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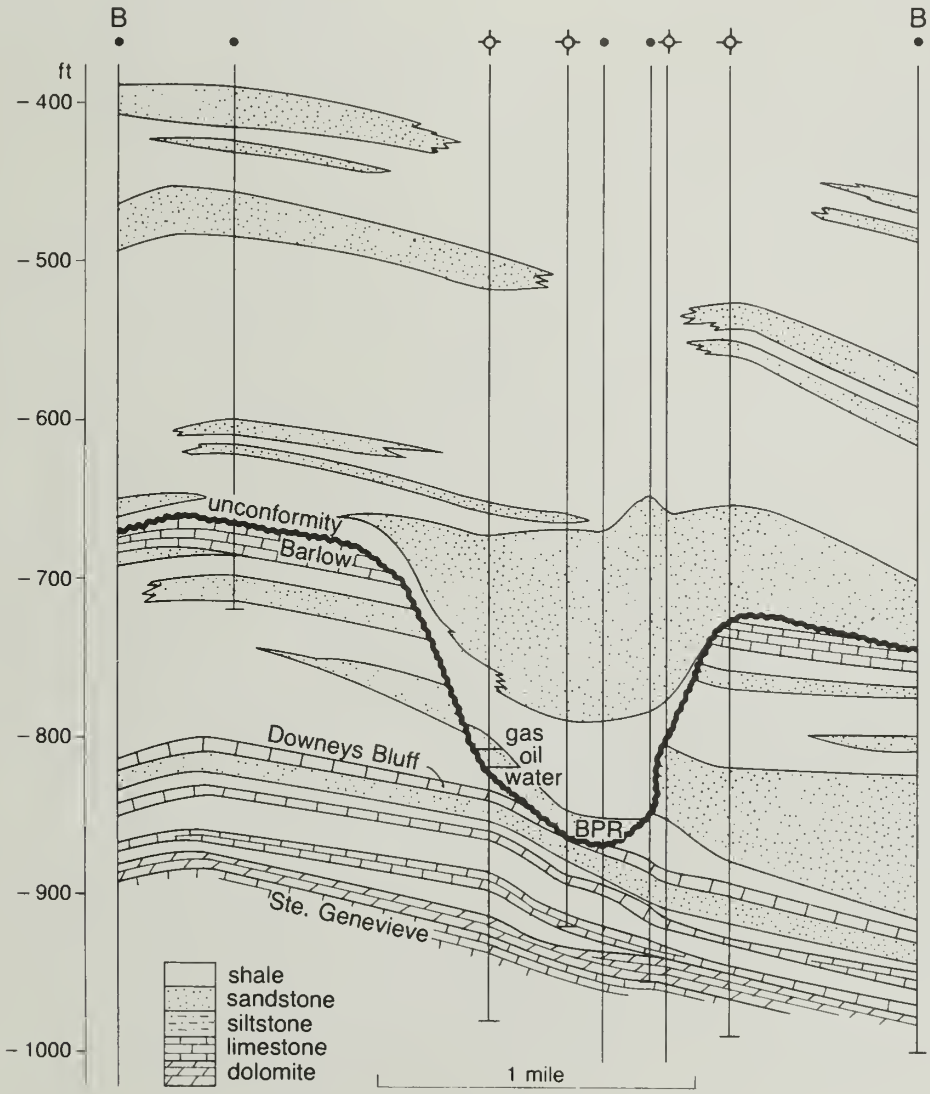
R. H. Howard and S. T. Whitaker



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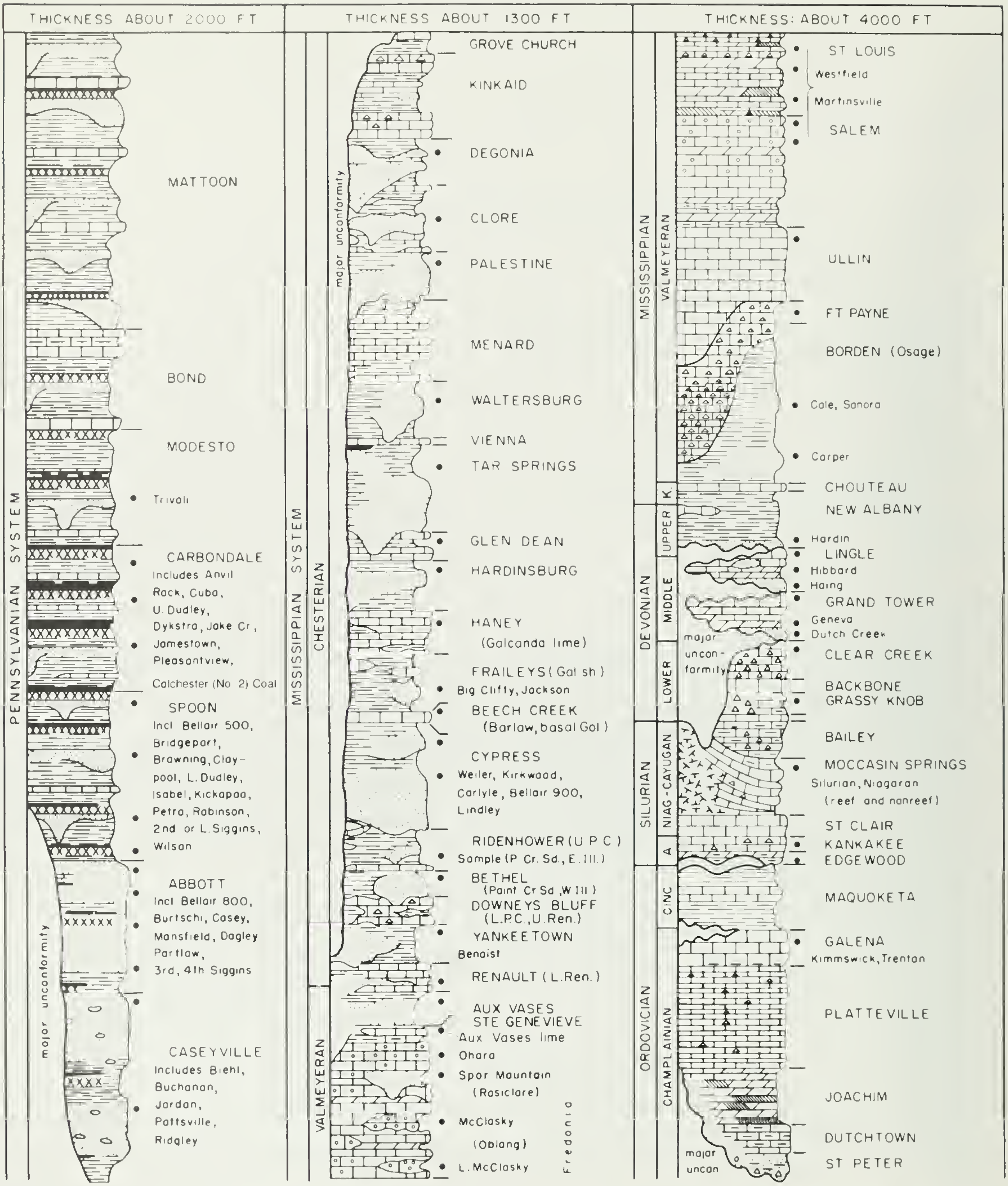


Figure 1 Generalized geologic column of southern Illinois (modified from Huff, 1987). Solid dots indicate oil and gas pay zones. Formation names are in capitals; other pay zones are not. About 4,000 feet of lower Ordovician and upper Cambrian rocks under the St. Peter Sandstone are not shown. The Kinderhookian, Niagaran, Alexandrian, and Cincinnatian Series are abbreviated as K., Niag., A., and Cinc. Variable vertical scale. (Originally prepared by David H. Swann)

ABSTRACT

The surface of the Mississippian-Pennsylvanian unconformity in the Illinois Basin is characterized by an anastomosing pattern of paleovalleys eroded by the ancient Michigan River System. Fluvial sandstones deposited within these valleys commonly were buried by transgressive Pennsylvanian marine shales, creating the potential for stratigraphic entrapment of hydrocarbons.

One such trap was discovered accidentally on the northeast flank of the Hardinville Anticline in 1955. The exploration significance of a linear sandstone body within a paleovalley was not recognized at that time, and only four producing wells resulted.

Not until 1974 was this reservoir again fortuitously encountered 1½ miles to the southwest on the anticline's southwest flank. Correct log correlations led to its identification in 1976 as a 3-mile long, 5- to 45-ft thick conglomeratic sandstone body along one side of the paleovalley floor. Twenty wells will recover an estimated 1.5 million barrels of 36° API oil from the reservoir.

The experience with this reservoir illustrates the difficulties and rewards involved in developing exploration models for stratigraphic traps. Traps associated with paleovalleys at the Mississippian-Pennsylvanian unconformity could prove to be important targets for future exploration. Maps showing the paleogeology and paleotopography of the sub-Pennsylvanian surface and the structure of overlying Pennsylvanian coals can be used to delineate paleovalleys on the unconformity surface and potential hydrocarbon reservoir strata associated with sedimentary fill. Seismic data may also be useful, but careful computer modeling of seismic responses to lithologies expected to be encountered in and along the paleovalleys, as well as field testing, would be required to maximize the effectiveness of a seismic program.

INTRODUCTION

Hydrocarbon reservoirs that have been discovered in relatively shallow Pennsylvanian sedimentary rocks within the Illinois Basin (fig. 1) account for more than 13 percent of the nearly 4 billion barrels of oil that has been produced in the basin. Most Pennsylvanian production has come from reservoirs along the La Salle Anticlinal Belt (fig. 2), in basal sandstones at the Mississippian-Pennsylvanian unconformity or from sandstones higher in the sequence of the lower Pennsylvanian System (Swann and Bell, 1958). Away from the La Salle belt about half of the Pennsylvanian oil is found along fault lines and half in basal sandstones.

The nature and evolution of the anastomosing erosional pattern inscribed on the Mississippian-Pennsylvanian unconformity surface (fig. 3) has been widely studied and discussed in the literature (Siever, 1951; Bristol and Howard, 1971; Howard, 1979a). The character, distribution, and depositional environments of the sediments that buried this surface, however, have received only relatively local documentation (Davis, Plebuch, and Whitman, 1974; Pryor and Potter, 1979). With the exception of Shiarella's (1933) report on the Buford area in Ohio County, Kentucky, published studies of hydrocarbon traps in basal Pennsylvanian sandstones in the Illinois Basin are virtually nonexistent. A recently completed but unpublished master's thesis by Stephen F. Greb, University of Kentucky, is devoted to the study of the Madisonville Paleovalley (fig. 3) and the basal Pennsylvanian oil pools it contains, including those in the Buford area.

This report is the first to describe the relationship of a sub-Pennsylvanian unconformity paleovalley to a specific hydrocarbon reservoir in Illinois. The description of the basal Pennsylvanian reservoir (BPR) at Hardinville is a step toward according basal Pennsylvanian hydrocarbon entrapment the local and regional analyses its economic significance deserves. From these analyses will emerge hydrocarbon play models that can be used to indicate additional prospective areas for similar paleogeomorphic traps.

