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MEASURING AND PREDICTING RESERVOIR HETEROGENEITY IN COMPLEX DEPOSYSTEMS

Annual Report for the Period
September 20, 1990-September 20, 1991

By
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August 1992

Performed Under Contract No. AC22-90BC14657

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Appalachian Oil and Natural Gas Research Consortium
Morgantown, West Virginia

Bartlesville Project Office
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Prepared for
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ABSTRACT

The Lower Mississippian Big Injun sandstone, a major oil producer in the western half of West Virginia, consists of several sandstones that overstep each other from east to west. In Granny Creek field, Roane and Clay counties, the Big Injun can be subdivided into three informal units, designated A, B, and C from top to bottom, based on the bulk density log. Furthermore, the lower C unit can be divided into ascending C1, C2, and C3 subunits that overstep each other to the west. An unconformity between the A unit and the overlying Greenbrier Limestone represents an erosional episode that has progressively eliminated the A, B and C2 units eastward across Granny Creek field.

The distribution of Big Injun oil fields in south central West Virginia is influenced by geologic structure. Oil fields have been developed on the flanks of anticlines and synclines in the area, and can be observed to wrap around the nose of the Parkersburg Syncline and the northeastward plunging nose of the Warfield Anticline. Seismic data collected across Granny Creek field have good resolution in the Greenbrier-Big Injun interval and strengthen stratigraphic and structural interpretations based on geophysical logs and drillers' data.

Examination of cores and thin sections has led to preliminary interpretations of depositional environments for the Big Injun. These include distributary-mouth bars with associated distal, bar crest and back bar environments in a marine-deltaic system; and channel, point bar and chute environments in a fluvial system. Overall, the Big Injun is a medium-grained sublitharenite in which initially high porosity has been modified by compaction and diagenesis. Chlorite grain coatings helped to preserve original porosity, whereas illite promoted pressure solution during compaction, resulting in a loss of porosity. Diagenetic effects within specific environments are being evaluated to determine if environmental interpretations can be used to predict porosity preservation.

Core plugs taken from cores in Granny Creek field were analyzed for porosity and horizontal and vertical permeability. Directional permeability was negligible, but permeability does correlate with depth. Changes in permeability with depth can be related to subdivisions of the Big Injun determined from density logs. Permeability also correlated with porosity, but porosity values derived from both cores and logs show no significant correlation trend at present. A layered reservoir model is being developed to evaluate the effect of these vertical heterogeneities.

Initial attempts to characterize the heterogeneity of the Big Injun reservoir in Granny Creek field used a number of direct and indirect methods. A plot of annual production versus time reveals several production spikes that can be interpreted to be the result of introduction of new production techniques or to the discovery of a previously untapped compartment in the reservoir. Plots of the number of wells completed versus year of completion yield a series of slopes (large number of wells completed) and plateaus (few or no completions). The suggestion is made that the slope regions are analogous to spikes on the production-time graph. Location maps of wells completed during specific time intervals represented by slopes on

the completion-time curve show strong clustering trends. We suggest that the observed clustering of well completions in both time and space probably reflects the heterogeneous nature of the Big Injun reservoir in Granny Creek field.

The Late Cambrian Rose Run sandstone comprises a sequence of mixed siliciclastic and carbonate lithologies deposited on a gently sloping, rimmed continental shelf on the southwestern coast of the North American plate, called Laurentia. Facies mixing occurred at the boundaries between paralic siliciclastics, peritidal carbonates, and subtidal carbonates. The nature of the dolostones indicates that carbonate sediments developed in semi- to fully arid conditions caused by proximity of the continental margin to a subequatorial oceanic and meteorological high pressure cell between Laurentia and Gondwana to the south. Intermittent erosion of the exposed craton accounts for the deposition of subordinate quartzose to arkosic arenites.

The Rose Run sandstone gradually thickens to the east across the study area in Ohio and Pennsylvania. In eastern Ohio and northwestern Pennsylvania the Rose Run thickens from 0 ft to about 200 ft. Farther east, in central Pennsylvania, it reaches thicknesses in excess of 700 ft. In the zone where it is less than 150 ft thick, the unit is incomplete due to erosional truncation during the Early Ordovician. The erosional surface, called the Knox unconformity, developed when the passive Laurentian plate margin became convergent with the northern margin of Gondwana and uplift occurred. The newly exposed surface tilted toward the plate margin; therefore, the unconformity developed on older and older rocks from what is now east to west. In central Pennsylvania, the position of the unconformity occurs within the upper portion of the Early and Middle Ordovician Beekmantown Group, whereas in northwestern Pennsylvania and eastern Ohio it occurs on the Rose Run sandstone.

The regional structural attitude of both the Knox unconformity and the top of the Rose Run sandstone is gently dipping to the east. At a regional scale it is difficult to observe the paleotopography developed on the eroded surface of the Rose Run in eastern Ohio and northwestern Pennsylvania. However, basement-related structures such as wrench faults and growth faults developed over the Rome trough exert enough structural displacement to be seen at the regional scale.

EXECUTIVE SUMMARY

The Appalachian Oil and Natural Gas Research Consortium (AONGRC) is conducting multidisciplinary research designed to measure and predict reservoir heterogeneity in complex deposystems. Two producing sandstones have been selected for both regional and local (field scale) studies: the Lower Mississippian Big Injun sandstone in West Virginia and the Upper Cambrian Rose Run sandstone in Ohio and Pennsylvania.

