nelson.
5. Quarry highwall, Anna Quarries, Inc., Hartline (east) Pit, W½ NW¼ NW¼, Sec. 21 and parts of adjacent sections, T12S, R1W, Union County. Section measured by Smith and Nelson, Ste. Genevieve and St. Louis.
6. Road cut, I-57, mile 27.4, east side of northbound lanes, W½ NW¼ SW¼, Sec. 6, T13S, R1E, Union County. Section measured by Smith and Nelson, Aux Vases and Ste. Genevieve.
7. Quarry highwall, Columbia Quarries-Cypress Quarry (formerly Charles Stone Co.), S½ SW¼, Sec. 5, T14S, R2E, Johnson County. Section measured by Smith and Nelson, Aux Vases and Ste. Genevieve.
8. Core, Abner Field borehole, NW¼ NW¼ SE¼, Sec. 19, T13S, R6E, Pope County. Core No. C-46 logged by Smith and Nelson, Tar Springs to Ste. Genevieve.
9. Core, Ozark-Mahoning No. BM-225, NW¼ NE¼ Sec. 33, T12S, R7E, Pope County. Core C-13076 logged by Nelson, Hardinsburg to Bethel.
10. Core, Ozark-Mahoning No. KT-19S, NE¼ NE¼, Sec. 21, T12S, R8E, Hardin County. Core C-12781 logged by J. Treworgy, Hardinsburg to Beech Creek.
11. Core, U.S. Bureau of Mines, Knox and Yingling borehole K-4, 762′ SL, 1590′ WL, Sec. 11, T11S, R7E, Hardin County. Core C-13277 logged by D.B. Saxby, also by Smith and Nelson, Waltersburg to St. Louis.
12. Core, Ozark Mahoning borehole USHC-55S, 1210′ NL, 1120′ WL, Sec. 17, T11S, R9E, Hardin County. Core C-12782 logged by Nelson and Z. Lasemi, Glen Dean to Ste. Genevieve.
13. Core, Ozark-Mahoning, No. DT-134, SW¼ SW¼, Sec. 9, T11S, R9E, Hardin County, logged by Nelson and Smith, Tar Springs to Ste. Genevieve. *This is well 1 on Section IL-4 (Appendix 2).*
14. Quarry highwall, Hardin County Materials Co. No. 2, SE¼ NE¼, Sec. 2, T12S, R9E, Hardin County. Section measured by Smith and Nelson with input from J. Fred Read and Aus Al-Tawil, Bethel to Ste. Genevieve.
15. Quarry highwall, Martin Marietta Corp., Cave in Rock Quarry, SE¼ SW¼, Sec. 8, T12S, R10E, Hardin County. Section measured by Smith and Nelson, Bethel to Ste. Genevieve.

KENTUCKY

Cores are stored at the Kentucky Geological Survey (KGS) in Lexington.

16. Quarry highwall, Martin Marietta Co., Three Rivers Quarry, on U.S. Rt. 60, 6.25 miles northeast of Smithland, Carter Sec. 17-I-14, Livingston County, Aux Vases to uppermost St. Louis.
17. Quarry highwall, Denny and Simpson Co., Fredonia Quarry, on U.S. Rt. 641, 2.5 miles south of Fredonia, Sec. 23-I-18, Caldwell County; plus core drilled in quarry floor, KGS borehole C-218, Ste. Genevieve.
18. Quarry highwall, Kentucky Stone Co., Princeton Quarry, on IL Rt. 91, 2.75 miles southeast of Princeton, Sec. 21-H-20, Caldwell County, lower Bethel to Ste. Genevieve.
19. Road cut, Stevens Hill Cut on Western Kentucky Parkway east of Princeton, 1800′ WL, 2800′ SL, Sec. 6-H-21, Caldwell County; Tar Springs to Cypress (see Trace 1981).
20. Core, Shrewsbury Collins borehole No.1, Sec. 2-I-20, Caldwell County, KGS Core C-216.
21. Core, Cobb No.1 borehole, Sec. 2-I-20, Caldwell County, KGS Core C-220.
22. Quarry highwall, Rogers Group, South Hopkinsville Quarry, on U.S. Alt. 41, 4.5 miles south of Hopkinsville, Sec. 8-D-25, Christian County, Ste. Genevieve.
23. Quarry highwall, Christian Quarry (abandoned), on east side of Hopkinsville along U.S. Rt. 68, 0.5 mile east of Alt. 41, Sec. 14-E-25, Christian County, Bethel to Ste. Genevieve.
24. Quarry highwall, Kentucky Stone Co., Todd Quarry, on U.S. Rt. 68, 7 miles west of Elkton, Sec. 4-D-28, Todd County, Paoli.
25. Road cut, U.S. 68 bypass on west side of Russellville, Sec. 25-E-32, Logan County, Bethel to upper Ste. Genevieve.
26. Quarry highwall, Kentucky Stone Co., Russellville Quarry, on IL Rt. 79, 1 mile northeast of Russellville, Sec. 18-E-32, Logan County, Paoli to St. Louis.
27. Quarry highwall, Southdown/Medusa Crushed Stone, Hartford Quarry, 600′ EL, 2000′ NL, Sec. 18-M-33, Ohio County.
28. Road cut, Green River Parkway, milepost 9.1, northwest of Bowling Green, Sec. 19-G-36, Warren County, Paoli to Ste. Genevieve.
29. Road cut, Green River Parkway, milepost 9.5, northwest of Bowling Green, Sec. 19-G-36, Warren County, Big Clifty to Beaver Bend.
30. Quarry highwall, Kentucky Stone Co., Rockfield Quarry, on U.S. Rt. 68 near Rockfield, Sec. 9-E-35, Warren County, Ste. Genevieve.
31. Core, Marathon Oil Co. No. 22 Lindsey, 2240′ NL, 1850′ WL, Sec. 4-I-39, Edmonson County, KGS core C-1244.
32. Quarry highwall, Medusa Crushed Stone Co., Park City 31W Quarry, on U.S. Rt. 31 W about 3 miles west of Park City, Sec. 23-H-41, Edmonson County, Big Clifty to Ste. Genevieve.
33. Road cut, I-65, Milepost 48, just northeast of Park City exit, Sec. 24-H-42, Barren County; Big Clifty to Ste. Genevieve.
34. Quarry highwall, East Park City Quarry (abandoned), 2 miles east of Park City on Old Bardstown Road, Sec. 20-H-42, Barren County, Ste. Genevieve.
35. Quarry highwall, Scotty's Paving Co., Cave City Quarry, on IL Rt. 90 about 5 miles south of Cave City, Sec. 2-G-43, Barren County, Ste. Genevieve and St. Louis.

36. Road cut, I-65, near Milepost 64, 1 mile south of Munfordville exit, Sec. 16-J-44, Hart County, Ste. Genevieve.

37. Road cut, I-65, 0.5 mile north of Munfordville exit, 800′ EL, 2000′ SL, Sec. 6-J-44, Hart County, Big Clifty to Ste. Genevieve.

38. Quarry highwall, Kentucky Stone Co., Upton Quarry, on IL Rt. 224 (Quarry Road) 2 miles east of Upton, Sec. 14-L-44, Larue County.

39. (Not used.)

40. Core, KGS and USGS, Summit Area No.1, Sec. 6-M-42, Hardin County, KGS core C-117.

41. Quarry highwall, Larry Glass Paving, Cecilia Quarry, on U.S. 62, 3 miles west of Cecilia, Sec. 25-N-42, Hardin County; Beech Creek to Ste. Genevieve.

42. Core, KGS and USGS Dennis No.1, Sec. 10-N-38, Breckinridge County, KGS Core C-118.

43. Quarry highwall, Stephensburg Quarry (abandoned), on dirt road 2 miles north of Stephensburg, Sec. 18-N-42, Hardin County; Paoli and Ste. Genevieve.

44. Quarry highwall, Kentucky Stone Co., Irvington Quarry, on IL Rt. 477 about 2 miles northwest of Irvington, Sec. 7-Q-39, Breckinridge County; Paoli and Ste. Genevieve.

45. Quarry highwall, Kosmos Cement Co., Battletown Quarry, on IL Rt. 228 about 0.5 mile north of Battletown, Sec. 3-S-39, Meade County; Big Clifty through Ste. Genevieve.

INDIANA

Cores are stored at the
Indiana Geological Survey (IGS) in Bloomington.

46. Quarry highwall, Mulzer Crushed Stone Co., Cape Sandy Quarry, about 4 miles east of Alton, Sec. 30, T4S, R2E, Perry County; Big Clifty through Ste. Genevieve.

47. Core, IGS No. SDH-152, Sec. 14, T4S, R2E, Harrison County, Call No. C-339.

48. Core, IGS No. SDH-132, Sec. 10, T4S, R1W, Perry County, Call No. C-303. *This is well 52 on section IN-2 (Appendix 2).*

49. Quarry highwall, Mulzer Crushed Stone Co., Tower Quarry, 2 miles north of Leavenworth, Sec. 29, T3S, R2E, Crawford County.

50. Road cut, I-64 at Scout Mountain, milepost 99, 7 miles west of Corydon exit, Sec. 24, T3S, R2E, Harrison County, Reelsville through Ste. Genevieve.

51. Quarry highwall, Corydon Crushed Stone Co., off IL Rt. 135 about 2.5 miles northwest of Corydon, Sec. 14, T3S, R3E, Harrison County, Paoli through St. Louis.

52. Quarry highwall, Robertson Crushed Stone, Inc., on IL Rt. 64 1 mile northwest of Depauw, Sec. 13, T2S, R3E, Harrison County, Beaver Bend through St. Louis.