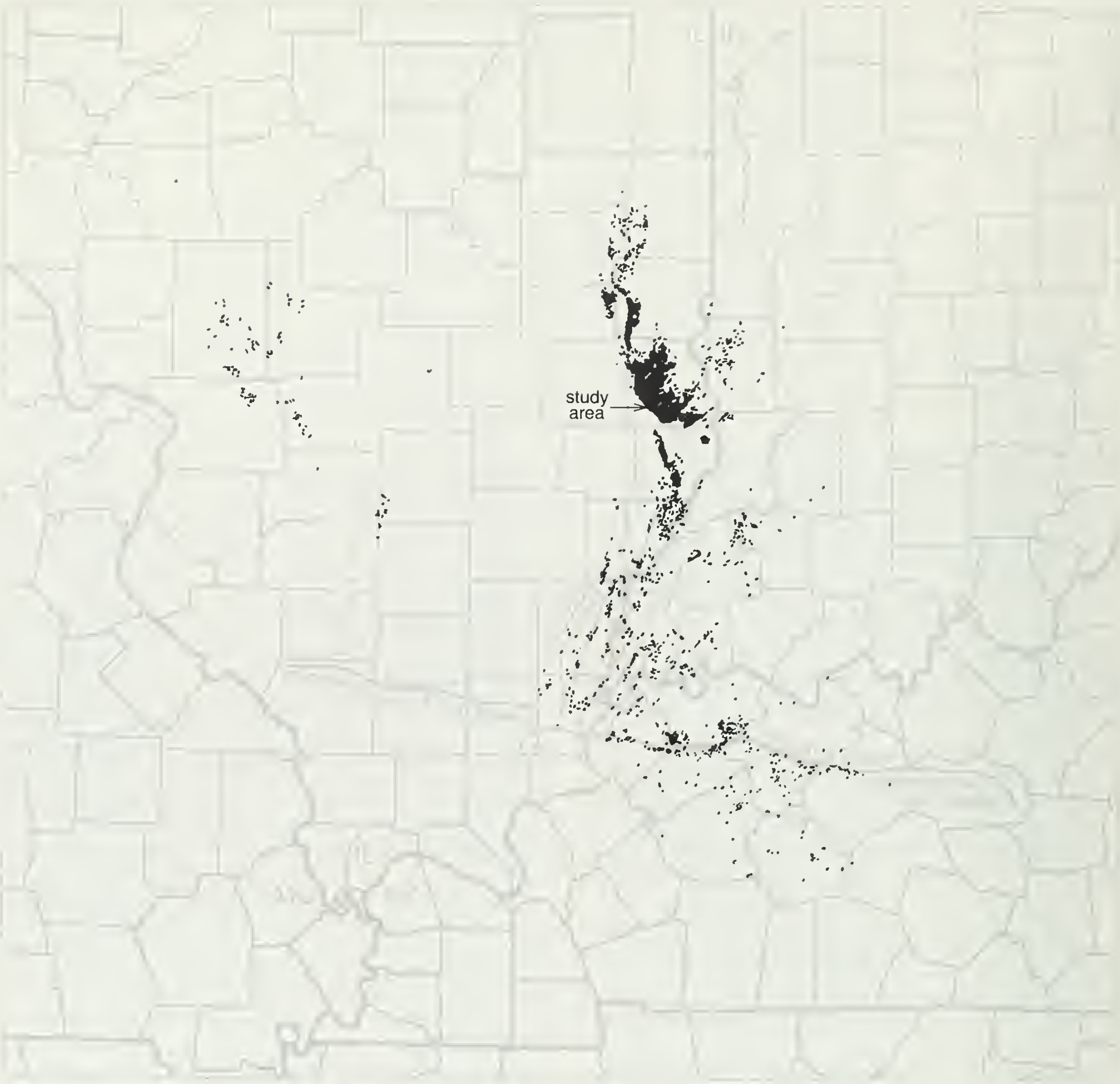


Figure 2 Map showing hydrocarbon productive area of Pennsylvanian strata in the Illinois Basin, related major structural features, and location of study area.

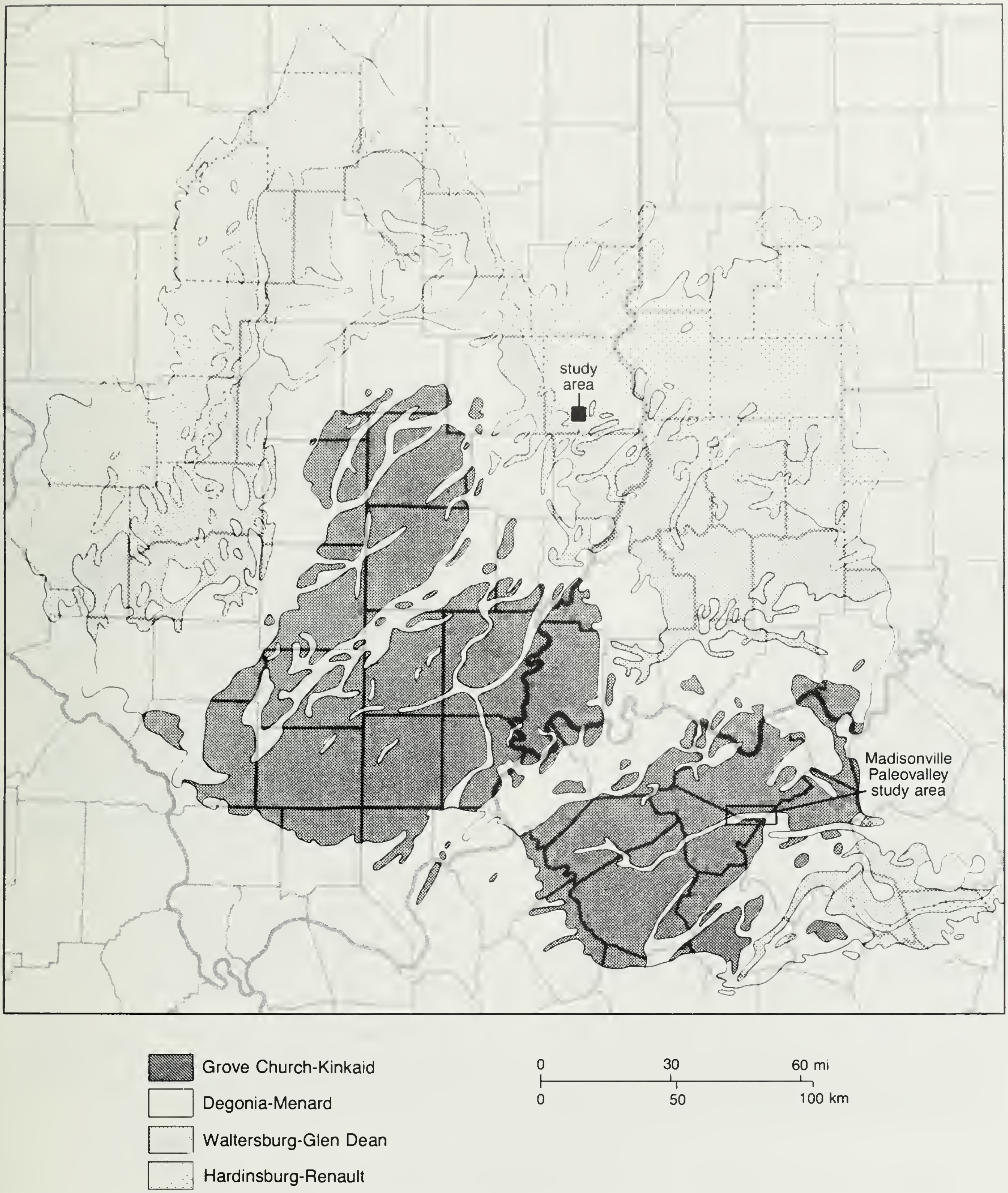


Figure 3 Paleogeologic map of the sub-Pennsylvanian Chesterian surface in the Illinois Basin (modified from Bristol and Howard, 1971, plate 1; Howard, 1979a, fig. 2). The study area and location of studies of basal Pennsylvanian hydrocarbon accumulation along the Madisonville Paleovalley in Daviess, McLean, and Ohio Counties, Kentucky, are shown.

BASAL PENNSYLVANIAN RESERVOIR AT HARDINVILLE

History of oil discovery

The occurrence of a relatively shallow, oil-filled conglomeratic sandstone lens draped across the crest of a major anticline in the heart of the oldest oil-producing area in Illinois should have guaranteed its early discovery. In the study area, however, the discovery and exploitation of hydrocarbon accumulations in shallower Pennsylvanian Robinson sands and in the deeper Mississippian Chesterian and Valmeyeran strata (fig. 1) effectively concealed the existence of a basal Pennsylvanian oil accumulation there during the first seven decades of oil exploration in Crawford County.

Oil production from the basal Pennsylvanian reservoir (BPR) was finally established two miles east of Hardinville in December 1955, when Miracle and Wooster plugged back their #1 Richart well (SW NW NE Sec. 36, 6N-13W), a McClosky (Ste. Genevieve) test on the northeast flank of a structural closure herein named the Hardinville Anticline (fig. 4). This well was completed in the BPR for 120 barrels of oil per day, but only three successful north and south offsets followed. Apparently the exploration significance of an oil-bearing basal Pennsylvanian sandstone body situated along the floor of a deeply incised paleovalley was not recognized. Consequently no further attempts were made to develop the lenticular reservoir at that time.

It was not until 1974 that the basal Pennsylvanian reservoir was again fortuitously encountered, this time on the anticline's southwest flank, during drilling of the Energy Resources of Indiana (E.R.I.) #1 Richart Heirs (NE NE SE Sec. 2, 5N-13W), which was drilled to the McClosky (fig. 5). Unfortunately the BPR was mistaken for Chesterian sandstones that were expected at about the same depth, thereby preventing recognition of the paleovalley.

Finally, in 1976, the E.R.I. #1 Due Heirs II (NE SW SW Sec. 1, 5N-13W) encountered the BPR at about the expected depth of the Yankeetown Sandstone. Its correct identification as a Pennsylvanian fluvial sandbar deposited along the floor of an unconformity paleovalley (probably extending NNE across Sec. 36, 6N-13W) led to the completion of 16 oil wells in the southwestern portion of the reservoir (fig. 5). The potential for miscorrelation of the BPR with Chesterian sandstones is shown in figure 6 along with the paleotopographic relief of the unconformity surface.

E.R.I. estimates that primary and secondary production methods will recover approximately 1.4 million barrels of oil from its 16 producing wells (J. G. Peters and E. L. Whitmer, Jr., personal communication). Another estimated 100,000 barrels will be recovered from the four wells in Section 36, in the northeastern portion of the reservoir. Two additional wells, the #1-A Richart Heirs (NE NE SE Sec. 2, 5N-13W) and the #1-A Coulter Heirs (SE SE NE Sec. 2, 5N-13W), are shut-in gas wells. High gas-oil ratios in wells updip from the #1-A Richart Heirs, particularly where the BPR is less than 15 feet thick, suggest that a gas cap existed. Although E.R.I. estimates that the southwestern portion of the reservoir originally contained 277 million cubic feet of gas, produced gas has been flared due to lack of market. Initial production figures of all wells completed in the BPR are shown in table 1.

Reservoir lithology

In February 1977, E.R.I. drilled the #1-A Richart Heirs 50 feet south of its #1 Richart Heirs (NE NE SE Sec. 2, 5N-13W), in which the BPR had been penetrated but not recognized in 1974. Although the BPR was encountered and cored in the #1-A Richart Heirs, a poor cement job prevented its completion as an oil producer. R. M. Cluff and R. H. Howard described this core, consisting of 20 feet of the BPR and 40 feet of underlying Chesterian strata (fig. 7). The BPR core is oil stained throughout. Photographs of selected core slabs are shown in appendixes 1 and 2.

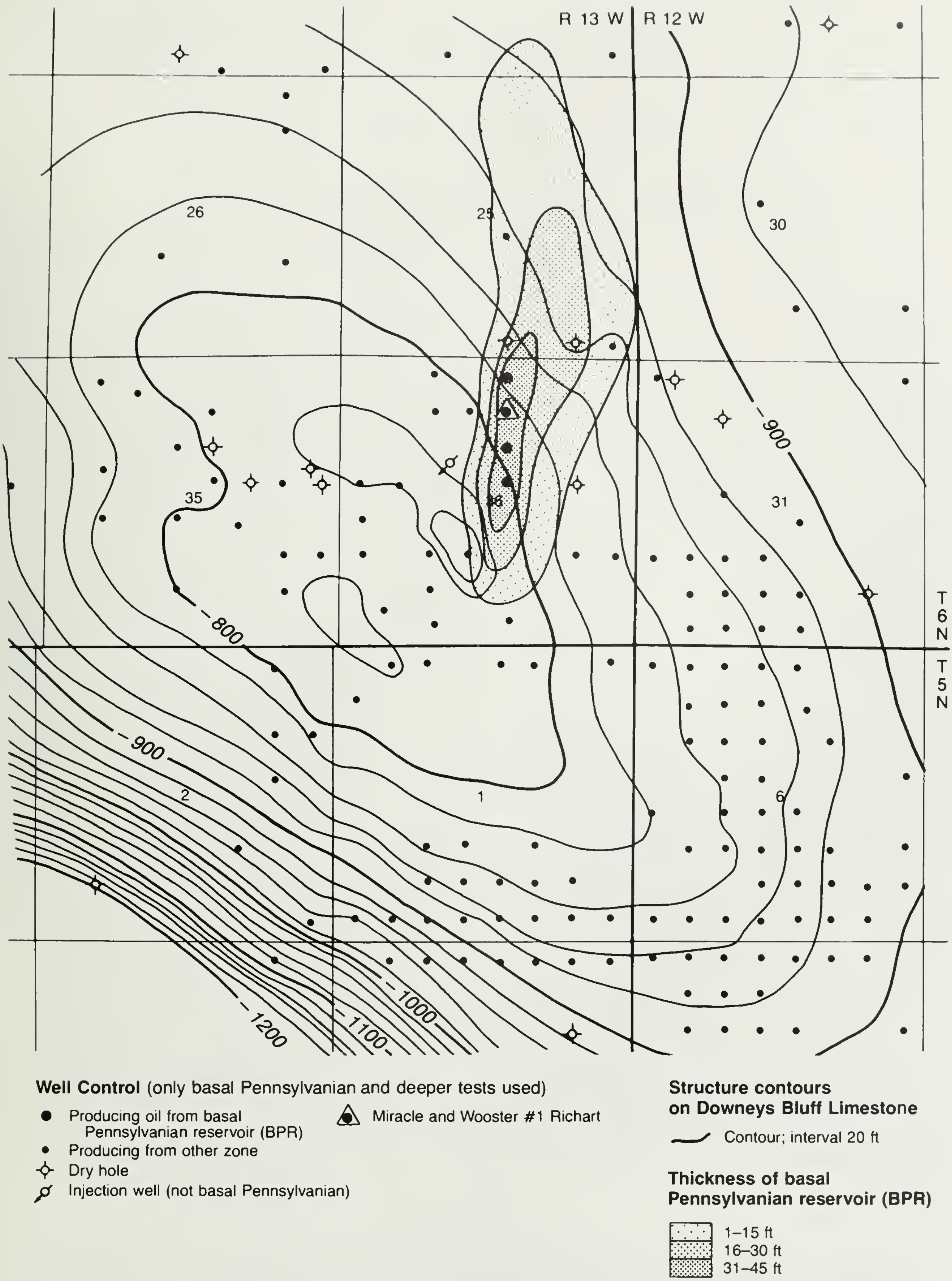


Figure 4 Oil productive basal Pennsylvanian sandstone reservoir on the northeast flank of the Hardinville Anticline, discovered in Miracle and Wooster's #1 Richart in 1955. Chesterian Downeys Bluff Limestone structure is shown with respect to mean sea level. No wells producing from the basal Pennsylvanian reservoir that were drilled after 1956 are shown.

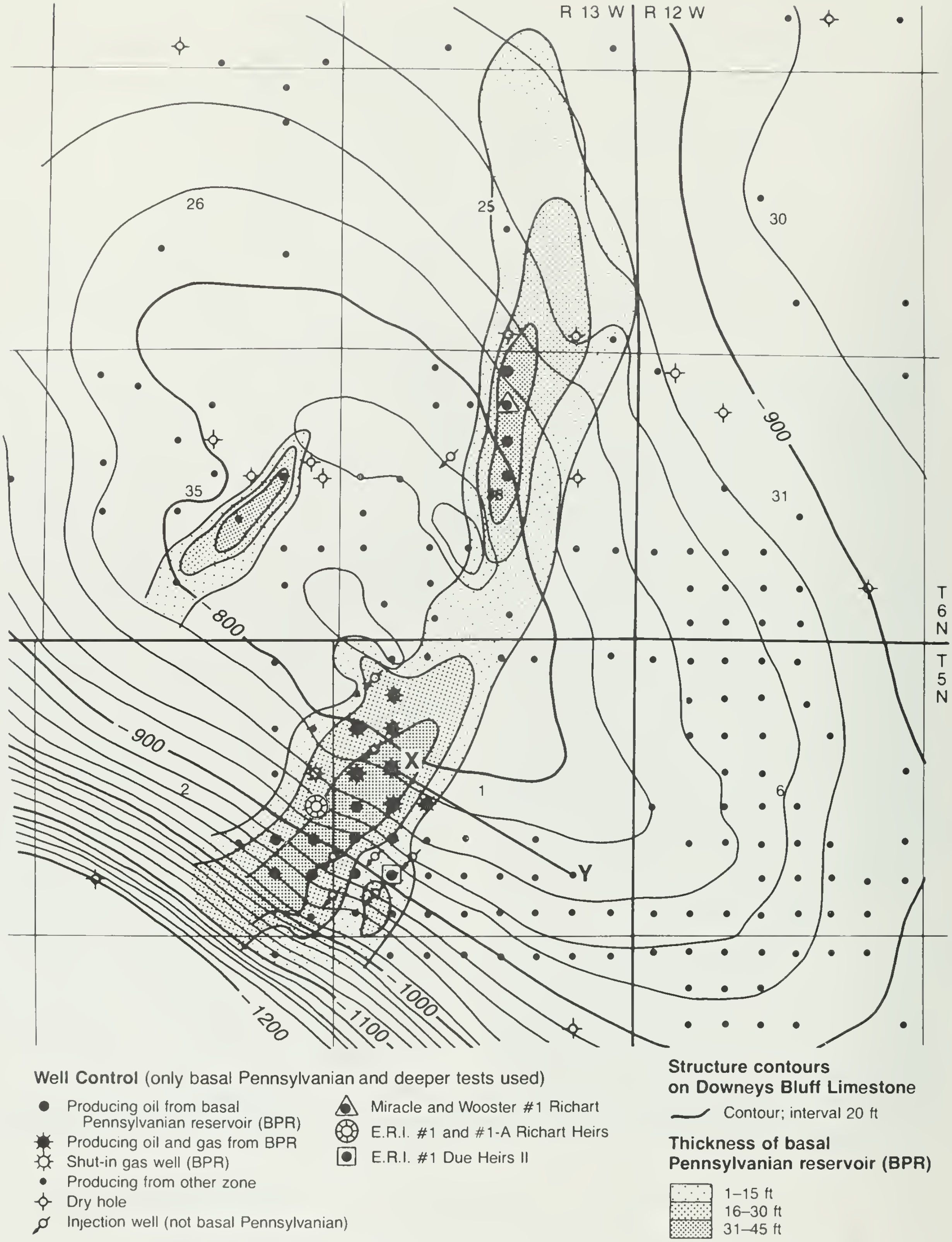


Figure 5 Basal Pennsylvanian sandstone deposits across the Hardinville Anticline. The oil-bearing BPR on the southwest flank of the anticline was transected but unrecognized and unexploited in 1974 by E.R.I. #1 Richart Heirs. In 1976 E.R.I. completed #1 Due Heirs II, the first of 16 producers in the sand bar, whose relation to the BPR in Section 36 was then recognized. A thick basal Pennsylvanian sandstone accumulation in Section 35 is barren because of its communication with overlying porous strata. Downeys Bluff Limestone structure is shown with respect to mean sea level. Location of cross section X-Y (fig. 6) is shown.

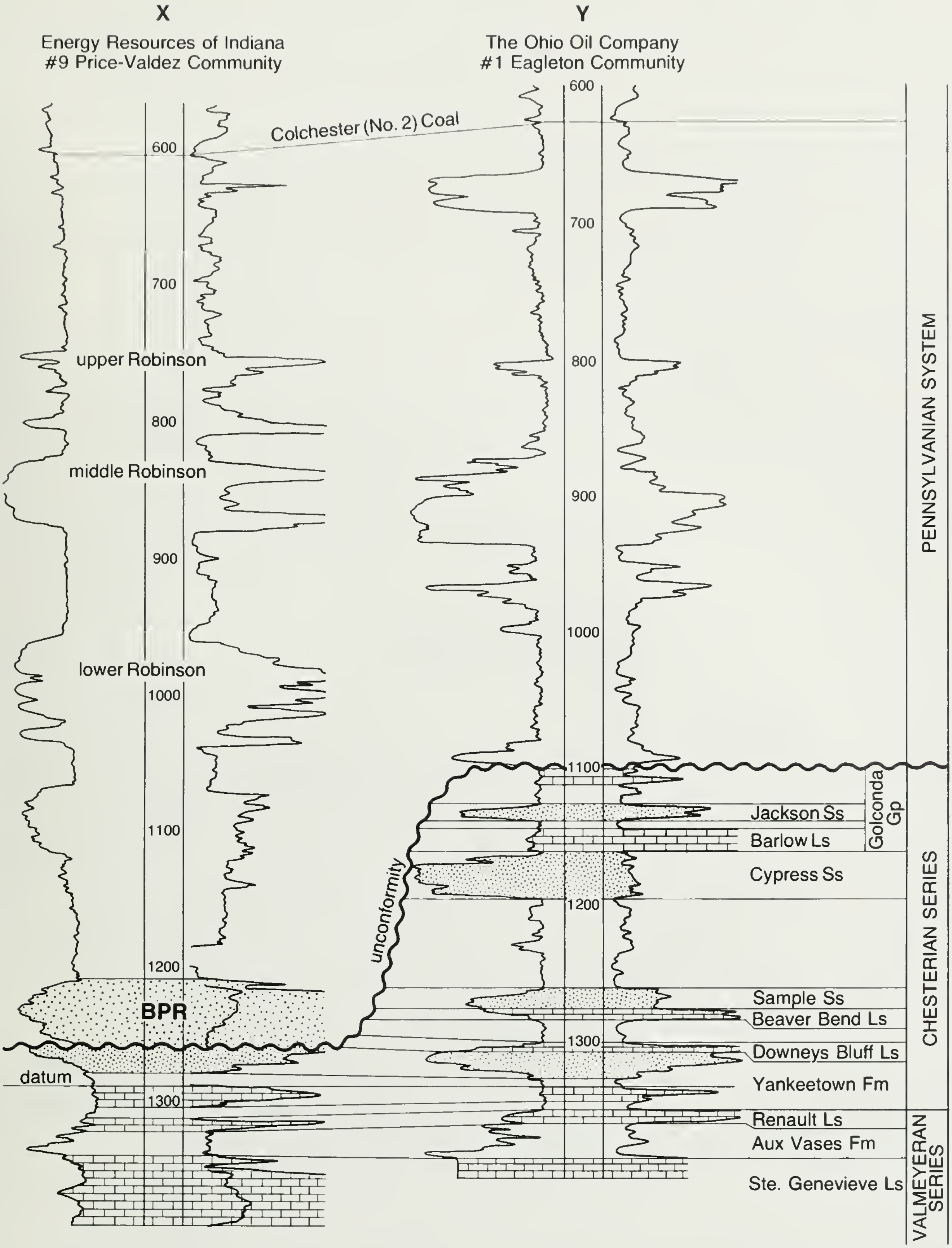


Figure 6 Two-well electric log cross section X-Y (location shown in fig. 5) shows paleotopographic relief at the sub-Pennsylvanian unconformity. Note the potential for correlation difficulties due to the spatial relation of the basal Pennsylvanian reservoir (BPR) on the paleovalley floor to Chesterian sandstones. Exploitation of extensive Pennsylvanian Robinson sand reservoirs and reservoirs in Chesterian and Valmeyeran strata inhibited recognition and identification of the BPR.

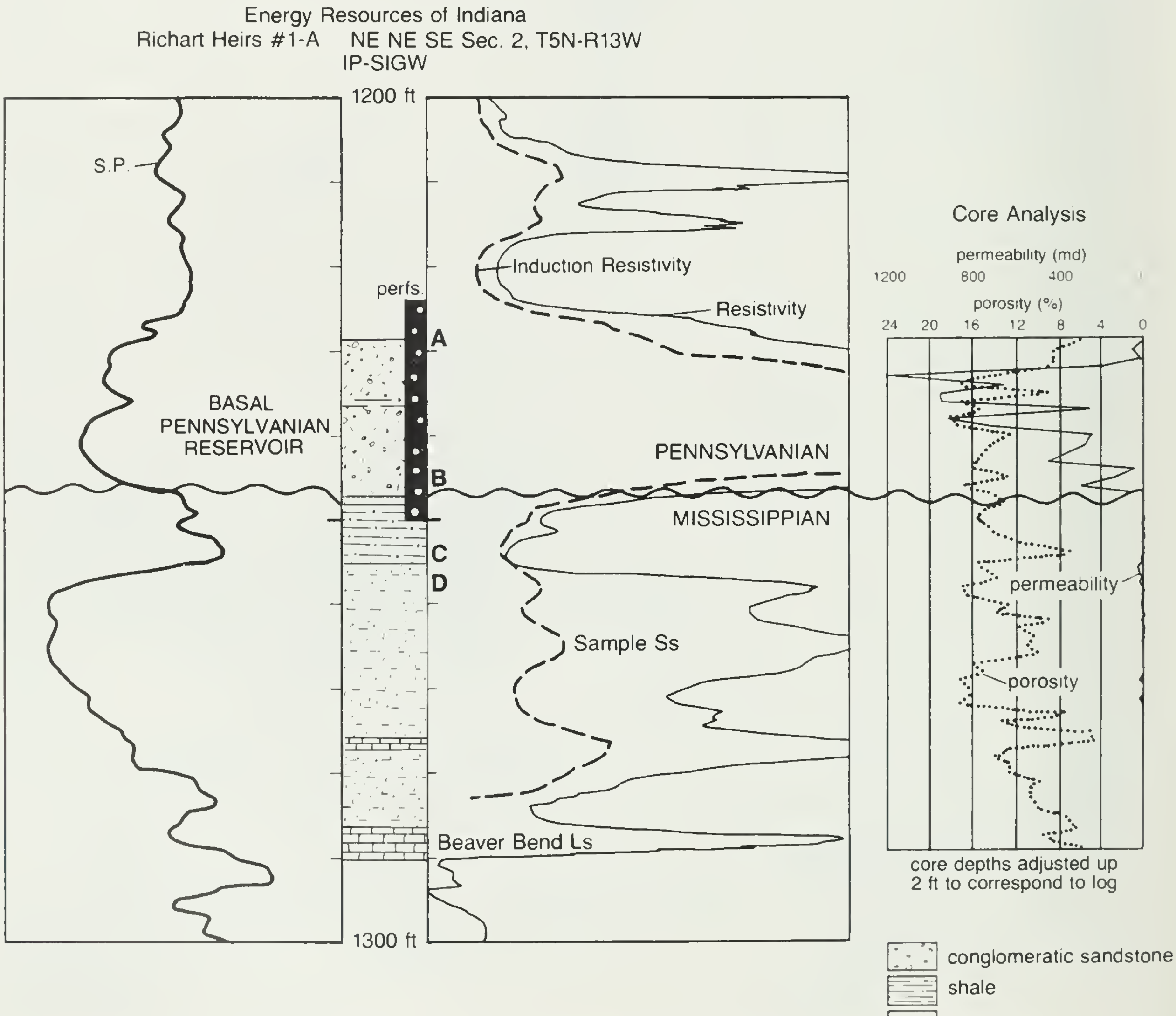


Figure 7 Induction log of bottom portion of E.R.I. #1-A Richart Heirs (see fig. 5). Lithology, porosity, and permeability of a 60-foot core, including 20 feet of the BPR and 40 feet of subjacent Chesterian strata, are graphically depicted. Letters A, B, C, and D, indicate positions of core slabs shown in appendixes 1 and 2.