53. Road cut, I-64 at Sulphur interchange (Exit 86), Sec. 24, T3S, R1W, Crawford County, Hardinsburg through Reelsville.

54. Core, IGS No. SDH-313, Sec. 7, T2S, R2E, Crawford County, Call No. C-626.

55. Core, IGS No. SDH-320, Sec. 14, T2S, R3W, Dubois County, Call No. C-643.

56. (Not used.)

57. Core, IGS No. SDH-151, Sec. 15, T1S, R1E, Orange County, Call No. C-338.

58. Core, IGS No. SDH-83, Sec. 11, T3S, R1W, Dubois County, Call No. C-230.

59. Core, IGS No. SDH-311, Sec. 30, T1S, R2W, Orange County, Call No. C-625. *This is well 45 on section IN-1 (Appendix 2).*

60. Core, IGS No. SDH-326, Sec. 34, T1N, R2W, Orange County, Call No. C-651. *This is well 46 on section IN-1 (Appendix 2).*

61. Core, IGS No. SDH-48, Sec. 32, T2N, R2W, Orange County, Call No. C-167.

62. Quarry highwall, Cave Quarries, Inc., West Paoli Quarry, on U.S. Rt. 150, 3.5 miles northwest of Paoli, Sec. 29, T2N, R1W, Orange County, Reelsville through Ste. Genevieve.

63. Core, U.S. Gypsum No. 10-60, Sec. 23, T2N, R3W, Martin County, Call No. C-214.

64. Quarry highwall, Rogers Group, Mitchell Quarry, on IL Rt. 60, 5 miles west of Mitchell, Sec. 12, T3N, R2W, Lawrence County, Cypress through Ste. Genevieve.

65. Core, IGS No. SDH-153, Sec. 27, T4N, R1W, Lawrence County, Call No. C-340.

66. Core, U.S. Army Corps of Engineers No. C-3, Sec. 28, T5N, R3W, Martin County, Call No. C-735.

67. Core, U.S. Army Corps of Engineers No. DB-1, Sec. 15, T5N, R3W, Martin County, Call No. C-797.

68. Quarry highwall, Rogers Group, Sieboldt Quarry, about 5 miles north of Oolitic on county roads, Sec. 11, T6N, R2W, Lawrence County, Bethel through Ste. Genevieve.

69. Core, IGS No. SDH-208, Sec. 29, T7N, R5W, Greene County, Call No. C-487.

70. Core, IGS No. SDH-330, Sec. 22, T7N, R2W, Monroe County, Call No. C-672.

71. Quarry highwall, Rogers Group, Bloomington Crushed Stone, on Oard Road 4 miles west of Bloomington, Sec. 27, T9N, R2W, Monroe County, Paoli and Ste. Genevieve.

72. Core, IGS No.SDH-155, Sec. 7, T8N, R2W, Monroe County, Call No. C-342.

73. Core, IGS No. SDH-186, Sec. 23, T11N, R6W, Clay County, Call No. C-444.

74. Quarry highwall, Kentucky Stone Co., Cloverdale Quarry, on IL Rt. 343 1 mile west of Cloverdale, Sec. 1, T12N, R4W, Putnam County, Beaver Bend through Ste. Genevieve.

75. Core, IGS No. SDH-8A, Sec. 16, T13N, R5W, Putnam County, Call No. C-105.

APPENDIX 2

List of Wells Used in Subsurface Cross Sections

SECTION IL-1 by Janis Treworgy

MADISON COUNTY

Log quality is good to excellent, unless indicated otherwise.

1. Madison Coal Corp. No. 4 Smith, William (Mine No. 2), 0′ N 0′ E SW/c NW NE, Sec. 9, T3N, R8W, API 1211900351.
2. Madison Coal Corp. No. 6 Mine No. 4, 375′ N 340′ E SW/c SE SW, Sec. 26, T4N, R8W, API 1211900096. Core description by John Nelson and Taury Smith. *This is well 1 on outcrop sections (Appendix 1).*
3. Lessing Alch No. 1 Mick, Gus, 330′ NL 330′ EL SE NE, Sec. 29, T4N, R7W, API 1211900940.
4. Kingwood Oil Co. No. 1 Castor, 330′ SL 330′ EL SE SE NE, Sec. 22, T4N, R7W, API 1211900939. Company sample study of poor quality.
5. C.E. Brehm Drlg. and Prod. No. 1 Grotefendt, 330′ NL 330′ WL SW, Sec. 19, T4N, R6W, API 1211902510.
6. Kenneth M. Bayer No. 1 Grimm, 330′ SL 330′ EL SE NE SW, Sec. 20, T4N, R6W, API 1211900742.
7. Pointer Oil Company No. 1 Grotefendt Comm., 330′ NL 330′ WL SW SE NW, Sec. 28, T4N, R6W, API 1211900795. Composite log, no sample study.
8. G.L. Reasor No. 1 Hess, Fred, 330′ SL 330′ WL, Sec. 27, T4N, R6W, API 1211900740. Sample study in drill hole in Sec. 15, T4N, R6W.
9. J. William Everhart No. 1 Steinkoenig, J.O., 330′ NL 330′ WL SW NW, Sec. 35, T4N, R6W, API 1211900738.
10. B.F. Thompson No. 1 Reynolds, 330′ NL 330′ WL NE SW, Sec. 36, T4N, R6W, API 1211900737.
11. California Co. No. 1 Kurz, 330′ SL 330′ WL SE SE, Sec. 1, T3N, R6W, API 1211900673. Sample study one mile away.
12. Thomas Doran No. 1 Widmer, 330′ SL 330′ WL SE SW, Sec. 5, T3N, R5W, API 1211900676.
13. T.W. George Trust No. 1 Isert, Joseph, 330′ SL 330′ WL SE NW, Sec. 16, T3N, R5W, API 1211900804.
14. Shure Oil Corp. No. 1 Rutz-Weiss Community, 330′ NL 330′ EL SE SW NE, Sec. 22, T3N, R5W, API 1211901186. Sample study six miles away.
15. McCulloch Drlg. Co. No. 1 Blacet Estate, 330′ SL 330′ EL NW, Sec. 23, T3N, R5W, API 1211900674.

CLINTON COUNTY

16. Ohio Oil Co. No. 1 Detmer, 330′ NL 330′ EL SW, Sec. 18, T3N, R4W, API 1202701603.
17. Tatum, W.S. No. 1 Frank Schrage, 330′ NL 330′ EL NE NE SW, Sec. 17, T3N, R4W, API 1202700541. Company sample study.
18. Braun, C.F. and Co. No. 1-21 Henrichs, 330′ SL 330′ EL NE SW, Sec. 21, T3N, R4W, API 1202724416.
19. Texas Company No. 1 Buehne, 330′ NL 330′ WL NE SW, Sec. 22, T3N, R4W, API 1202701521.
20. Eiteljorg Harrison No. 1 Lutheran Orphans' Home, 330′ SL 330′ WL SE, Sec. 27, T3N, R4W, API 1202701522.
21. Gulf Oil Corporation No. 1 Unger, 330′ NL 330′ WL SW NE, Sec. 25, T3N, R4W, API 1202701679.
22. Gulf Refining Co. No. 2 Liening, 660′ NL 330′ EL SE, Sec. 36, T3N, R4W, API 1202703114.
23. Doran Thomas S No. 1 Dorries, 330′ NL 330′ WL SW NE, Sec. 6, T2N, R3W, API 1202701744. Sample study by Elwood Atherton in Sec. 5, API 1202702744.
24. Standolind Oil and Gas No. 1 Phillips, 330′ NL 330′ WL, Sec. 4, T2N, R3W, API 1202702742.
25. Harry Swartz No. 1 Schlafly, 660′ NL 330′ EL SE, Sec. 3, T2N, R3W, API 1202700557.
26. Jet Oil Co. No. 1 Diekemper, 330′ NL 330′ WL SW, Sec. 1, T2N, R3W, API 1202701593.
27. Thomas R. Kerwin No. 1 Schneider, 1640′ SL 1657′ WL SW, Sec. 31, T3N, R2W, API 1202703212. Company sample study.
28. Ernest A. Obering No. 1 Beckemeyer, 390′ SL 380′ WL NW SW, Sec. 33, T3N, R2W, API 1202701493.
29. The Texas Company No. 1 Gray, P., 990′ NL 660′ WL SE, Sec. 35, T3N, R2W, API 1202700823.
30. Texaco, Inc. No. 1 Cooley, George, 330′ SL 330′ WL NE SW, Sec. 36, T3N, R2W, API 1202702959.
31. Louisiana Land and Expl. No. 1 Hemminghaus, 330′ SL 990′ EL SE NW, Sec. 31, T3N, R1W, API 1202725591.
32. Jordan Oil and Gas Co. No. 1 Tyberendt, 330′ NL 330′ EL NE SE, Sec. 32, T3N, R1W, API 1202725615.
33. C.E. Brehm Drlg. and Prod. No. 1 Hemminghaus Comm., 330′ SL 380′ WL NE SE, Sec. 33, T3N, R1W, API 1202724548. Sample study by Elwood Atherton. *This is well 35 on Section IL-3.*
34. V S & S Drilling Co. No. 1 Conrad, 330′ NL 330′ EL NE NE NE, Sec. 3, T2N, R1W, API 1202701224.

MARION COUNTY

35. John E. Carson No. 1 Olsen, 330′ SL 330′ WL SW SW SW, Sec. 6, T2N, R1E, API 1212101804.
36. So-Western Oil and Gas No. 28 Benoist, 1200′ NL 1185′ WL NE, Sec. 8, T2N, R1E, API 1212101443. Sample study.
37. Florence Oil Co No. 1 Meredith, 275′ NL 100′ EL NW, Sec. 10, T2N, R1E, API 1212100485. Sample study (depths not adjusted to log).
38. Frank W. Firman No. 1 Suggs, SE SE SW NE, Sec. 11, T2N, R1E, API 1212100486.
39. Wausau Petroleum Corp. No. 1-D Reuben-Young, 330′ SL 380′ WL NW, Sec. 7, T2N, R2E, API 1212101779. Sample study in Ste. Genevieve and St. Louis.
40. Paul Doran Est. No. 1 Moore, 330′ SL 330′ WL NW, Sec. 8, T2N, R2E, API 1212103259.
41. Arthur J. Slagter, Jr. No. 2 Branch, 1350′ NL 990′ WL SE, Sec. 4, T2N, R2E, API 1212103211.
42. Frank E. Dingle No. 1 Dingle, 755′ SL 537′ EL SW SW, Sec. 2, T2N, R2E, API 1212103203. Sample study by Elwood Atherton; no wireline log.
43. Harexco, Inc. No. 1 Griggs, 450′ SL 330′ WL SW, Sec. 6, T2N, R3E, API 1212127562.
44. Richard W. Beeson No. 1 Garner Unit, 500′ SL 330′ WL SE, Sec. 31, T3N, R3E, API 1212126797.
45. Collins Brothers Oil Co. No. 1 Stevenson, 330′ SL 660′ EL NW, Sec. 32, T3N, R3E, API 1212125803.
46. E. Zekel and J.D. Fry No. 1 Smalley, 330′ NL 330′ EL SW SW, Sec. 35, T3N, R3E, API 1212126611. No wireline log, scout tops only.

47. Jet Oil Co. No. 1 John Kagy et al., 330′ NL 330′ WL SE, Sec. 36, T3N, R3E, API 1212105166.

48. Pawnee Oil and Gas, Inc. No. 1 Crippen, 330′ SL 330′ EL SW SE, Sec. 30, T3N, R4E, API 1212126956.

49. Radliff Drilling Co. No. 1 Shufeldt, 330′ NL 330′ EL SE NE, Sec. 33, T3N, R4E, API 1212126775.

50. Helmerick and Payne et al. No. 1 Stephens, SW SW SW, Sec. 35, T3N, R4E, API 1212100702. Sample study by Elwood Atherton.

51. K Oil Incorporated No. 1 Jordan, 330′ SL 330′ WL SE NW, Sec. 36, T3N, R4E, API 1212126869. No wireline log, company sample study only; nearest log 0.5 miles away.

CLAY COUNTY

52. Crest Oil Co., Inc. No. 1 Knapp Estate, 330′ NL 330′ EL SE NW, Sec. 5, T2N, R5E, API 1202526944.

53. Diamond Energy Co. No. 1 Spicer, 660′ SL 330′ WL SE SW, Sec. 4, T2N, R5E, API 1202527101.

54. Hed Oil Co No. 1 Maude Tully et al., 330′ NL 330′ WL NE NW NE, Sec. 10, T2N, R5E, API 1202500563.

55. Shakespeare Oil Co. No. 1 Woomer Unit, 330′ NL 430′ WL SE SE, Sec. 2, T2N, R5E, API 1202526864.

56. Carter Oil Company No. 1 Markham, 330′ NL 330′ EL NW SE, Sec. 7, T2N, R6E, API 1202501219.

57. Hall Edwards No. 1 Koontz, 330′ NL 330′ EL SW, Sec. 8, T2N, R6E, API 1202501220.

58. Humbolt Oil, Inc. No. 1 Given, 330′ NL 330′ WL NE NW, Sec. 9, T2N, R6E, API 1202527049.

59. Lohmann-Johnson Drlg. No. 1 Valbert and Leslie et al., 330′ NL 330′ WL SW, Sec. 11, T2N, R6E, API 1202500569. Company sample study.

60. Indiana Farm Bureau Co-op Assoc No. 1 Pearce, 330′ SL 330′ WL NW, Sec. 12, T2N, R6E, API 1202500912. Core description by Elwood Atherton from Bethel to T.D. in nearby drill hole.

61. Pollack Bros. Oil Prod. No. 1 Bogard Comm., 380′ NL 990′ WL SW NE, Sec. 7, T2N, R7E, API 1202525430.

62. J.W. Rudy Estate No. 1 Bay, 330′ NL 330′ WL SE, Sec. 8, T2N, R7E, API 1202500578. Brief sample study.

63. Samuel E. Boxwell No. 1 Leak, 330′ SL 330′ EL NE SE, Sec. 9, T2N, R7E, API 1202501649. Sample study.

64. J.W. Rudy Company No. B-1 Mix, 330′ SL 330′ WL SE NW, Sec. 11, T2N, R7E, API 1202525611.

65. Earl B. Reynolds No. 1 Tullett, 660′ NL 330′ EL NW NW, Sec. 12, T2N, R7E, API 1202501886. Sample study, no wireline log above Beech Creek.

66. Union Oil Co. of California No. 35 Leon Clark, 330′ SL 330′ EL SE, Sec. 7, T2N, R8E, API 1202527208.

67. Union Oil Co. of California No. 5 Carroll, 330′ NL 430′ EL NE SE, Sec. 8, T2N, R8E, API 1202526298. Sample study in same section, API 1202502276.

68. Union Oil Co. of California No. A-19 Teetrick, 330′ SL 330′ WL NE, Sec. 9, T2N, R8E, API 1202526994.

69. Gray, James A. No. 1 Brother-Russell Comm., 330′ NL 330′ WL NE SW, Sec. 10, T2N, R8E, API 1202525192.

70. Griffin and Walker Assoc No. 1 Moseley, 330′ NL 330′ WL NE SW, Sec. 11, T2N, R8E, API 1202501235.

RICHLAND COUNTY

71. Don Baines Drilling Co. No. 1 Sager, 330′ SL 330′ WL SE NW, Sec. 12, T2N, R8E, API 1215900969.

72. M.M.W. Oil Properties No. 1 Effie Rule, 330′ NL 330′ WL SW NE, Sec. 7, T2N, R9E, API 1215924348.

73. E.H. Kaufman No. 1 Taylor, 330′ NL 330′ EL SW NE, Sec. 8, T2N, R9E, API 1215902586.

74. Ashland Oil and Refining Co. No. 1 Gillespie, 330′ SL 330′ WL NE NE, Sec. 16, T2N, R9E, API 1215900353.

75. L.A. Kapp, Jr., No. 1 Westall, 330′ SL 330′ EL NE SE, Sec. 15, T2N, R9E, API 1215923864.

76. Pure Oil Co. No. A-2 William Winter, 330′ NL 330′ EL NE, Sec. 14, T2N, R9E, API 1215901038.

77. Co-op Refinery Assoc. No. 2 Ede Albert et al., 330′ SL 990′ EL SE NW, Sec. 7, T2N, R10E, API 1215900230.

78. Wayne Smith Operating, Inc.. No. 1 Paul Matthews et al., 330′ NL 330′ EL NW, Sec. 8, T2N, R10E, API 1215924092.

79. Mega Oil, Inc. No. 2 Pitts, 330′ NL 330′ WL SW NW, Sec. 9, T2N, R10E, API 1215925205.

80. Viking Oil Company No. 1 Waxler et al., 990′ NL 330′ WL SW, Sec. 10, T2N, R10E, API 1215924112.

81. Sun Oil No. 1 M.R. Martin, 330′ SL 330′ EL NE NW, Sec. 11, T2N, R10E, API 1215900712.

82. The Texas Co. No. 1 Noland, 330′ NL 330′ EL NW SE, Sec. 12, T2N, R10E, API 1215901093.

83. Illinois Basin Explor., Inc. No. 1 Miller, 330′ NL 330′ WL SW SE, Sec. 6, T2N, R11E, API 1215924467. Poor company sample study, no wireline log, used drilling time log. *This is well 69 on Section IL-4.*

84. R. K. Petroleum Corp. No. 1 Dundhee, Ivan, 380′ NL 330′ EL SW NW, Sec. 6, T2N, R14W, API 1215903318.

85. Lewis, Donald L. No. 1 Hunley, 400′ NL 330′ WL SW SW, Sec. 4, T2N, R14W, API 1215923692.

86. Donahue Oil Company No. 1 Yonaka, 330′ NL 330′ WL SW SE, Sec. 9, T2N, R14W, API 1215924510.

87. D & E Galloway No. 1 Treece, 990′ SL 330′ EL SW SE, Sec. 10, T2N, R14W, API 1215924325.

88. C.E.R. Production Co. No. 1 Schick Comm., 390′ SL 330′ EL SE, Sec. 2, T2N, R14W, API 1215923637.

89. Toler, W. W. Drlg. Corp. No. 1 Williams, G. F., 330′ SL 330′ WL NE SW, Sec. 1, T2N, R14W, API 1215900587. Company sample study.

LAWRENCE COUNTY

90. Morris Albert No. 1 Kieffer et al., 330′ NL 330′ EL NE, Sec. 7, T2N, R13W, API 1210129428.

91. M & H Energy, Inc. No. 1 Hasewinkle, 330′ NL 330′ EL NE NW, Sec. 8, T2N, R13W, API 1210129270.

92. Nat'l. Assoc. Petro. Co. No. 1 Hobbs, 330′ NL 330′ EL SW, Sec. 9, T2N, R13W, API 1210107182.

93. Sanders H C No. 1 Cunningham, 330′ SL 330′ WL NE, Sec. 10, T2N, R13W, API 1210100339. Company sample study.

94. Ashland Oil and Refining Co. No. 1 Cunningham et al., 990′ NL 330′ EL SW NW, Sec. 11, T2N, R13W, API 1210100026. Sample study by Elwood Atherton.