Richart Heirs #1-A

UNIT	CORE DESCRIPTION	DEPTH (FT)
	PENNSYLVANIAN SYSTEM	
Sandstone	interbedded medium gray and light olive gray quartz sand with minor feldspar, chert, and rock fragments; angular to subrounded; mostly poorly sorted; mostly siliceous cement with some calcite cementation. Porosity is variable. Interval consists of seven fining-upward cycles ranging from 0.2 to 1.5 ft thick. Grain size at base ranges from coarse sand to granule or pebble; at top, fine to coarse sand. Basal contact of each cycle is sharp, may be pyritic, and is commonly inclined (giving some impression of crossbedding). Several shale chips up to 5 cm across occur at 1237 ft	1231-1237.2
Shale	medium dark gray, soft, fissile; thin, discontinuous, parallel silt laminae 1 to 2 mm thick, pyritic; irregular bottom contact and sharp upper contact	1237.2-1237.35
Sandstone	light olive gray; quartz sand with minor fragments of chert, subrounded to rounded, very poorly sorted; irregular grain size variation from fine sand to pebble; mostly medium to coarse matrix with coarse to very coarse floating grains; numerous shale chips scattered throughout; siliceous and calcareous cement; variable intergranular porosity	1237.35-1247.8
Sandstone	dark yellowish brown, medium- to fine-grained, well-sorted, siliceous cement with some calcareous cement near top, 20° planar crossbedding throughout; bottom contact sharp, pyritic	1247.8-1250.0
	MISSISSIPPIAN SYSTEM **Chesterian Series** **Ridenhower Formation**	
Sample Sandstone Member		
Siltstone	very light gray; numerous wavy shale partings, very fine sandstone streaks, wavy bedding; scattered 2- to 5-mm pyrite nodules	1250.0-1257.0
Sandstone	very light gray, very fine, very silty, well cemented with silica and calcite, oil stained in part; many wavy, hairline, pyritized shale partings	1257.0-1275.5
Sandstone	light gray, very fine, silty; up to 50% white to brown, coarse, limestone fragments	1275.5-1277.5
Limestone	white speckled brown, fine to very coarse, few granules, very fossiliferous, oolitic, silty, dense	1277.5-1279.0
Sandstone	light gray, very fine, very silty, many wavy hairline streaks of pyrite and gray shale, slightly calcareous, dense, with scattered brown, white, medium to coarse limestone fossil fragments, scattered pyrite; wavy, gray, silty shale partings very numerous below 1281 ft (one every 1/4 to 3/4 inch); shale becomes very carbonaceous below 1284 ft; ball and pillow structure at 1287 ft	1279.0-1287.5
Beaver Bend Limestone Member ("Paint Creek" Ls.)		
Limestone	white speckled brown, grading downward to white speckled very light brown, fine to very coarse, few granules and pebble-size fragments, mostly coarse crinoid columnal segments, slightly silty, dense at top, grading downward to vuggy in streaks with 15° dip	1287.5-1290.5
Limestone	dark yellowish brown, very coarsely white speckled, mainly crinoidal, pyritic, silty, dense	1290.5-1290.7
Limestone	olive black, scattered, coarse to very coarse light grains, carbonaceous, silty, pyritic	1290.7-1291.0
Limestone	brownish black, argillaceous, silty, dense, speckled with coarse to granule-size fossil fragments	1291.0-1291.5

Table 1. Initial production of wells completed in the BPR at Hardinville, Crawford County, Illinois

Operator	#	Farm	Location S-T-R	Spot	No. feet Perf.	Production (BOPD) Oil	Water	Oil Grav °API @ 60°	Gas Volume (MCFD)	Gas Gravity	Gas Oil Ratio
1955											
Miracle and Wooster	1	Richart	36-6N-13W	SW NW NE	4	120					
Miracle and Wooster	2	Richart	36-6N-13W	NW NW NE	7	120					
1956											
Miracle and Wooster	4	Richart	36-6N-13W	NW SW NE	6	100	100				
1958											
Ohio Oil Co.	14	Adams	36-6N-13W	SW SW NE	10	14	84				
1976											
E.R.I.	1	Due Heirs II	1-5N-13W	NE SW SW	18	103					
E.R.I.	3	Valdez	1-5N-13W	SW NW SW	34	72					
E.R.I.	2	Due Heirs II	1-5N-13W	NW SW SW	12	126					
E.R.I.	4	Valdez	1-5N-13W	SE NW SW	18	75					
E.R.I.	2	Richart Heirs	2-5N-13W	SE NE SE	30	81		35	198	.65	2,750
E.R.I.	5	Valdez	1-5N-13W	NW NW SW	19	67			1630		23,285
E.R.I.	3	Richart Heirs	2-5N-13W	NE SE SE	24	240					
E.R.I.	6	Valdez	1-5N-13W	NE NW SW	22	60					
E.R.I.	7	Valdez	1-5N-13W	SW SW NW	18	108					
E.R.I.	4	Richart Heirs	2-5N-13W	SW NE SE	10	60					
E.R.I.	8	Valdez	1-5N-13W	NW SW NW	20	5					
E.R.I.	9	Price-Valdez	1-5N-13W	SE SW NW	32	60					
E.R.I.	1-A	Coulter Heirs	2-5N-13W	SE SE NE	17	SIGW					
E.R.I.	10	Price-Valdez	1-5N-13W	NE SW NW	20	50					
1977											
E.R.I.	1-A	Wiseman Heirs	1-5N-13W	NW NE SW	10	30					
E.R.I.	13	Baldwin-Valdez	1-5N-13W	SE NW NW	6	15					
E.R.I.	6	Richart Heirs	2-5N-13W	NW SE SE	12	65					
E.R.I.	1-A	Richart Heirs	2-5N-13W	NE NE SE	26	SIGW					

Reservoir geometry

The configuration and apparent topographic relief of the unconformity surface are revealed by maps portraying the thickness of Chesterian strata preserved above the Downeys Bluff Limestone (fig. 8) and the thickness of Pennsylvanian strata beneath the Colchester (No. 2) Coal (fig. 9). Although both isopach maps clearly show a south-southwest-trending valley crossing the study area, their portrayal of paleotopographic relief is somewhat distorted because of the evolution of the Hardinville Anticline. The former map provides a more accurate portrayal of the valley's maximum topographic relief, which was about 250 feet across the anticline's crest. Deeper stratigraphic erosion along the rising crest of the anticline opened two "windows" in the Downeys Bluff Limestone (fig. 8), however, and might lead one to mistakenly infer centripetal drainage.

The Colchester (No. 2) Coal-to-unconformity isopach map (fig. 9) is a more accurate indicator of the sub-Pennsylvanian drainage pattern across the study area than is the previously discussed isopach map, since variable stratigraphic erosion is not a factor. The actual topographic relief of the valley was undoubtedly somewhat different than indicated in figure 9, however, because the relief has been masked by compaction of Pennsylvanian shales in the valley below the coal (fig. 10). Additionally, divergence between the unconformity surface and the Colchester (No. 2) Coal along the steeply dipping southwest flank of the anticline creates the illusion of deeper valley incision there than along the anticline's crest.

Stratigraphic and structural relationships of the main paleovalley are shown in the cross section north of clean sandstone development in the BPR (fig. 12) and across the northern BPR (fig. 13). Cross section C-C′ (fig. 14) intersects the BPR in the main valley and reveals a thick basal sandstone in the smaller valley to the northwest. The possibility of a trap there, however, has been precluded by younger sandstones that were deposited directly on the fluvial sand bar, thus allowing hydrocarbons to migrate into shallower Robinson traps. Cross section D-D′ (fig. 15) shows good development of the BPR across the southwest flank of the anticline.

A longitudinal section along the main valley course (fig. 16) reveals that (1) the upper half of the basal sandstone grades into siltstone across the crest of the anticline, and (2) the sandstone body interfingers with shale down the anticline's steeply dipping southwest flank.

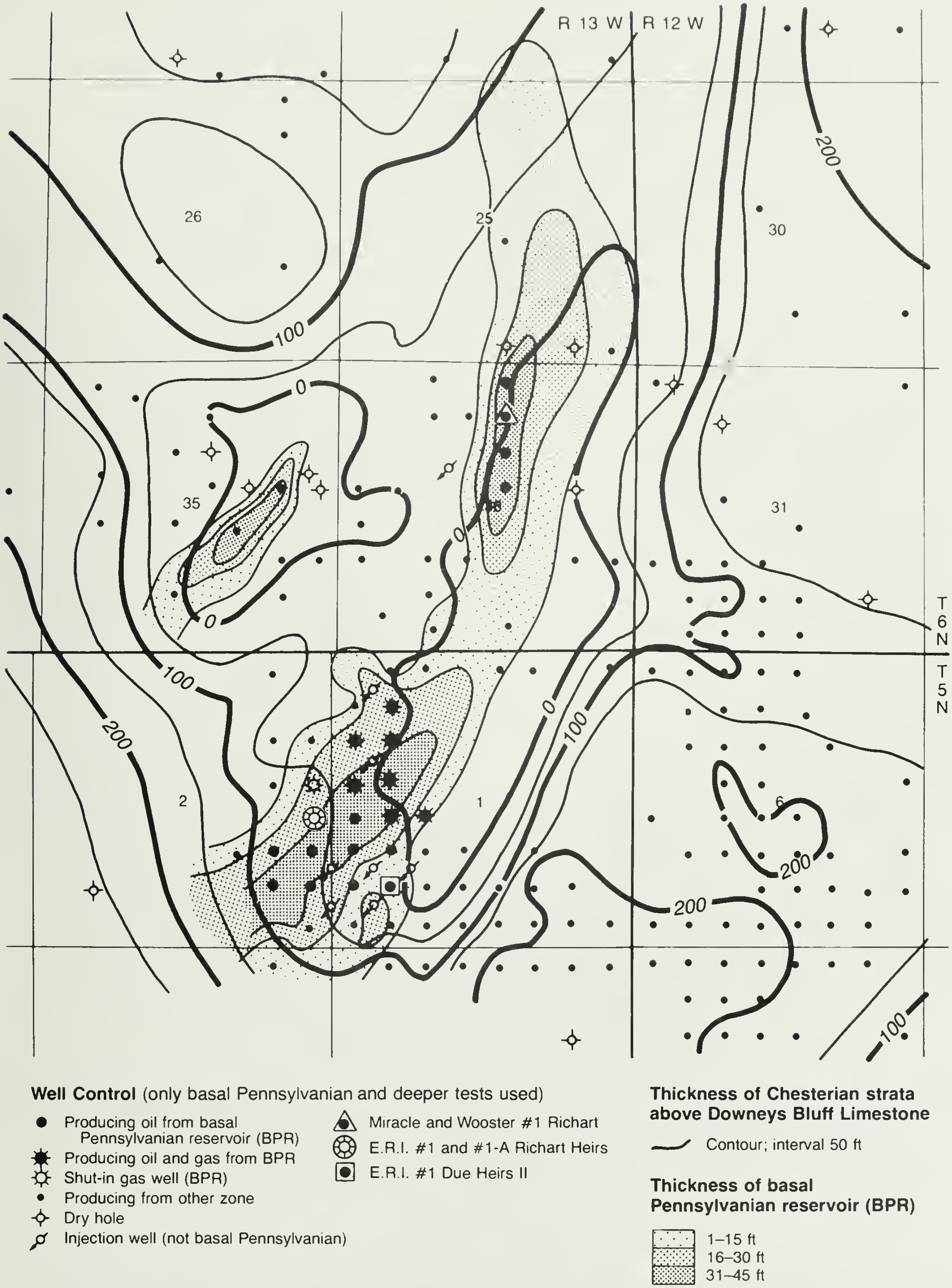


Figure 8 Thickness of the interval between the Downeys Bluff Limestone and the base of the Pennsylvanian approximates the paleotopographic relief of the study area immediately before inundation by the Pennsylvanian sea. Note the distribution of the basal Pennsylvanian reservoir (BPR) along the western side of the main paleovalley.