95. Bauer, Joseph E. No. 2 Ott et al., 330N NL 330N EL SW, Sec. 12, T2N, R13W, API 1210103414.

96. Anderson, W. D. No. 1 Starkman, 330N NL 330N WL SW SW, Sec. 7, T2N, R12W, API 1210100640. Sample study by Elwood Atherton.

97. Ryan and Sharp No. 2 King, 330′ SL 330′ EL NE NW, Sec. 8, T2N, R12W, API 1210103167. Company sample study.

98. Glass, Theo G. No. 1 Saums, 330′ SL 330′ EL NW SE, Sec. 9, T2N, R12W, API 1210100672.

99. Engle, George S. No. 1 W Buchanan, 330′ SL 330′ WL SW SW NE, Sec. 16, T2N, R12W, API 1210100037. Company sample study.

100. I. Shen, Inc. No. 2 Ramsey-Airport, 330′ NL 990′ WL SW SW, Sec. 14, T2N, R12W, API 1210130055.

101. Brinkley, Harold W. No. 1-D Seigle, 330′ SL 330′ EL NE, Sec. 13, T2N, R12W, API 1210106759.

102. Brinkley, Harold W. No. 1-A Pepple, 330′ SL 990′ EL, Sec. 18, T2N, R11W, API 1210102201.

103. Brinkley, Harold W. No. 1 Burns, 2310′ SL 330′ EL SW, Sec. 17, T2N, R11W, API 1210100740.

104. Steve A. Zanetis Drlg. and Prod. No. 1 Hopkins, Grace L., 330′ NL 330′ EL NW SE, Sec. 16, T2N, R11W, API 1210100046. *This is well 1 on Section IN-1.*

105. Bauer Bros. No. 17 Allstate Life Insurance, 330′ SL 990′ WL SW, Sec. 15, T2N, R11W, API 1210106489.

SECTION IL-2 by John Nelson

RANDOLPH COUNTY

1. Andrews No. 1 Frazer, SW¼ NE¼ SW¼, Sec. 6, T8S, R5W, County No. 1919. Electric log, sample study by John Nelson (sample quality poor to good).

JACKSON COUNTY

2. Jackson County Oil Promoters No. 1 Dierks, SW¼ NW¼ SW¼, Sec. 36, T7S, R5W, County No. 21992. Electric log.

3. Stanolind No. 1 Leiner, NE¼ NW¼ SW¼, Sec. 20, T7S, R4W, County No. 1040. Electric log (primitive) and sample study by G.W. Prescott (good).

4. Magnolia No. 1 Froemling-Reuscher, NW¼ SE¼ SW¼, Sec. 11, T7S, R4W, County No. 963. Electric log and sample study by Hubert Bristol (sample study is cursory and covers only part of interval of interest).

5. Middleton No. 2 Rickenberg, NW¼ NW¼ SW¼, Sec. 12, T7S, R4W, County No. 23084. Dual-induction, gamma ray, neutron, and density logs.

6. Stephens No. 1 Speith, NW¼ NE¼ NW¼, Sec. 6, T7S, R3W, County No. 905. Electric log and sample study by John Nelson, sample quality poor to fair.

PERRY COUNTY

7. Cities Service No. 1 Greer, NE¼ NE¼ SW¼, Sec. 27, T6S, R3W, County No. 2546. Electric log and company sample study, both of poor quality.

8. Texaco No. 1 Epplin, SW¼ SW¼ SW¼, Sec. 23, T6S, R3W, County No. 3017. Electric log and sample study by John Nelson, sample quality good to excellent.

9. Byers No. 1 McIntyre, NE¼ SE¼ SW¼, Sec. 36, T6S, R3W, County No. 2475. Electric log.

10. Magnolia No. 1 Hahn, NE¼ NE¼ NW¼, Sec. 34, T6S, R2W, County No. 2024. Electric log and sample study by Elwood Atherton.

11. Eason No. 1 Perfection Coal, NW¼ SE¼ NE¼, Sec. 17, T6S, R1W, County No. 1996. No geophysical log. Sample study by I.T. Schwade.

12. Forester Borehole No. 1, 1980′ NL, 330′ WL, Sec. 5, T6S, R1W, County No. 1951. Continuous core from surface to 1,486 (in Aux Vases), then sample study based on cuttings to T.D. of 5,257 feet. Core logged by ISGS geologists but not saved. *This is well 1 in Section IL-3.*

13. Texaco No. 1 Coen, NW¼ NW¼ SE¼, Sec. 4, T6S, R1W, County No. 23527. Dual-induction, gamma ray, neutron, and density logs.

14. Lindsay No. 1 Brown, SE¼ NE¼ NW¼, Sec. 7, T6S, R1E, County No. 2161. Electric log.

FRANKLIN COUNTY

15. Horn No. 1 Greenwood, NW¼ NW¼ SE¼, Sec. 17, T6S, R1E, County No. 1511. Electric log and sample study by John Nelson.

16. Horn No. 1 Phillips, SE¼ NE¼ SE¼, Sec. 20, T6S, R1E, County No. 1512. Electric log.

17. Sharp No. 1 Snider, SW¼ NW¼ SE¼, Sec. 22, T6S, R1E, County No. 1250. Electric log (photocopy; bastard scale).

18. Shulman No. 1 Snider, NE¼ SE¼ NW¼, Sec. 26, T6S, R1E, County No. 321. Electric log and sample study by Elwood Atherton begins in Cypress.

19. Lampley No. 1 Hoe, SW¼ NE¼ NE¼, Sec. 35, T6S, R1E, County No. 2075. Electric log.

20. Inland No. 1 Goldstein, SW¼ SE¼ NE¼, Sec. 2, T7S, R1E, County No. 852. Electric log and sample study by Elwood Atherton.

21. Gardner No. 1 Turner, NE¼ SE¼ NW¼, Sec. 1, T7S, R1E, County No. 23838. Dual-induction and gamma ray logs.

22. Budmark No. 1 Meadows, SW¼ NE¼ SE¼, Sec. 6, T7S, R2E, County No. 23278. Dual-induction electric log.

23. Pure No. 1 C.W. and F. Coal, SE¼ SE¼ SW¼, Sec. 8, T7S, R2E, County No. 1462. Electric log.

24. Adkins No. 1 Cambon, NW¼ NW¼ SW¼, Sec. 16, T7S, R2E, County No. 708. Electric log and sample study by Elwood Atherton begins in Fraileys Shale.

25. Howard and Howell No. 1 C.W. and F. Coal, SW¼ SE¼ SW¼, Sec. 15, T7S, R2E, County No. 1630. Electric log.

26. Mosebach No. 1 Burr Oak, SE¼ SW¼ SE¼, Sec. 23, T7S, R2E, County No. 959. Electric log and sample study by Elwood Atherton.

27. Shell No. 2 Brown, NW¼ NE¼ NW¼, Sec. 25, T7S, R2E, County No. 839. Electric log and sample study by Elwood Atherton begins in Fraileys Shale.

28. Mosebach No. 1-A Lawrence, SW¼ NE¼ NW¼, Sec. 30, T7S, R3E, County No. 1332. Electric log and sample study by Elwood Atherton begins near base of Cypress.

29. Stewart No. 1-A Becker, SW¼ NE¼ NW¼, Sec. 32, T7S, R3E, County No. 2612. Electric and dual-induction logs; also, a gamma ray log that covers part of the interval.

WILLIAMSON COUNTY

30. Bufay No. 4 Madison, SW¼ NE¼ SE¼, Sec. 4, T8S, R3E, County No. 2398. Electric log.

31. Shell No. A-1 Madison, NW¼ SE¼ NW¼, Sec. 10, T8S, R3E, County No. 1207. Electric log and company core descriptions of 18 short core segments from Tar Springs to Ste. Genevieve.

32. Mutual No. 1 Madison, NE¼ SE¼ NE¼, Sec. 14, T8S, R3E, County No. 2200. Electric log.

33. Superior No. 1 Rogers-Harris, NE¼ SW¼ NW¼, Sec. 24, T8S, R3E, County No. 1113. Electric log and sample study by Elwood Atherton.

34. Rehn No. 1 La Salle, SW¼ SW¼ NW¼, Sec. 25, T8S, R3E, County No. 1932. Electric log.

35. Smokey No. 1 Isaacs, 2310N NL, 1980N WL, Sec. 36, T8S, R3E, County No. 2043. Electric log and sample study by Elwood Atherton.

36. Arrow No. 1 Fuller, NW¼ SW¼ SE¼, Sec. 31, T8S, R4E, County No. 1044. Electric log and sample study by Elwood Atherton begins in Fraileys Shale.

37. Morris No. 1 Sims, SE¼ SE¼ NW¼, Sec. 32, T8S, R4E, County No. 2274. Electric log.

38. Amerada No. 1 Gent, SW¼ NW¼ SE¼, Sec. 33, T8S, R4E, County No. 2006. Electric log and sample study by Elwood Atherton.

39. Calvert No. 1 Mitchell, SW¼ SW¼ NW¼, Sec. 35, T8S, R4E, County No. 1888. Electric log.

SALINE COUNTY

40. Kingwood No. 1 Gullett, NE¼ NE¼ SW¼, Sec. 31, T8S, R5E, County No. 2425. Electric log and fair to good sample study by company geologist.