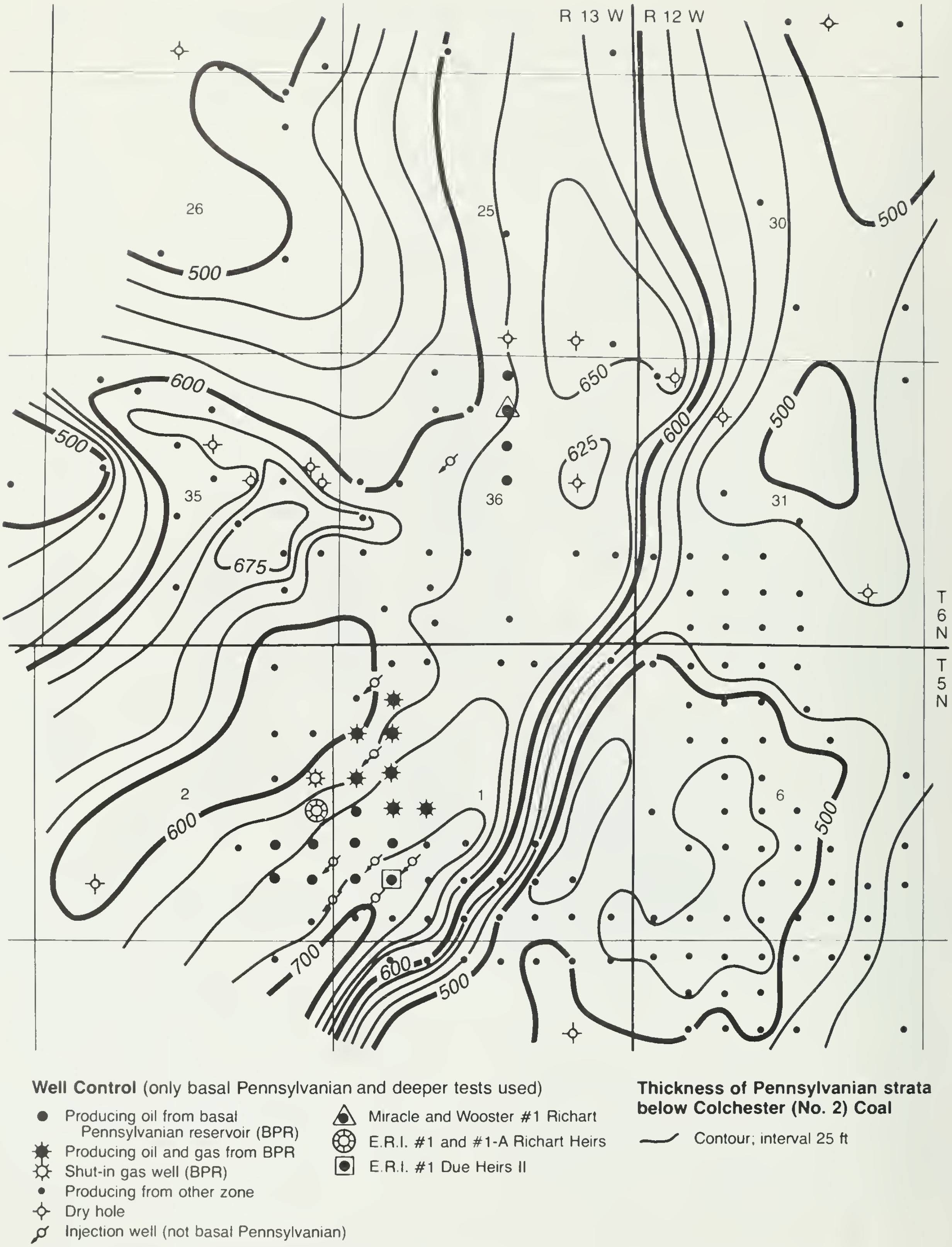


Figure 9 Thickness of Pennsylvanian strata below the Colchester (No. 2) Coal shows the configuration and apparent paleotopographic relief of the sub-Pennsylvanian surface. A south-southwest-trending bifurcating valley crosses the study area.

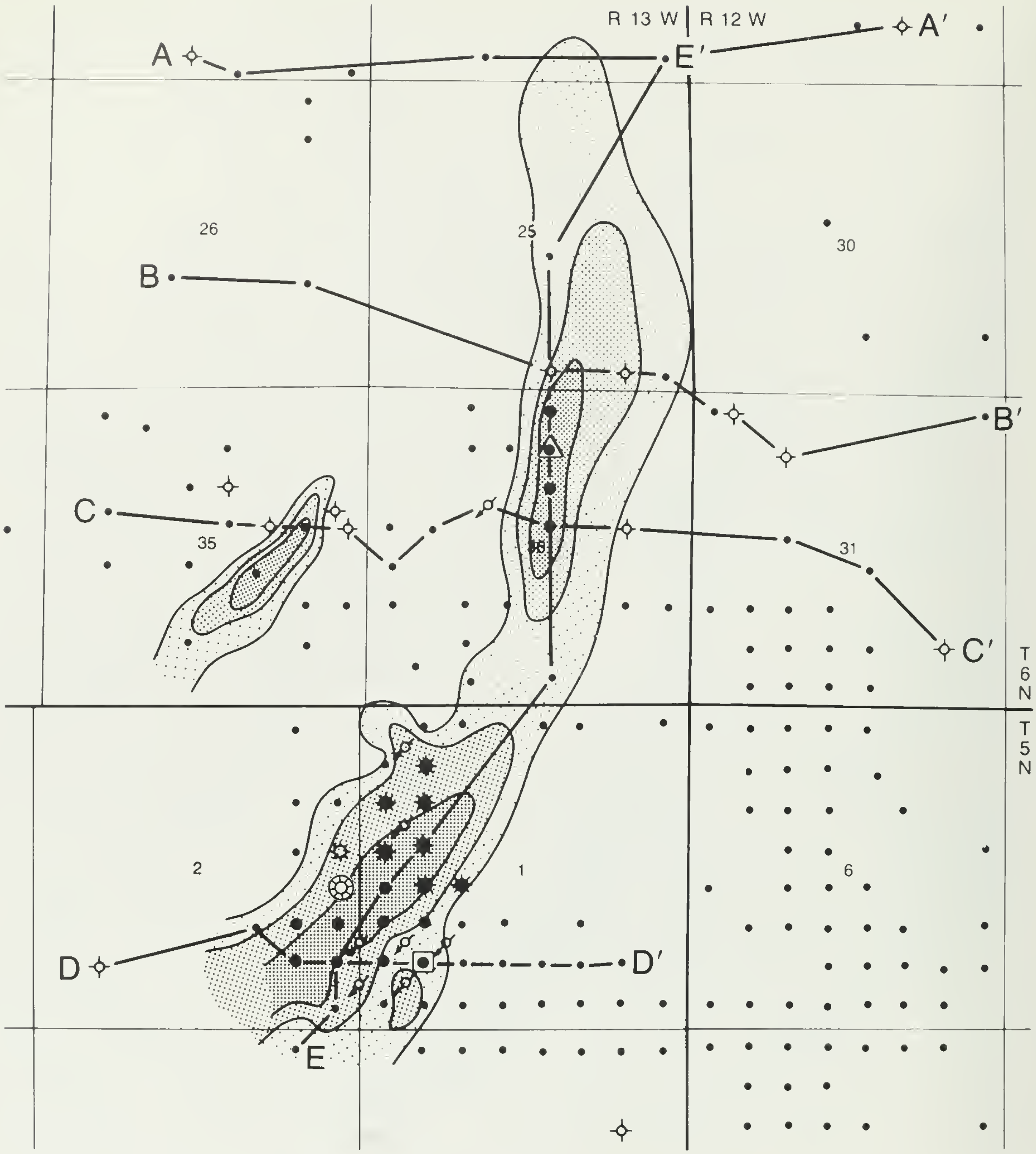
Well Control (only basal Pennsylvanian and deeper tests used)

- Producing oil from basal Pennsylvanian reservoir (BPR)
- Producing oil and gas from BPR
- Shut-in gas well (BPR)
- Producing from other zone
- Dry hole
- Injection well (not basal Pennsylvanian)
- Miracle and Wooster #1 Richart
- E.R.I. #1 and #1-A Richart Heirs
- E.R.I. #1 Due Heirs II

Structure of Colchester (No. 2) Coal

Contour; interval 20 ft

Figure 10 Structure map of Colchester (No. 2) Coal Member with respect to mean sea level. Compaction of shales infilling the paleovalley has caused mappable subsidence in overlying strata.



Well Control (only basal Pennsylvanian and deeper tests used)

- Producing oil from basal Pennsylvanian reservoir (BPR)
- Producing oil and gas from BPR
- Shut-in gas well (BPR)
- Producing from other zone
- Dry hole
- Injection well (not basal Pennsylvanian)
- Miracle and Wooster #1 Richart
- E.R.I. #1 and #1-A Richart Heirs
- E.R.I. #1 Due Heirs II

Thickness of basal Pennsylvanian reservoir (BPR)

- 1–15 ft
- 16–30 ft
- 31–45 ft

Figure 11 Map showing basal Pennsylvanian reservoir and locations of holes used in cross sections A-A′ (fig. 12) B-B′ (fig. 13), C-C′ (fig. 14), D-D′ (fig. 15), and E-E′ (fig. 16).

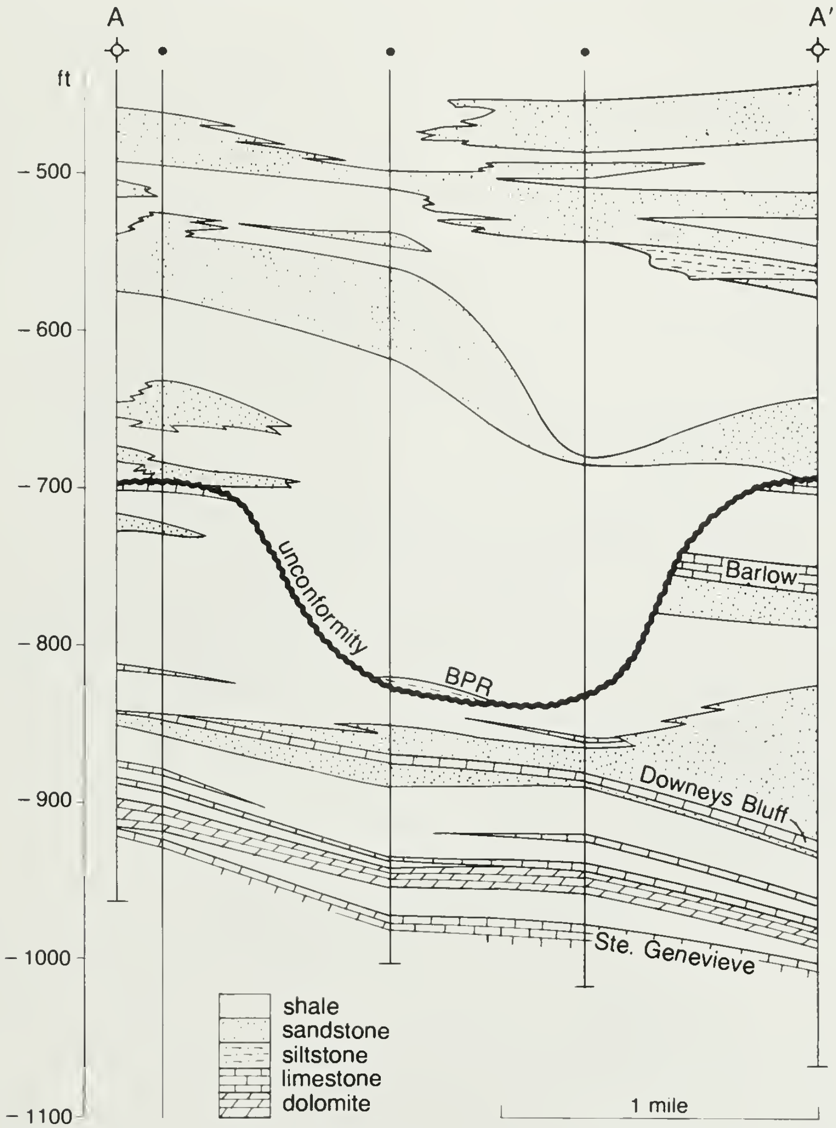


Figure 12 Cross section A-A′ (location shown in fig. 11) shows structural and stratigraphic relations of strata along an east-west transect north of clean sandstone development in the BPR. Datum is mean sea level.