41. Calvert No. 1 Unsell-Small, NE¼ SE¼ NW¼, Sec. 4, T9S, R5E, County No. 2717. Electric log.

42. Brehm No. 1 Pankey, 50′ NL, 330′ WL, Sec. 10, T9S, R5E, County No. 3643. Electric log.

43. Brehm No. 1 Lewis, SW¼ SW¼ NW¼, Sec. 11, T9S, R5E, County No. 1410. Electric log and sample study by Elwood Atherton.

44. Meridian No. 1 Cotton-Barter, SE¼ NW¼ SE¼, Sec. 13, T9S, R5E, County No. 25559. Electric, gamma ray, density, and sonic logs, plus drilling time log and sample study by company geologist.

45. Athene No. 1 Wilson, NW¼ NE¼ SE¼, Sec. 20, T9S, R6E, County No. 2743. Electric log and sample study by McKay and Littlejohn.

46. Goad No. 3 Parker, NW¼ NE¼ NW¼, Sec. 22, T9S, R6E, County No. 3051. Electric log.

47. Williams No. 1 McCarty, SE¼ NE¼ NW¼, Sec. 25, T9S, R6E, County No. 849. Electric log and sample study by Elwood Atherton begins in Fraileys Shale.

48. Skiles No. 2 Johnson, SW¼ SW¼ SW¼, Sec. 20, T9S, R7E, County No. 3020. Electric log and company sample study (cursory).

49. Stelle No. 1 Ragsdale, NW¼ SE¼ SW¼, Sec. 10, T9S, R7E, County No. 2715. Electric log.

50. Kingwood No. 1 Allyn, SW¼ SW¼ NE¼, Sec. 11, T9S, R7E, County No. 847. Electric log and sample study by I.T. Schwade.

51. Brehm No. 1 Spencer, SE¼ NW¼ SE¼, Sec. 12, T9S, R7E, County No. 1414. Electric log and sample study by Elwood Atherton begins in Fraileys Shale.

GALLATIN COUNTY

52. Turner and Crum No. 1 Muenstermann, SW¼ NW¼ NE¼, Sec. 18, T9S, R8E, County No. 296. Electric log.

53. Marshall No. 1 Beverly, NE¼ NE¼ NW¼, Sec. 17, T9S, R8E, County No. 1635. Electric log.

54. The Texas Co. No. 1 McGuire, SE¼ NE¼ SW¼, Sec. 15, T9S, R8E. Electric log.

55. George No. 1-A Sanks, SW¼ SW¼ SW¼, Sec. 14, T9S, R8E, County No. 2046. Electric log.

56. George No. 1 Sanks, NE¼ NE¼ SE¼, Sec. 11, T9S, R8E, County No. 2045. Electric log.

57. Valter No. 1 Drone, NE¼ NE¼ SW¼, Sec. 7, T9S, R9E, County No. 1049. Electric log and sample study by Elwood Atherton. *This is well 8 in Section IL-4.*

SECTION IL-3 by John Nelson

PERRY COUNTY

1. Forester borehole No. 1, 1980′ NL, 330′ WL, Sec. 5, T6S, R1W, County No. 1951. Continuous core from surface to 1465 feet (in Aux Vases), then sample study to T.D. of 5,257 feet. Core logged by ISGS geologists, but core not saved. *This is well 12 in Section IL-2.*

2. McBride No. 1 Miller, NE¼ NW¼ SW¼, Sec. 30, T5S, R1W, County No. 2030. Electric log.

3. National Associated Petroleum No. 1 Bishop, SE¼ SE¼ NW¼, Sec. 20, T5S, R1W, County No. 2414. Electric log and sample study by John Nelson; sample quality poor to very good.

4. Hopkins No. 1 Heape, SE¼ NE¼ SW¼, Sec. 18, T5S, R1W, County No. 2237. Electric log.

5. Beadleston No. 1 Sprenger, SE¼ SE¼ NW¼, Sec. 7, T5S, R1W, County No. 2140. Electric log.

6. Simmel No. 1 Kimzey, NW¼ SE¼ SE¼, Sec. 6, T5S, R1W, County No. 1997. Electric log.

7. Weder No. 1 Anderson, NW¼ NW¼ NW¼, Sec. 31, T4S, R1W, County No. 2402. Electric log.

8. Dunnill No. 1 Grabowski, NE¼ SE¼ NE¼, Sec. 20, T4S, R1W, County No. 24002. Dual-induction, electric log, and a cursory sample study by company geologist.

9. Juniper No. 12X-8 Wisniewski, NE¼ SE¼ NW¼, Sec. 8, T4S, R1W, County No. 23209. Dual-induction, electric, gamma ray, and sonic logs.

10. Texas Co. No. 1 Schwind, SW¼ SW¼ SW¼, Sec. 5, T4S, R1W, County No. 2051. Electric log and sample study by Elwood Atherton.

WASHINGTON COUNTY

11. Ohio Co. No. 1 Schwind, SE¼ NE¼ NW¼, Sec. 33, T3S, R1W, County No. 1112. Electric log.

12. Lester No. 1-T Bender, SW¼ NW¼ NW¼, Sec. 20, T3S, R1W, County No. 1639. Electric log.

13. Thompson No. 1 Roznowski, SE¼ NE¼ NW¼, Sec. 19, T3S, R1W, County No. 208. Electric log (poor) and sample study by Lyman Huff (detailed, but depths do not match electric log accurately).

14. Magnolia No. 1 Labuda, NE¼ NW¼ NE¼, Sec. 18, T3S, R1W, County No. 1622. Electric log.

15. Shakespeare No. 1 Filipiak, 330′ NL, 660′ WL, Sec. 7, T3S, R1W, County No. 24166. Dual-induction and gamma ray-neutron logs.

16. Fowley No. 1 Sigmund, NE¼ NW¼ NW¼, Sec. 6, T3S, R1W, County No. 621. Electric log.

17. Shakespeare No. 1 Paszkiewicz, NE¼ SW¼ NE¼, Sec. 31, T2S, R1W, County No. 23909. Dual-induction and gamma ray-neutron logs.

18. Nelms Bros. No. 1 Zak-Bright, NW¼ NW¼ NW¼, Sec. 30, T2S, R1W, County No. 23921. Dual-induction and gamma ray-neutron logs, plus graphic drilling time log and sample log by company geologist.

19. National Associated Petroleum No. 1 Bernreuter, SE¼ SE¼ NE¼, Sec. 19, T2S, R1W, County No. 1879. Electric log.

20. Shulman No. 1 Siebert, NW¼ NW¼ SE¼, Sec. 20, T2S, R1W, County No. 1143. Electric log.

21. Ohio Oil Co. No. 1 Colvin, NW¼ NE¼ NW¼, Sec. 16, T2S, R1W, County No. 23. Sample study (good) by M.A. Blair but no geophysical log.

22. Collins Bros. No. 1 Mitchell, NW¼ SW¼ SE¼, Sec. 32, T1S, R1W, County No. 23418. Dual-induction log and sample study by Nelson.

23. Aetna No. 1 Gillian, NE¼ NE¼ SW¼, Sec. 28, T1S, R1W, County No. 410. Electric log.

24. Kingwood No. 1 Brink, SE¼ SW¼ SE¼, Sec. 15, T1S, R1W, County No. 59. Electric log (poor) and company sample study (fair to good).

25. Mazzarino No. 1 Kasten, NW¼ NW¼ SE¼, Sec. 9, T1S, R1W, County No. 1366. Electric log.

26. Gulf No. 1 Grathwohl, SW¼ SW¼ SE¼, Sec. 34, T1N, R1W, County No. 796. Electric log and sample study by D.B. Saxby, begins in Ste. Genevieve.

27. National Associated Petroleum No. 1 Kuhn, SW¼ SE¼ NW¼, Sec. 28, T1N, R1W, County No. 419. Electric log.

CLINTON COUNTY

28. National Associated Petroleum No. 1 Starr, 330′ NL, 660′ EL, Sec. 20, T1N, R1W, County No. 1815. Electric log.

29. Louisiana Land and Exploration No. 1 Kleine, 660′ NL, 1650′ EL, Sec. 18, T1N, R1W, County No. 25414. Dual-induction, gamma ray, density, and sonic logs, plus company geologist's report and sample study.

30. Seisma (St. Clair) No. 1 Johnson, 790′ SL, 2423′ EL, Sec. 6, T1N, R1W, County No. 26245. Dual-induction, gamma ray, density, and neutron logs.

31. Whitmer No. 1 Wesselman, NW¼ NW¼ NE¼, Sec. 30, T2N, R1W, County No. 24290. Dual-induction, electric, gamma ray, and sonic logs.

32. Ego Oil Co. No. 1 Defend, NW¼ NE¼ SW¼, Sec. 19, T2N, R1W, County No. 24431. Dual-induction, electric, gamma ray, and neutron logs and sample study by Elwood Atherton.

33. Texas Co. No. 1 Stokes, SW¼ SW¼ SE¼, Sec. 17, T2N, R1W, County No. 582. Electric log.

34. Cities Service No. 1 Hemminghaus, SE¼ NE¼ NE¼, Sec. 8, T2N, R1W, County No. 1656. Electric log and partial sample study by H.M. Bristol, plus a complete sample log by company geologist.

35. Brehm No. 1 Hemminghaus, 1650′ SL, 990′ EL, Sec. 33, T3N, R1W, County No. 24548. Dual-induction, gamma ray and sonic logs and sample study by Elwood Atherton. *This is well 33 in Section IL-1.*

SECTION IL-4 by John Nelson

HARDIN COUNTY

1. Ozark-Mahoning borehole DT-134, SW¼ SW¼, Sec. 9, T11S, R9E, County No. 21092. Continuous core described by L.B. Smith and John Nelson. *This is datum point 13 in outcrop sections (Appendix 1).*

2. Ozark-Mahoning borehole USBC-15, SW¼ SE¼ SE¼, Sec. 4, T11S, R9E, County No. 20792. Continuous core, described by John Nelson (core terminates in Sample Sandstone).

GALLATIN COUNTY

3. Mayfield No. 1 Brinkley-Willis, SW¼ NE¼ SE¼, Sec. 20, T10S, R9E, County No. 2586. Electric log and cursory sample study by company geologist.

4. U.S. Oil No. 1 Logsdon, NE¼ NE¼ NW¼, Sec. 3, T10S, R9E, County No. 23856. Electric log and cursory sample study by operator.

5. Ashland No. 1 Shea, NE¼ NE¼ NW¼, Sec. 32, T9S, R9E, County No. 1066. Electric log.

6. The Texas Co. No. 1 McGehee, SW¼ SW¼ NE¼, Sec. 29, T9S, R9E, County No. 1065. Electric log and sample study (beginning in Bethel Sandstone) by Elwood Atherton.

7. Rudy No. 1 Strong, NE¼ NE¼ SE¼, Sec. 19, T9S, R9E, County No. 1259. Electric log.

8. Valter No. 1 Drone, NE¼ NE¼ SW¼, Sec. 7, T9S, R9E, County No. 1049. Electric log and sample study by Elwood Atherton. *This is well 57 in Section IL-2.*

9. White No. 1 Rollman, NW¼ SE¼ NW¼, Sec. 8, T9S, R9E, County No. 24500. Dual-induction, electric, gamma ray, neutron, and density logs.

10. Reznik No. 1 Valter, SE¼ SE¼ NE¼, Sec. 3, T9S, R9E, County No. 1041. Electric log and sample study (beginning in lower Cypress Formation) by Elwood Atherton.

11. Nation No. 3 McCormick, SW¼ NW¼ NE¼, Sec. 34, T8S, R9E, County No. 1219. Electric log.

12. James Carter No. 1 Miner, SE¼ SE¼ NW¼, Sec. 27, T8S, R9E, County No. 2509. Electric log and sample study by John Nelson (sample quality fair to good).

13. Shafer and Toler No. 1 Green, NW¼ SW¼ SE¼, Sec. 22, T8S, R9E, County No. 748. Electric log; John Nelson spot-checked samples, but they are poor.

14. Jahn No. 1 Moye, SE¼ SE¼ NE¼, Sec. 15, T8S, R9E, County No. 2340. Electric log.

15. Slewmaker No. 1 Moye, NW¼ NW¼ NE¼, Sec. 10, T8S, R9E, County No. 662. Electric log.

16. Herndon No. 1 Harrington, NW¼ NW¼ NW¼, Sec. 3, T8S, R9E, County No. 655. Electric log and fair to good sample study by company geologist.

17. Murphy and Millison No. 1 Spence, NW¼ NE¼ NW¼, Sec. 33, T7S, R9E, County No. 134. Electric log and sample study by Elwood Atherton.

18. Yingling No. 1 Hale, NW¼ NW¼ NE¼, Sec. 26, T7S, R9E, County No. 377. Electric log.

19. Duncan No. 1 Knight, NE¼ NE¼ NW¼, Sec. 22, T7S, R9E, County No. 133. Electric log.

WHITE COUNTY

20. Engle No. 1 Knight, NE¼ SW¼ NE¼, Sec. 15, T7S, R9E, County No. 7002. Electric log.

21. Athene No. 1 Grant, SE¼ SE¼, Sec. 13, T7S, R9E, County No. 2314. Electric log and detailed sample study by McKay and Littlejohn.

22. McCummings No. 1 Questell, SW¼ NW¼ SE¼, Sec. 2, T7S, R9E, County No. 1299. Electric log and a cursory sample study by D.L. Stevenson.

23. Miskell No. 1 Roser, NW¼ NW¼ SW¼, Sec. 36, T6S, R9E, County No. 2376. Electric log.

24. Eastern Petroleum No. 1 Edwards, SW¼ NW¼ SE¼, Sec. 25, T6S, R9E, County No. 6234. Electric log.

25. Slagter No. 1 Bennett, SW¼ NW¼ NE¼, Sec. 24, T6S, R9E, County No. 2236. Electric log.

26. Crawford No. 1 Varner, NE¼ SW¼ NE¼, Sec. 18, T6S, R10E, County No. 3028. Electric log.

27. Skelly No. 1 McCarty, NE¼ NE¼ NW¼, Sec. 7, T6S, R10E, County No. 1069. Electric log.

28. Lesh No. A-1 Brimble-Combe, NE¼ NW¼ NW¼, Sec. 5, T6S, R10E, County No. 387. Electric log and sample study by Elwood Atherton.

29. Rider No. 2 Ferguson, SE¼ NW¼, Sec. 31, T5S, R10E, County No. 2409. Electric log.

30. Hiawatha No. 4 Hanna, NE¼ NW¼ SW¼, Sec. 29, T5S, R10E, County No. 7341. Electric log.

31. George and Wrather No. 1 Land, NE¼ NW¼ SW¼, Sec. 21, T5S, R10E, County No. 3090. Electric log.

32. Dirickson No. 1 Walsh, NW¼ NW¼ SW¼, Sec. 16, T5S, R10E, County No. 5156. Electric log.

33. Ryan No. 1 Storms, SW¼ NW¼, Sec. 9, T5S, R10E, County No. 321. Electric log and sample study by Elwood Atherton.

34. McIntyre No. 1 Williams, SW1/4 SW¼ NW¼, Sec. 3, T5S, R10E, County No. 1945. Electric log.

35. F-B Drilling No. 1 Stanley, SW¼ SE¼ NE¼, Sec. 34, T4S, R10E, County No. 1210. Electric log.

36. National Associated No. 1 Bramlet et al., NW¼ NW¼ SE¼, Sec. 26, T4S, R10E, County No. 2275. Electric log.

37. Skelly No. 1 Stanley, 330′ NL, 408′ EL, Sec. 30, T4S, R11E, County No. 516. Electric log and sample study by Elwood Atherton.

38. Tidewater No. B-15 Dennis, SW¼ NE¼ SW¼, Sec. 18, T4S, R11E, County No. 7673. Electric log.

39. Calvin No. 1 Pritchard, SE¼ SW¼ SW¼, Sec. 7, T4S, R11E, County No. 3189. Electric log.

40. Dee Miller No. 1 Johnston, NE¼ SE¼ SW¼, Sec. 6, T4S, R11E, County No. 4148. Electric log and sample study by Elwood Atherton. *This is well 1 in Section IN-2.*

41. Diamond Energy No. 2 Cleveland, SE¼ NW¼ NW¼, Sec. 31, T3S, R11E, County No. 29977. Dual-induction, gamma gay, density, neutron, and sonic logs.

42. Pessina No. 8 Morris, NE¼ NE¼ NW¼, Sec. 30, T3S, R11E, County No. 28957. Dual-induction, electric, gamma ray, and density logs.

43. Craden No. 7 Hortin, SW¼ NW¼ NE¼, Sec. 19, T3S, R11E, County No. 30224. Dual-induction log.

EDWARDS COUNTY

44. Harris No. B-1 Steele, NW¼ NE¼ SW¼, Sec. 18, T3S, R11E, County No. 23886. Dual-induction, gamma ray, density, and neutron logs.

45. Gary-Williams No. 5 McGowan, center SE¼ NW¼, Sec. 7, T3S, R11E, County No. 23863. Dual-induction, gamma ray, density, and neutron logs.

46. Superior No. A-13 Blood, NE¼ NW¼ SW¼, Sec. 6, T3S, R11E, County No. 23899. Dual-induction, gamma ray, density, and neutron logs.

47. J and N No. 1 Pollard, NW¼ NE¼ SW¼, Sec. 31, T2S, R11E, County No. 23431. Dual-induction, electric, gamma ray, and density logs.

48. Superior No. 9 Willett, NE¼ NE¼ SW¼, Sec. 30, T2S, R11E, County No. 23523. Dual-induction, gamma ray, density, and neutron logs.

49. Superior No. 9 Woods, SE¼ SE¼ NW¼, Sec. 19, T2S, R11E, County No. 23377. Dual-induction, gamma ray, density, and neutron logs.

50. Hux and Wyman No. 1 Hedge, NW¼ NE¼ SE¼, Sec. 18, T2S, R11E, County No. 23673. Dual-induction, gamma ray, and density logs.

51. Jack Inglis No. 1 Hortin, SW¼ SW¼ NW¼, Sec. 7, T2S, R11E, County No. 718. Electric log.

52. Warrior No. 7 Fewkes-Shaw, NE¼ NW¼ NE¼, Sec. 6, T2S, R14W, County No. 22424. Dual-induction, gamma ray, and density logs.

53. Superior No. 1 Lambert, SE¼ SE¼ NW¼, Sec. 31, T1S, R11E, County No.177. Electric log and sample study by John Nelson (sample quality poor to good, worsening downward).

54. Hux and Wyman No. 1 Smith, NE¼ NE¼ SW¼, Sec. 30, T1S, R11E, County No. 23856. Dual-induction, gamma ray, density, and neutron logs.

55. Juniper No. 82X-24 St. Ledger, 660′ NL, 330′ EL, Sec. 24, T1S, R10E, County No. 22349. Dual-induction, gamma ray, and neutron logs.