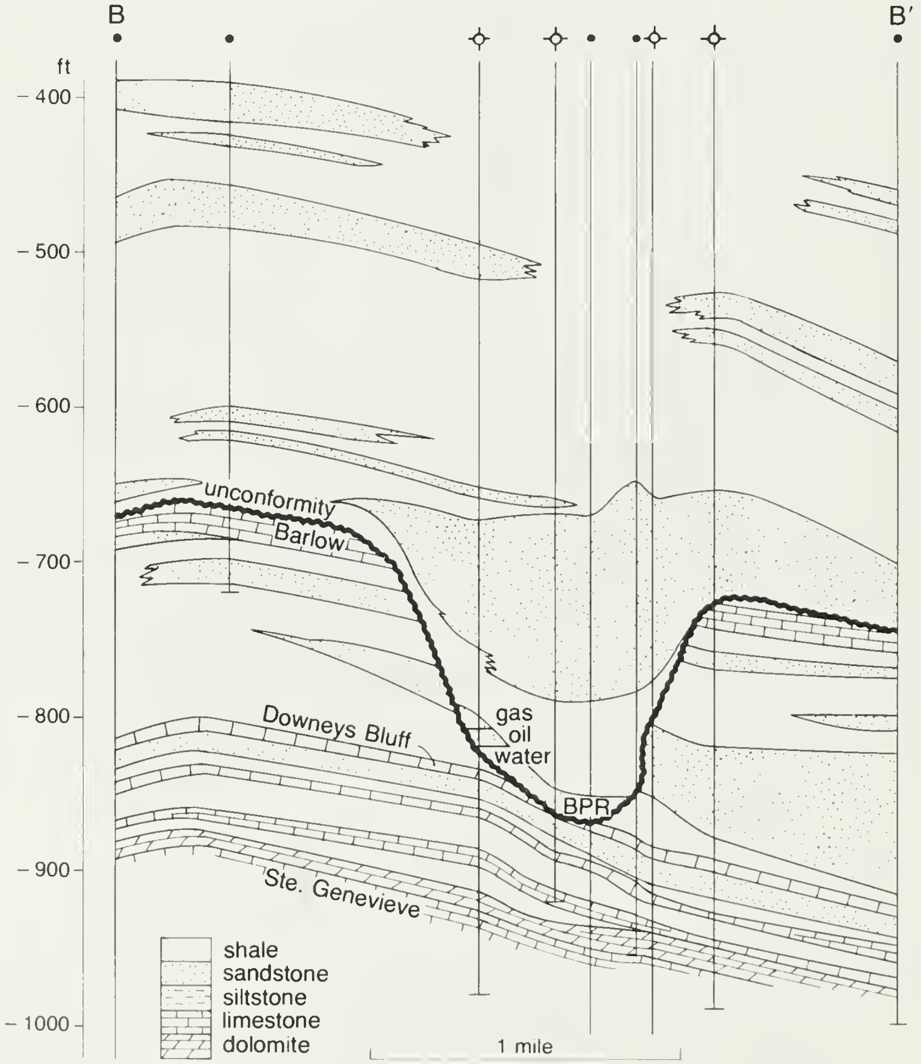


Figure 13 Cross section B-B′ (location shown in fig. 11) shows BPR situated along the western, updip, side of the paleovalley. Post-depositional uplift has skewed the structural position of the BPR. Note draping of Robinson sands into the paleovalley. Datum is mean sea level.

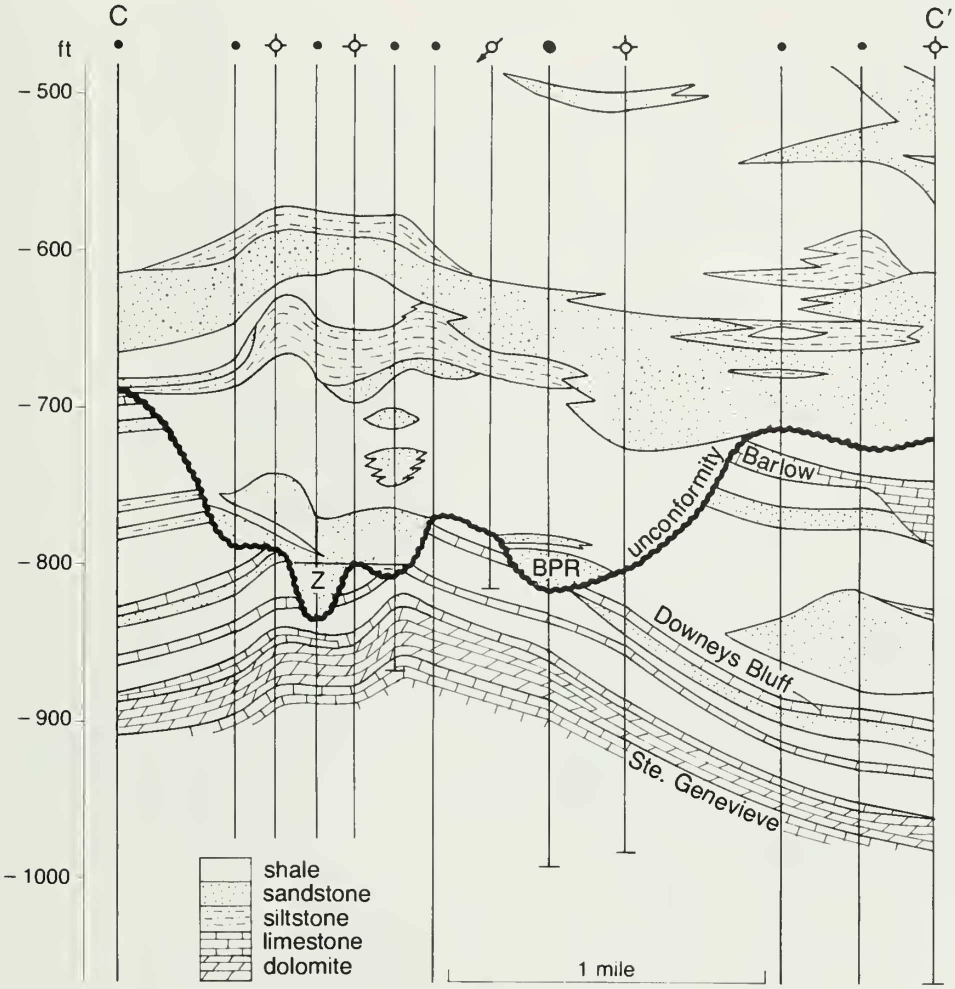


Figure 14 Cross section C-C′ (location shown in fig. 11) shows structural and stratigraphic relations of Chesterian and basal Pennsylvanian strata along the crest of the anticline. Note that Pennsylvanian shales cover the thin basal Pennsylvanian sandstone in the main valley and form a stratigraphic seal there. In the valley to the west of the main valley, communication between a basal Pennsylvanian sandstone (Z) and younger Pennsylvanian sandstones precludes a stratigraphic seal. Datum is mean sea level.

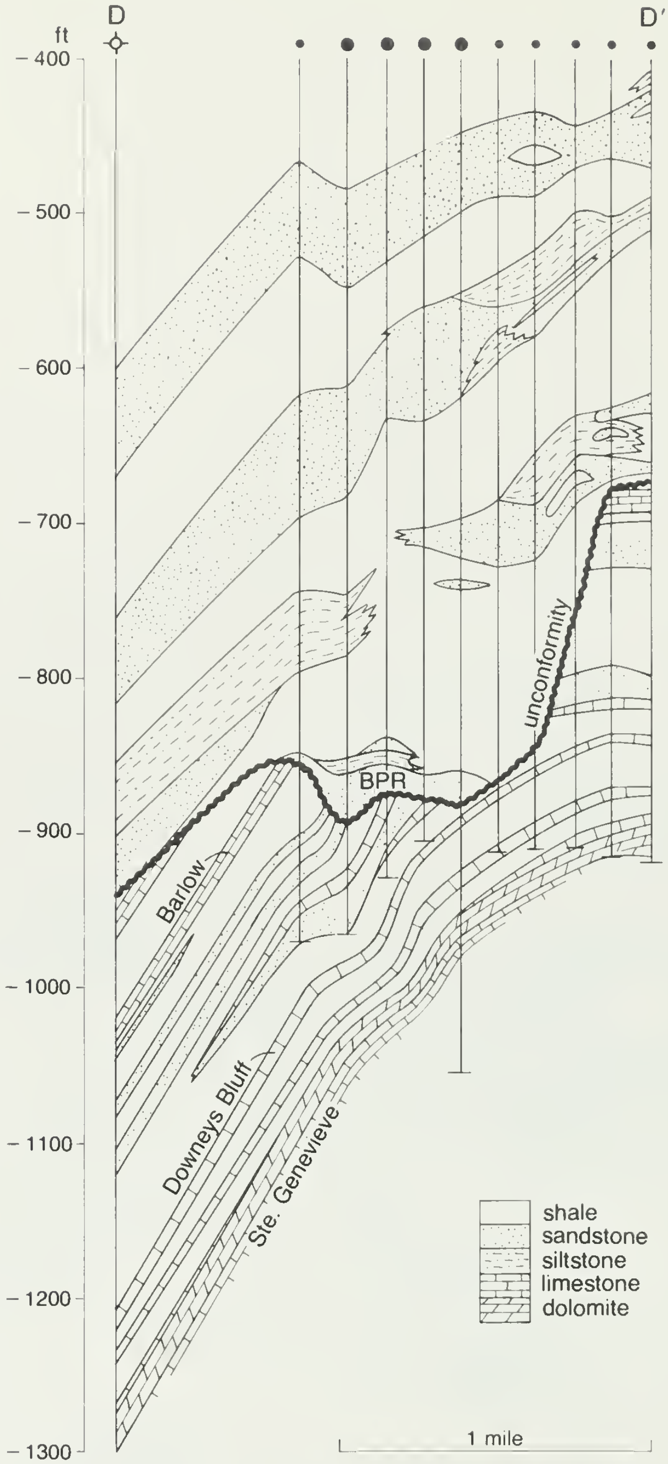


Figure 15 Cross section D-D′ (location shown in fig. 11). A relatively thick basal Pennsylvanian reservoir (BPR) is preserved along the western side of the paleovalley. Although structural deformation has severely tilted the valley to the west, deeper stratigraphic erosion of the valley immediately east of the BPR is evident. Datum is mean sea level.

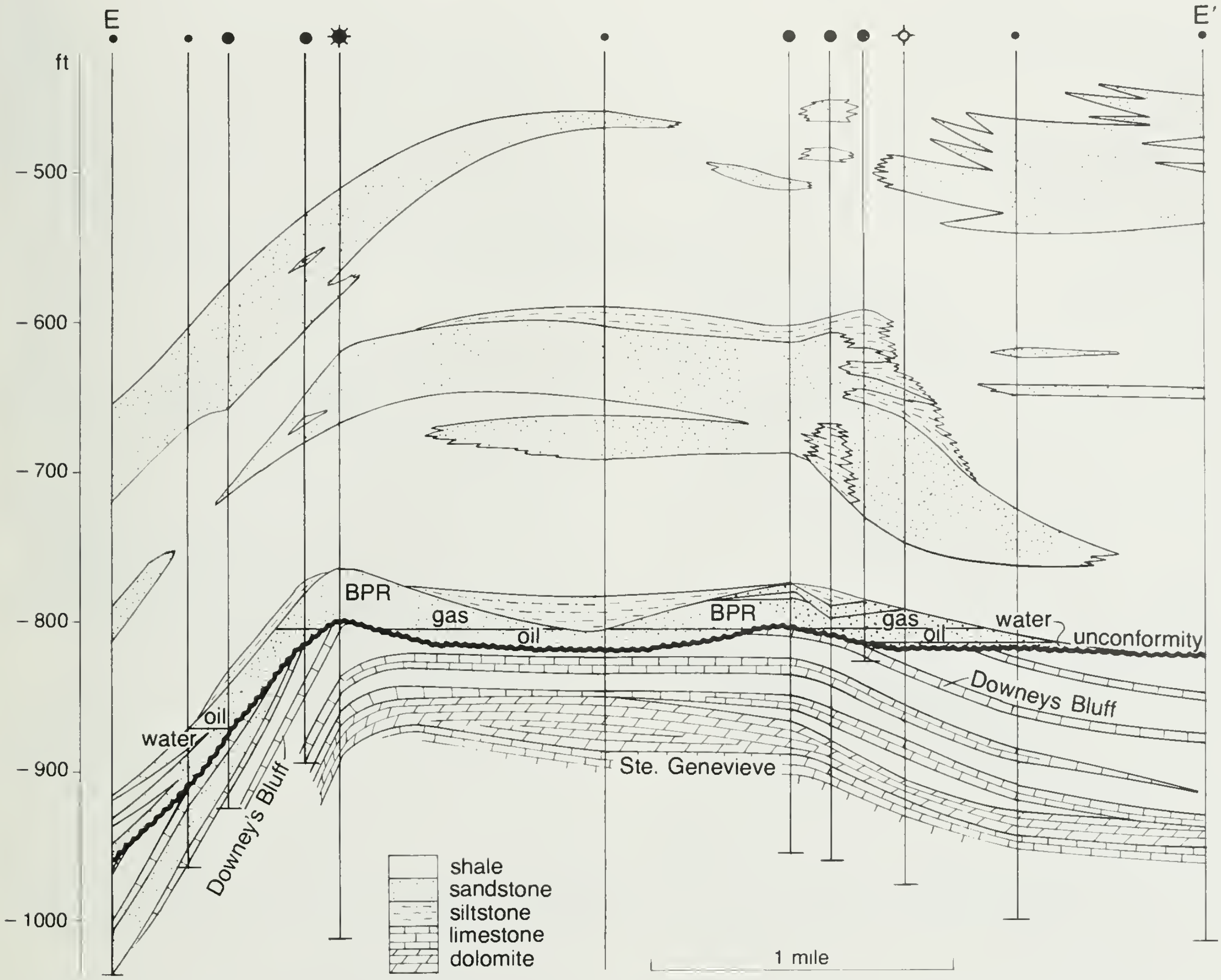


Figure 16 Cross section E-E′ (location shown in fig. 11) is a longitudinal section along the paleovalley showing the changing thickness of the basal Pennsylvanian reservoir (BPR) across the Hardinville Anticline. Note that the BPR interfingers with shales on the extreme southwestern flank of the structure. Datum is mean sea level.

EVOLUTION OF THE BASAL PENNSYLVANIAN RESERVOIR

Development and infilling of paleovalleys

During late Chesterian (latest Mississippian) time the sea that had covered most of Illinois, southwestern Indiana, and western Kentucky began to recede to the south and southwest. The ancient Michigan River System (Swann, 1963) advanced southwestward across the expanding flatlands (Pryor and Sable, 1974). As base level continued to drop, high flow rates and episodic catastrophic flooding incised an anastomosing drainage pattern on the emergent coastal plain (Howard, 1979a, b). In the study area, incision of the bifurcating valley (fig. 17a, b) was enhanced by slow uplift of the La Salle Anticlinal Belt, which had already begun by early Mississippian time (Atherton and Palmer, 1979; Clegg, 1965; Craig and Varnes, 1979). The prevalence of Mississippian slump blocks along steep-walled valleys (Bristol and Howard, 1974) suggests that the Mississippian strata were already at least partly lithified when incision occurred.

During early Pennsylvanian time the returning sea inundated the valleys progressively from south to north. As the encroaching Pennsylvanian sea entered the valley at Hardinville, gravelly sand bars were deposited along the valley floor. Final scouring occurred along the eastern, downdip portion of the valley floor (fig. 17c), leaving a 3-mile-long conglomeratic sandstone body ¼- to ½-mile wide, ranging up to 45 feet thick along the western part of the valley (figs. 8 and 9). Where marine shale was deposited over the bar, a potential stratigraphic trap was created. Where shale did not adequately seal a bar, as in the western valley of the study area (figs. 8, 9, and 14), no trap existed.

This interpretation is consistent with the results of an excellent sedimentological study by Pryor and Potter (1979), which contains abundant outcrop and subsurface data to substantiate the erosional and depositional history of a similar sub-Pennsylvanian paleovalley at the southeastern end of the Illinois Basin — the Brownsville Paleovalley in Edmonson and Hart Counties, Kentucky. Modern anastomosing river valleys in Alberta that were filled with coarse sediment during post-Pleistocene alluviation (Smith and Smith, 1980) also appear in some respects to be genetically analogous to the one that deposited the BPR.

The lack of adequate core data in the study area precludes a thorough understanding of the geometry of these basal Pennsylvanian sandstone lenses, but in the preceding core study of the #1-A Richart Heirs several fining-upward cycles were noted. Apparent clay drape separates some of these cycles locally, and can be observed in several wireline logs (e.g., fig. 7) and in the #1-A Richart Heirs core at about 1,237 feet. When the clay layers are thick enough to deter communication between otherwise vertically contiguous sand lenses, a compartmentalization of the reservoir may result that could influence oil recovery.

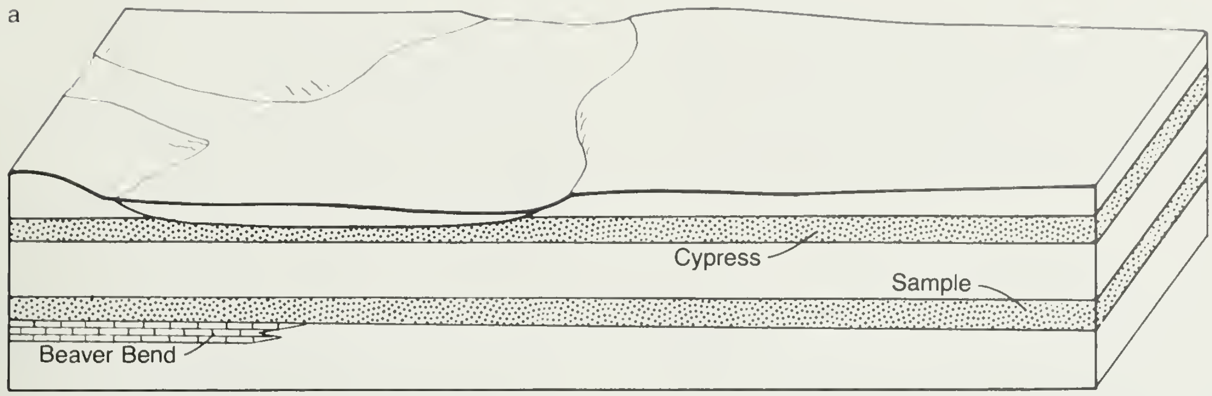
An important change in reservoir character is apparent in Section 36, where the upper portion of the BPR contains a sizable component of siltstone and shale along its eastern side (figs. 8, 9, and 16). Resultant reduction in reservoir quality there could have significantly limited hydrocarbon production.

A detailed investigation of numerous cores and logs, however, would be required to predict reservoir heterogeneity in the BPR and in similar reservoirs within the Illinois Basin. Ideal well spacing and development practices could be developed from such an investigation, which would ensure that all the isolated sand lenses, or compartments, were subject to drainage by producing wells.

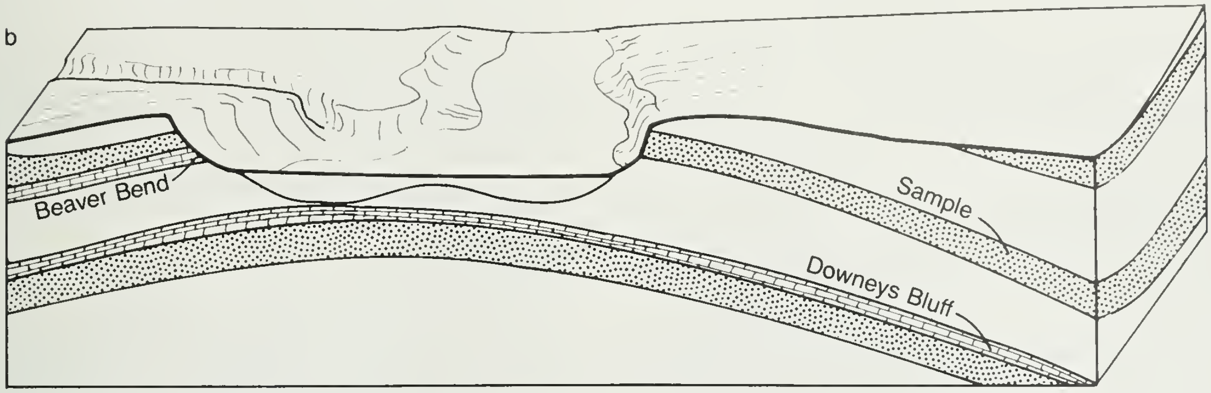
Oil migration into Pennsylvanian reservoirs

Studies in progress at the Illinois State Geological Survey suggest that Pennsylvanian shales and probably Mississippian shales as well were too immature to have generated hydrocarbons. It is apparent that most, if not all, hydrocarbons in Pennsylvanian reservoirs were generated from the Devonian-Mississippian New Albany Shale and migrated into the Pennsylvanian rocks after passing through Mississippian strata (Barrows and Cluff, 1984). Paleovalleys that have transected known hydrocarbon-bearing Mississippian units would facilitate such migration.

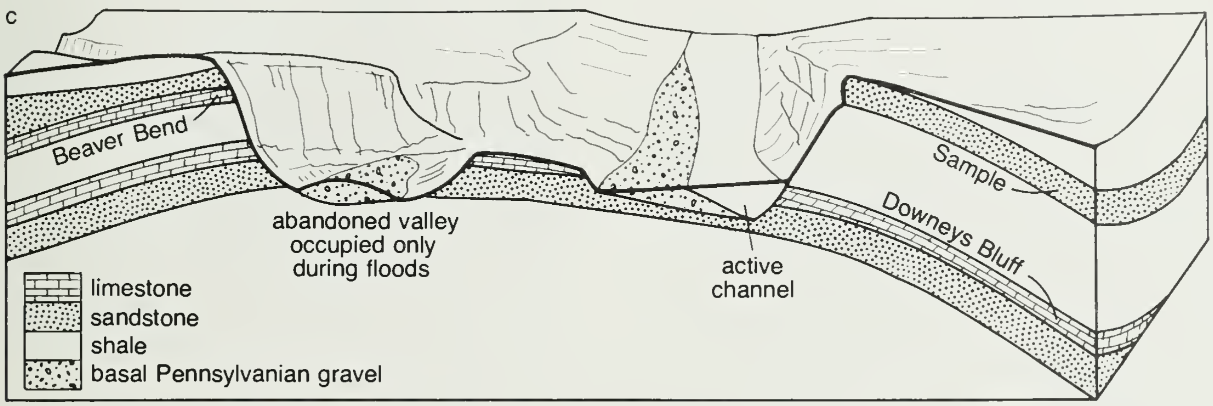
Hydrocarbon migration into the basal Pennsylvanian reservoir in the study area was probably not greatly affected by reservoir heterogeneity. As oil and gas migrated into the BPR, a gas cap began to form in the highest structural positions. The fact that the gas was unable to escape is a testament to the effectiveness of the overlying Pennsylvanian shales as a seal. The gas cap continued to grow until it encompassed enough of the highest portions of the BPR to act as a barrier to further oil migration between the southern



LATE MISSISSIPPIAN
Rivers flow across low-relief plains. Anastomosing pattern develops because of high flow rates and periodic flooding.



LATEST MISSISSIPPIAN
Slow uplift of the anticline enhances incision of rivers.



EARLY PENNSYLVANIAN
Continued incision of valleys across uplifting dome. Gravelly sand bars are deposited along paleovalleys at end of each period of high flow. Gravel and sand are carried away by continuing stream flow along lower side of valley.

Figure 17 Evolution of paleovalleys at the Mississippian-Pennsylvanian unconformity and subsequent sand bar deposition across Hardinville Anticline during early Pennsylvanian time.

and northern portions (fig. 16). Since the oil-water contact is lower in the southern portion of the BPR than in the northern portion, it is likely that the pathway for hydrocarbon migration into basal Pennsylvanian rocks was from the south. As migration continued, the southern part of the BPR filled with oil, but the gas cap prevented oil from spilling over into the northern part.