56. Mortimer No. B-1 Reid, NW¼ SW¼ NE¼, Sec. 18, T1S, R11E, County No. 576. Electric log and sample study by C.T. Snider, consulting geologist (an excellent, detailed study).

57. Petro-Halogen No. 1 Pritchett, NE¼ SW¼ SW¼, Sec. 7, T1S, R11E, County No. 22634. Dual-induction, electric, gamma ray, and density logs.

58. Skiles No. 1 Dean, SE¼ NE¼ SW¼, Sec. 6, T1S, R11E, County No. 930. Electric log.

59. Terrell No. 2 Hering-Glover, SE¼ NW¼ SE¼, Sec. 31, T1N, R14W, County No. 23485. Dual-induction log.

60. Central Pipe Line No. 1 Tarpley, NE¼ NE¼ NW¼, Sec. 31, T1N, R14W, County No. 33. Electric log and sample study by B. Pretzer.

61. McDowell No. 2 Kollack, SE¼ SE¼ NE¼, Sec. 19, T1N, R11W, County No. 24309. Dual-induction, gamma ray, neutron, density, and sonic logs.

62. Tussey No. 1 McDowell, SW¼ SE¼ NE¼, Sec. 18, T1N, R11E, County No. 22690. Dual-induction, electric, gamma ray, and density logs.

63. Pessina No. 1 Fryman, NW¼ NW¼ SW¼, Sec. 7, T1N, R11W, County No. 22724. Dual-induction, electric, gamma ray, and density logs.

64. Rothrock and Thomson No. 11 Rothrock, SW¼ SE¼ NE¼, Sec. 6, T1N, R11W, County No. 23067. Induction electric log.

65. Podolsky No. 6 Judge, NW¼ NE¼ SE¼, Sec. 31, T2N, R11E, County No. 24209. Dual-induction, gamma ray, neutron, and density logs.

RICHLAND COUNTY

66. Gulf Coast Expl. No. 1 Koertge, NE¼ SE¼ NW¼, Sec. 30, T2N, R11E, County No. 25148. Dual-induction, gamma ray, density, and neutron logs.

67. C.E. Brehm No. 1 Fobroy, NW¼ SW¼ NE¼, Sec. 24, T2N, R10E, County No. 717. Electric log.

68. Fulk No. 1 Bogard, NW¼ NW¼ NE¼, Sec. 18, T2N, R11E, County No. 387. Electric log.

69. Double J No. 1 Miller, NW¼ SW¼ SE¼, Sec. 6, T2N, R11E, County No. 24467. Drilling time and sample log (entire section), dual-induction log below Paoli. Calibrated with electric logs of several wells within 0.5 mile. *This is well 83 in Section IL-1.*

SECTION IN-1 by Lloyd Furer and Brian Keith

LAWRENCE COUNTY, ILLINOIS

1. Steve Zanetis No. 1 Grace Hopkins, NE¼ NW¼ SE¼, Sec. 16, T2N, R11W. Electric log. *This is well 104 in Section IL-1.*

KNOX COUNTY, INDIANA

2. R.K. Petroleum Corp. No. 1 Stella Courter, NE¼ NE¼ SW¼, Sec. 27, T2N, R11W. Electric log and sample study by Brian Keith.

3. R.K. Petroleum Corp. No. 1 Curtis Kimmel, NW¼ NE¼ SE¼, Sec. 35, T2N, R11W. Electric log.

4. Sandy Ridge Oil No. 1 Juanita Meyer, SW¼ NE¼ SE¼, Sec. 36, T2N, R11W. Electric log.

5. Raymond Messman No. 1 Bryan Horrall, NE¼ SW¼ NE¼, Sec. 7, T1N, R10W. Electric log and sample study by Brian Keith.

6. R.K. Petroleum No. 2 Bringwald, SW¼ SE¼ SE¼, Sec. 5, T1N, R10W. Electric log.

7. Olen D. Sharp No. 2 Jordan Farms, SW¼, Sec. 9, T1N, R10W. Electric log.

8. T & H Corp. No. 1 Ralph Lane, NE¼ NE¼ NW¼, Sec. 10, T1N, R10W. Electric log.

9. Downstate Drilling No. 1 Pahmeier Community, NW¼ NW¼ SW¼, Sec. 11, T1N, R10W. Electric log.

10. Ram Oil No. 1 Small Farms, NW¼ NW¼ NW¼, Sec. 11, T1N, R10W. Electric log and sample study by Brian Keith.

PIKE COUNTY

11. Stanford Oil No. 1 C.Y. Davidson, SW¼ SW¼, Sec. 7, T1N, R9W. Electric log.

12. Kirk D. Holland No. 2 George Roth, NE¼ NE¼ NE¼, Sec. 17, T1N, R9W. Electric log.

13. Booth Oil No. 1 Perry, NE¼ NE¼ NW¼, Sec. 21, T1N, R9W. Electric log and sample study by Brian Keith. See Droste and Carpenter (1990) for correlated cross sections that include this well.

14. Ecus Corp. No. 1 Cory and Richardson, NE¼ SW¼ SE¼, Sec. 16, T1N, R9W. Electric log.

15. Ecus Corp. No. 2 Carey and Richardson, NW¼ SE¼ SE¼, Sec. 16, T1N, R9W. Electric log.

16. D.C. Schoonmaker No. 1A Ester Hunter, NW¼ NE¼ SE¼, Sec. 15, T1N, R9W. Electric log.

KNOX COUNTY

17. Ivan McCandlish No. 1 Cora Snyder, NW¼ SE¼ NE¼, Sec. 15, T1N, R9W. Electric log.

18. Albert P. Heeb No. 2 Holman Heirs, NE¼ SW¼ SE¼, Sec. 11, T1N, R9W. Electric log.

19. Howard Cleff No. 1 R, NE¼ NE¼ NE¼, Sec. 7, T1N, R8W. Electric log and sample study by Brian Keith.

20. Russ Randall No. 1 Wayman, Buchanan, and Hinkle, NW¼ SW¼ NW¼, Sec. 9, T1N, R8W. Electric log.

21. R.E. Fortner No. 1 M. Martin, SW¼ SW¼ NE¼, Sec. 15, T1N, R8W. Electric log.

PIKE COUNTY

22. T & H Corp. No. 1 M. Stone et al., NE¼ NW¼ SW¼, Sec. 14, T1N, R8W. Electric log.

23. Sandy Ridge Oil No. 1 Pauw, SW¼ NW¼ NW¼, Sec. 24, T1N, R8W. Electric log.

24. Dolan Delaney No. 1 Louis and Mary Eisele, SW¼ SE¼ SW¼, Sec. 19, T1N, R7W. Electric log and sample study by Brian Keith.

25. Texas Gas Transmission No. 3 R.M. Craig Heirs, SW¼ SW¼ NW¼, Sec. 20, T1N, R7W. Electric log.

26. Howard Energy No. 1 Orville and Clarice (?) Hale, NW¼ SW¼ SE¼, Sec. 22, T1N, R7W. Electric log.

27. Bert Cheatham No. 1 Thomas, NW¼ NW¼ NE¼, Sec. 26, T1N, R7W. Electric log.

28. Associated Petroleum (?) Co. No. 1 Harley Doades, SW¼ SE¼ SW¼, Sec. 19, T1N, R6W. Electric log and sample study by Brian Keith.

29. A.M. Energy No. 1 John Gray, NE¼ NE¼ SW¼, Sec. 20, T1N, R6W. Electric log.

DUBOIS COUNTY

30. Lear Resources No. 1 Hoffman, SE¼ SW¼ NW¼, Sec. 3, T1S, R6W. Electric log and sample study by Brian Keith.

31. Fred McCrary No. 1 Kevin Schnarr, NE¼ NE¼ NE¼, Sec. 2, T1S, R6W. Electric log.

32. Cordell Oil No. 1 Bessie and Dorothy Schnarr, SW¼ SE¼ NE¼, Sec. 30, T1N, R5W. Electric log and sample study by Brian Keith.

33. Anderson Oil No. 1 Hilbert Popp, NE¼ NE¼ NE¼, Sec. 28, T1N, R5W. Electric log.

34. Cabot Oil and Gas No. 1 Schmitt-Buchta Unit, NW¼ NE¼, Sec. 26, T1N, R5W. Electric and gamma ray logs.

35. Lyle Young No. 1 LMS Farm Partnership, SW¼ NE¼ NE¼, Sec. 36, T1N, R5W. Electric log.

36. Frank McHale No. 1 Edward and Oleta Sendelweek, SE¼ SE¼ SW¼, Sec. 32, T1N, R4W. Gamma ray-neutron log and sample study by Brian Keith.

37. Conservative Associates No. 1 Luther Eisenhut, NE¼ NW¼ SE¼, Sec. 29, T1N, R4W. Electric log.

38. F.T. Shelton No. 1 Otto J. Bauer et al., SW¼ NE¼ SE¼, Sec. 22, T1N, R4W. Electric log and sample study by Brian Keith.

39. Buttercup Energy, borehole No. 37, SE¼ SW¼ SE¼, Sec. 34, T1N, R4W. Electric and gamma ray logs.

40. Rector and Stone No. 2 Armin Zehr, NE¼ SE¼ SW¼, Sec. 36, T1N, R4W. Electric and gamma ray logs and sample study by Brian Keith.

41. Buttercup Energy, borehole No. 40, NW¼ SW¼ SE¼, Sec. 6, T1S, R3W. Electric and gamma ray logs.

42. Coy Oil No. 1 Joseph H. Gress, NE¼ SE¼, Sec. 19, T1S, R3W. Electric log and sample study by Brian Keith.

43. Bury Drilling No. 1 H. and S. Smith, NE¼ SW¼ NE¼, Sec. 10, T1S, R3W. Electric log and sample study by Ernest Loveless, Jr.