POTENTIAL EXPLORATION METHODS

The primary consideration in most hydrocarbon exploration and development within the Illinois Basin has been relative structural position of the presumed reservoir. There is high potential, however, for discovering stratigraphic traps associated with paleovalleys at the Mississippian-Pennsylvanian unconformity that are not dependent upon structural closure.

Basal Pennsylvanian fluvial sand bars deposited along the floors of unconformity paleovalleys that were subsequently filled with marine shales offer excellent potential for the development of stratigraphic traps. These traps would not be limited to locations on the crests of anticlinal structures, but rather should be scattered along the courses of paleovalleys.

This is not to say, however, that the structural history of a potential reservoir may not have significance. In fact, the geology of the hydrocarbon reservoir within the paleovalley at Hardinville reveals that contemporaneous structural movement may have had an effect on depositional patterns of sand bars along the valley. For example, the rising apex of the Hardinville Anticline (figs. 4 and 5) apparently deflected final stream flow in the paleovalley downdip against the southeast bank, where it scoured any pre-existing sand accumulation prior to marine shale deposition (figs. 8, 9, and 17c). This distribution of clastic units further reveals that exploration for basal sand bars should not be limited to the thalwegs of these paleovalleys.

In addition to basal Pennsylvanian fluvial sandstones, other potential reservoirs and traps are associated with paleovalley systems (fig. 18). If filled with shale, a paleovalley itself could seal transected Mississippian reservoir rock. Additionally, compaction over a relatively deep paleovalley may have influenced the geometry of later drainage and depositional patterns, locally resulting in "stacked sandstones" that caused compaction anticlines in younger Pennsylvanian strata.

Mapping of unconformity from subsurface data

A regional paleogeologic map of the sub-Pennsylvanian Chesterian surface in the Illinois Basin has revealed a network of anastomosing valleys (Bristol and Howard, 1971). This kind of map makes it possible to predict areas within the basin that are most likely to contain paleovalleys and associated sandstone reservoirs.

The most common method of defining and mapping a paleovalley is to interpret logs from boreholes that penetrate the Mississippian-Pennsylvanian unconformity. The absence of significant limestone within the lower part of the Pennsylvanian helps to differentiate those strata from adjacent Mississippian rocks. Since Pennsylvanian valley-fill sediments bear only an erosional relationship to adjacent Mississippian strata (fig. 6), stratigraphic positions of sandstones and shales, when compared to that of adjacent strata, may reveal a paleovalley.

It is commonly difficult to determine the exact position of the Mississippian-Pennsylvanian unconformity from log analysis alone, and is therefore advisable and sometimes necessary to examine well cuttings or cores. For example, basal Pennsylvanian sandstones, particularly in paleovalleys, tend to be much coarser than Mississippian sandstones, and commonly contain clasts of Mississippian strata.

Mapping coals to indicate unconformity paleovalleys

Compaction of Pennsylvanian shales in an unconformity paleovalley may cause subsidence of overlying strata. In the study area this subsidence is reflected in the structure map of the Colchester (No. 2) Coal Member (fig. 10), which shows a subtle syncline above the buried paleovalley.

Elsewhere in the basin, however, narrow, linear compaction anticlines rather than synclines mirror the courses of paleovalleys in strata high above the unconformity. These anticlines, which themselves commonly contain hydrocarbon traps (J. D. Turner, personal communication), have resulted from shale compaction around "stacked sandstones" deposited in low-relief valleys that had persisted through time directly above paleovalleys at the unconformity surface (fig. 18).

Seismic mapping

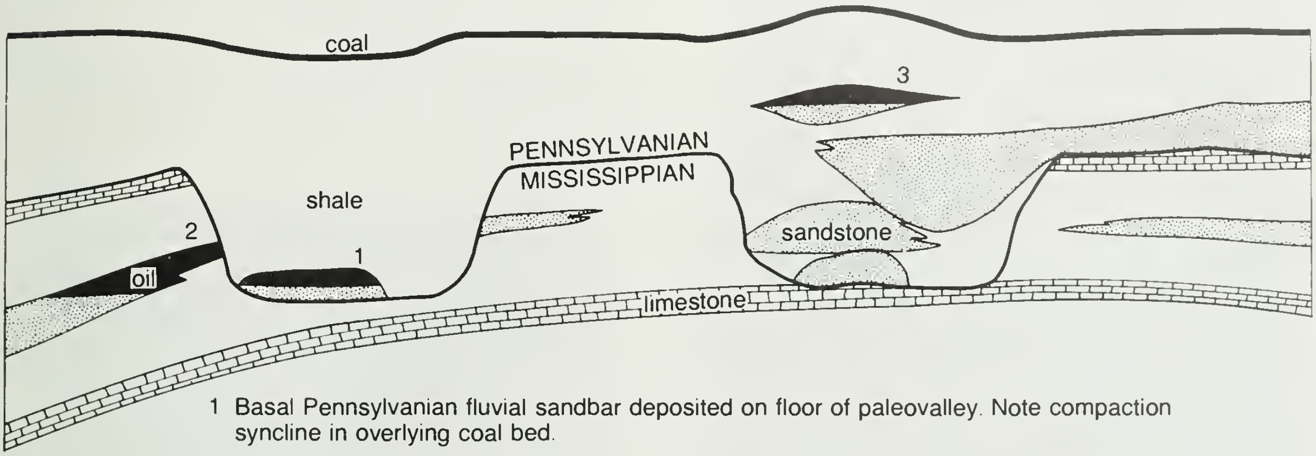
Seismic data have been used with varying degrees of success to identify and map paleovalleys in other basins. The accuracy of these data depends largely on their quality and the amount of contrast between the sedimentary rocks in the paleovalley and the strata surrounding them. For example, a valley filled with shale surrounded by dense, relatively tight limestone or sandstone may show a characteristic anomaly on good quality seismic data. Seismic studies could probably not delineate the entire course of paleovalley, however, because some lithologies occurring in and along the paleovalley may not provide adequate impedance contrast to produce good seismic reflection. Trends can be mapped, however, which should enhance exploration.

Relatively inexpensive computer modeling of seismic responses to anticipated paleovalley and surrounding lithologies is advisable for improving seismic exploration. The most accurate parameters for shooting and processing seismic data in a given area can be determined from these models and, when combined with field testing, can enhance the effectiveness of seismic program.

CONCLUSION

The play concept that has guided most hydrocarbon exploration and development in the Illinois Basin has been the anticlinal theory of petroleum accumulation. Significant reserves, however, remain to be discovered in a variety of subtle traps within the Illinois Basin. Those traps associated with paleovalleys at the Mississippian-Pennsylvanian unconformity could prove to be important targets for future oil and gas exploration.

Development of play models based on studies of paleogeomorphic stratigraphic traps such as the one at Hardinville and the use of state-of-the-art exploration methods will aid future hydrocarbon exploration in the Illinois Basin.



1 Basal Pennsylvanian fluvial sandbar deposited on floor of paleovalley. Note compaction syncline in overlying coal bed.

2 Pre-Pennsylvanian reservoir truncated by impermeable shale infilling paleovalley.

3 Anticline resulting from compaction of shales around stacked sandstones deposited within and above the paleovalley.

Figure 18 Diagrammatic portrayal of the kinds of stratigraphic traps associated with paleovalleys and their sedimentary fill.

APPENDIX 1

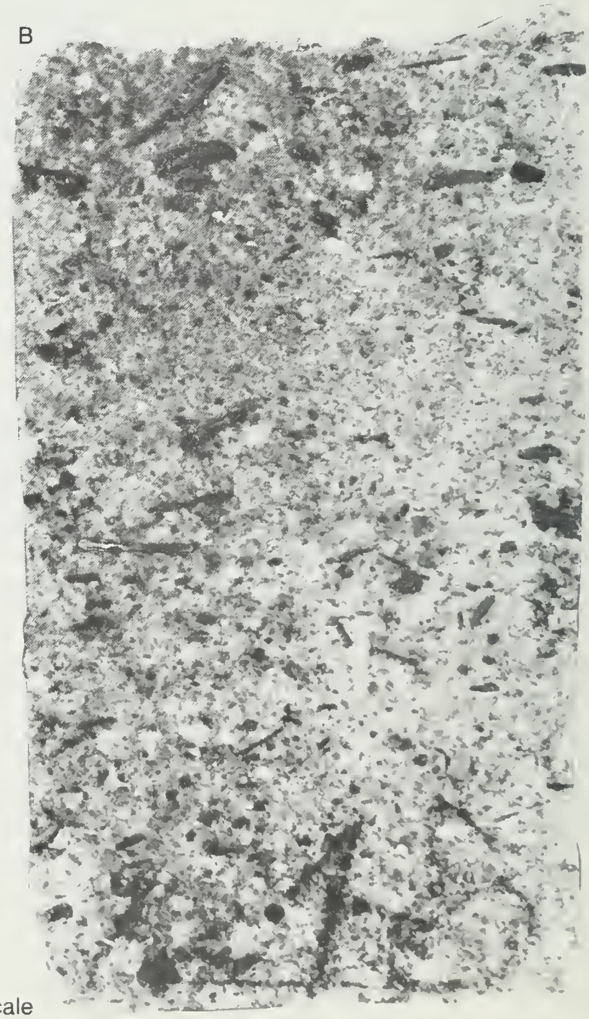
Core slabs from the basal Pennsylvanian reservoir (BPR) in the Energy Resources of Indiana #1-A Richart Heirs (380 ft NL, 330 ft EL, NE SE Sec. 2, T5N-R13W).

Upper portions of BPR display several fining-upward sequences. Slab A shows two such sequences. Very coarse, subangular-subrounded quartz grains at the base of each sequence grade upward to subrounded quartz grains of medium size; occasional quartz pebbles and clay clasts are scattered throughout.

Slab B from the lower BPR exhibits massive bedding with subangular to subrounded quartz grains ranging from pebble to medium size. Tabular shale chips are common.

A

B



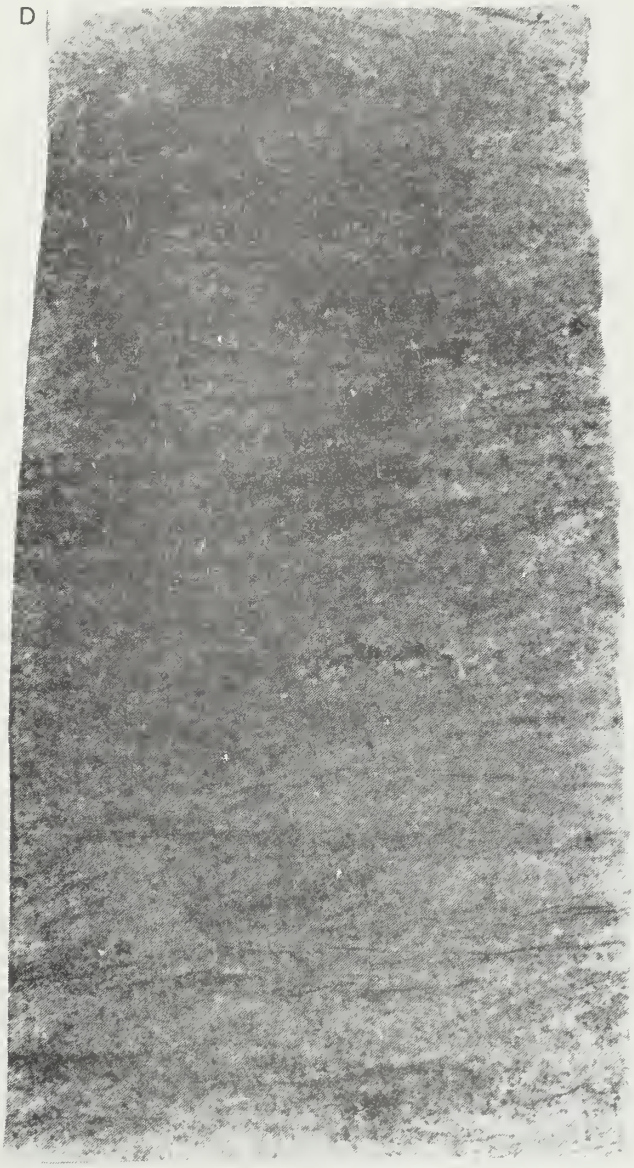
true scale

APPENDIX 2

Core slabs from Chesterian strata just below the Mississippian-Pennsylvanian unconformity in the Energy Resources of Indiana #1-A Richart Heirs (380 ft NL, 330 ft EL, NE SE Sec. 2, T5N-R13W). Wavy bedding appears throughout the shaly siltstone in slab C; black areas are pyrite nodules. Crossbedded, very fine-grained sandstone in slab D characterizes the Sample Sandstone Member.

C

D



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