44. National Associated Petroleum No. 1 Thews, SE¼ SW¼ NW¼, Sec. 36, T1S, R3W. Electric log and sample study by Brian Keith.

ORANGE COUNTY

These two cores also are used in the outcrop cross sections.

45. Indiana Geological Survey, borehole SDH-311, NW¼ Sec. 30, T1S, R2W. Core described by L.B. Smith. Sample study by Brian Keith. IGS Call No. C-625. *This is datum point 59 in outcrop sections (Appendix 1).*

46. Indiana Geological Survey, borehole SDH-326, SE¼ SW¼ SW¼, Sec. 34, T1N, R2W. Core described by L.B. Smith, plus gamma ray log and sample study by Brian Keith. IGS Call No. C-651. *This is datum point 60 in outcrop sections (Appendix 1).*

SECTION IN-2 by John Nelson

NOTE: Lithologic logs for Indiana consist of actual well cuttings glued to strip logs, on file at the Indiana Geological Survey in Bloomington.

WHITE COUNTY, ILLINOIS

1. Dee Miller No. 1 Johnston, NE¼ SE¼ SW¼, Sec 6, T4S, R11E, County No. 4148. Electric log and sample study by Elwood Atherton. *This is well 40 in Section IL-4.*

2. Calvin No. 3 Knight, NE¼ SW¼ NE¼, Sec. 7, T4S, R14W, County No. 4348. Electric log.

3. Magnolia No. 14 Bond, NE¼ NW¼ SE¼, Sec. 8, T4S, R14W, County No. 4346. Electric log.

4. Calvin No. 1-F Boultinghouse, NW¼ SW¼, Sec. 10, T4S, R14W, County No. 3394. Electric log.

POSEY COUNTY, INDIANA

5. Exxon No. 1 Ford-Corbin, NE¼ NW¼, Sec. 12, T4S, R14W. Electric log and lithologic log.

6. Cokes No. 1 Murphy, SE¼ SW¼ SE¼, Sec. 7, T4S, R13W, Electric log.

7. National Associated No. 1 Robbs, NE¼ NE¼ NE¼, Sec. 17, T4S, R13W. Electric log.

8. Slagter No. 1 Campbell, SW¼ SE¼ NW¼, Sec. 15, T4S, R13W. Electric log.

9. Calvert No. 1 Hungate, NE¼ NE¼ NE¼, Sec. 23, T4S, R13W. Electric log.

10. Calvin No. 2 Beuligman, NW¼ SE¼ SE¼, Sec. 24, T4S, R13W. Electric log.

11. T & H. Corp. No. 1 Bitzer, SE¼ SW¼ NW¼, Sec. 29, T4S, R12W. Electric log.

12. Sohio No. 1 Smith, SE¼ SW¼ SE¼, Sec. 21, T4S, R12W. Electric log.

13. Buchman and O'Neal No. 1 Seibert, NE¼ NE¼ SW¼, Sec. 23, T4S, R12W. Electric log.

14. Professional Petroleum Exploration No. 1 Schneider, NW¼ NW¼ SE¼, Sec. 24, T4S, R12W. Electric log.

VANDERBURGH COUNTY

15. Southern Triangle No. 1 Welborn-Adler, SE¼ SW¼ SE¼, Sec. 19, T4S, R11W. Dual-induction, electric, gamma ray, density, and lithologic logs.

16. Robinson Eng. No. 1 Baumgart and Calvert, SE¼ NE¼ NE¼, Sec. 29, T4S, R11W. Dual-induction, gamma ray, and density logs.

17. Reznik No. 1 Relleke, NW¼ NE¼ NE¼, Sec. 27, T4S, R11W. Electric log.

18. Beeson No. 6 Steckler, NW¼ NE¼ NW¼, Sec. 23, T4S, R11W. Dual-induction, gamma ray density, and lithologic logs.

19. Petro Union No. 1 Suhrheinrich, NW¼ SW¼ SE¼, Sec. 30, T4S, R10W. Dual-induction, gamma ray, and lithologic logs.

20. Johnson No. 1 Schmitt, NE¼ NW¼ NW¼, Sec. 33, T4S, R10W. Electric log.

21. Skiles No. 1 Curran-Miller, SW¼ NE¼ NW¼, Sec. 35, T4S, R10W. Electric log. Lithologic log from Ken-Tex No. 1 Miller-Curran at virtually the same location.

22. Coombs No. 1 Elliott, SE¼ SE¼ SE¼, Sec. 36, T4S, R10W. Electric log.

WARRICK COUNTY

23. Able Energy No. 1 Fisher, SW¼ NW¼ SE¼, Sec. 31, T4S, R9W. Dual-induction and gamma ray-density logs.

24. Unschuld No. 1 Scales, NW¼ SW¼ NE¼, Sec. 33, T4S, R9W. Electric log and a poor lithologic log.

25. Highwoods No. 1 Grimwood, SW¼ NW¼ SE¼, Sec. 26, T4S, R9W. Lithologic log only.

26. Indiana Farm Bureau Co-op No. 1 Aigner, NE¼ NE¼ SE¼, Sec. 25, T4S, R9W. Dual-induction, electric, and lithologic log.

27. Eastern States Exploration No. 4 Peabody Coal, NW¼ NE¼ NE¼, Sec. 30, T4S, R8W. Dual-induction, gamma ray, and density logs.

28. Eastern States Exploration No. 3 Peabody Coal, NW¼ NW¼ NW¼, Sec. 28, T4S, R8W. Dual-induction, gamma ray, and lithologic logs.

29. Strake No. 1 Whitney, SE¼ NE¼ SW¼, Sec. 26, T4S, R8W. Electric and lithologic logs.

30. Eastern States Exploration No. 13 Peabody Coal, SE¼ NW¼ SW¼, Sec. 19, T4S, R7W. Dual-induction and gamma ray logs.

31. Eastern Natural Gas No. 2 Peabody Coal, SE¼ SE¼ SE¼, Sec. 17, T4S, R7W. Dual-induction and lithologic logs.

32. Tamarack No. 1 Jourdan, SW¼ SE¼ NW¼, Sec. 14, T4S, R7W. Dual-induction, electric, and lithologic logs.

33. Shenandoah No. 1 Zirkelback, SE¼ NE¼ NW¼, Sec. 19, T4S, R6W. Dual-induction and lithologic logs.

34. Pip Petroleum No. 1-20 Bruce-Redkan, SE¼ NE¼ SE¼, Sec. 20, T4S, R6W. Dual-induction, gamma ray, and a poor lithologic log.

35. Hevron No. 1 Tuley, SE¼ NE¼ SE¼, Sec. 22, T4S, R6W. Dual-induction, gamma ray, and lithologic logs.

36. Pip Petroleum No. 1-23 Miller, NW¼ NE¼ NE¼, Sec. 23, T4S, R6W. Dual-induction and electric logs.

SPENCER COUNTY

37. Development Associates No. 1 Wedeking, SW¼ NE¼ NW¼, Sec. 30, T4S, R5W. Electric log annotated with sample descriptions by operator.

38. Cato Enterprises No. 1 Goeferich, NE¼ SW¼ NW¼, Sec. 29, T4S, R5W. Electric log.

39. Tamarack No. 1 Schaaf, NW¼ SW¼ SW¼, Sec. 26, T4S, R5W. Dual-induction, gamma ray, and lithologic logs.

40. The Texas Co. No. 1 Gogel, SE¼ NW¼ SW¼, Sec. 25, T4S, R5W. Electric and lithologic logs.

41. Atkins No. 1 Mahling, SW¼ NW¼ NE¼, Sec. 20, T4S, R4W. Lithologic log only.

42. Abraxas No. 1 Voelker, SE¼ SE¼ SE¼, Sec. 22, T4S, R4W. Dual-induction, electric, gamma ray, and density logs.

43. Hercules No. 1 Vaal, NE¼ NE¼ SE¼, Sec. 23, T4S, R4W. Lithologic log only.

44. Slim Rea Drilling No. 1 St. Meinrad Abbey, SW¼ NE¼ SW¼, Sec. 24, T4S, R4W. Electric log.

PERRY COUNTY

45. Skiles No. 1 Rice, NE¼ NE¼ SW¼, Sec. 20, T4S, R3W. Electric log and partial lithologic log.

46. R.K. Petroleum No. 1 Van Hoosier, SW¼ SW¼ SW¼, Sec. 21, T4S, R3W. Electric log and fair to poor lithologic log.

47. Reynolds No. 3 Gehlhausen, NE¼ NW¼ NE¼, Sec. 22, T4S, R3W. Dual-induction and lithologic logs.

48. Central Pipe Line No. 1 Delaise, SW¼ SW¼ NE¼, Sec. 25, T4S, R3W. Lithologic log only.

49. Griggs No. 1 Flamion, NE¼ NW¼ NE¼, Sec. 15, T4S, R2W. Gamma ray-neutron and lithologic logs.

50. St. Croix No. 4 Faulkenberg, SW¼ SW¼ SW¼, Sec. 18, T4S, R1W. Gamma ray and density logs.

51. Sunoco No. 1 Gibson, SE¼ SE¼ SE¼, Sec. 17, T4S, R1W. Lithologic log only.

52. Indiana Geological Survey Hole No. SDH-132, center SW¼, Sec. 10, T4S, R1W, continuous core (description of core published in IGS Occasional Paper 25). *This is datum point 48 in outcrop sections (Appendix 1).*