During the initial year of this research, geophysical logs from nearly 1200 wells were collected for the regional study of the Big Injun along with nearly 500 logs from Granny Creek field. A series of interlocking stratigraphic cross sections was constructed that illustrates regional geometry of several sandstone bodies collectively referred to as Pocono Big Injun, and the progressive erosional truncation of these sandstones eastward. In the field scale study, digitized logs were used to construct eighteen cross sections and sandstone isolith maps of the various subdivisions of the Big Injun. The bulk density log can be used to divide the Big Injun into informal A, B and C units, with the lowermost, or C unit, representing the reservoir. The C unit can be further divided into C1, C2 and C3 tongues that overstep each other and pinch out into shales westward.

A database consisting of tops reported on drillers' logs was used to generate a regional structural map on the top of the Greenbrier Limestone (Big Lime) 100 to 200 feet above the top of the Big Injun sandstone. Anomalous well data were identified on the map and eliminated from the database before final mapping. These regional maps illustrate the strong structural control on Big Injun oil fields in the study area. Preliminary structure maps on the Greenbrier (Big Lime) surface were prepared for Granny Creek and Rock Creek fields. These maps will be revised based on seismic data and geophysical log tops.

Approximately 20 miles of existing data and 13.6 miles of new seismic data revealed several stratigraphic and possible structural changes in the Big Injun interval across the field. The surface seismic data were then supplemented with a vertical seismic profile (VSP) run in a well recently drilled in the field. The Big Injun and adjacent intervals are well defined in the near-well VSP, and possible structural and stratigraphic variability can be observed in the offset VSP's.

Preliminary study of thin sections from cores in Granny Creek field indicates that the Big Injun is a medium to fine-grained sublitharenite. The preliminary study identified six different environments of deposition whose vertical sequence is consistent with westward progradation illustrated in stratigraphic cross sections. From bottom to top these environments are distal mouth bar, crest of mouth bar, back of mouth bar, channel lag, point bar, and chutes on point bars.

Efforts in the petroleum engineering portion of the Big Injun research were concentrated on data collection and analysis. Porosity and permeability values were determined from analyzing core samples and geophysical well logs, and porosity-permeability correlations were developed. The directional variation of permeability also was investigated and found to be negligible. Computer modeling

and simulation studies were initiated and continued throughout the year. A network model of porous media was developed to study the complexity of fluid flow paths. The entrainment of solid particles was used to investigate pore size distribution in porous media.

Production data from six Pennzoil leases (249 wells) in Granny Creek field and 14 Quaker State leases (75 wells) in Rock Creek field were collected. Initial potential data for all wells in both fields in the West Virginia Geological Survey's oil and gas database were extracted to be used in geostatistical analysis and testing software. Detailed well location maps were prepared for Granny Creek field using the Survey's database and maps from operating companies. Statistical, graphics, CAD, digitization and mapping software were obtained, installed and tested. Initial potential, cumulative production, porosity, permeability, and lithofacies data will be used in geostatistical modeling. Preliminary analyses of initial potential, production and completion data were completed. Spikes on production-time curves match steep slopes on completion-time curves and are thought to represent discovery of new compartments in the Granny Creek oil reservoir. Location maps of wells completed during corresponding time intervals illustrate geographic clustering of wells. The next step will be to examine the same data set for clustering by producing depth to see if deeper or shallow pays were being discovered and developed.

The Late Cambrian Rose Run sandstone, a unit composed of interbedded carbonate rock and sandstones, has produced both oil and natural gas in Ohio and Pennsylvania since the mid-1960's. Since 1961 more than 2,000 wells have been drilled in the two states in the search for exploitable hydrocarbons in Cambrian strata. Today, drilling of the Rose Run sandstone, centered in eastern Ohio, is one of the most active plays in the Central Appalachian Basin.

Many geologic factors affect the occurrence and producibility of oil and natural gas in the Rose Run sandstone. Among the most important factors are: 1) depositional setting, including paleogeography, plate tectonic history, and paleoclimate; 2) structural setting; and 3) development of an erosion surface on the formation. The proximity of folded and faulted Rose Run sandstone to the Knox unconformity, developed by regional uplift and erosion during the Early Ordovician, has produced a paleotopography on the underlying rocks that helps control reservoir potential.

During the first year of this study, the Ohio Division of Geological Survey and the Pennsylvania Bureau of Topographic and Geologic Survey evaluated the regional aspects of the stratigraphy, structural geology, petrology, and depositional setting of the Rose Run sandstone and adjacent units. Much of the information in this report has been gained by construction and study of regional cross sections, evaluation of geophysical logs, cores, and drill cuttings from numerous wells in both states, and application of data obtained from published reports. Included in this report are a summary of the history of drilling for, and production from Cambrian strata, and an evaluation of the regional geology of the Rose Run sandstone and adjacent units.

INTRODUCTION

Non-uniform composition and permeability of the reservoir, commonly referred to as reservoir heterogeneity, is now recognized as a major factor in the efficient recovery of oil during primary production and enhanced recovery operations. Heterogeneities are present at various scales and are caused by various factors; including folding and faulting, fractures, diagenesis and depositional environment. Thus, a reservoir consists of a complex flow system, or series of flow systems, dependent on lithology, sandstone genesis, and structural and thermal history. Ultimately, however, the fundamental flow units are controlled by the distribution and type of depositional environment.

Reservoir heterogeneity is difficult to measure and predict, especially in more complex reservoirs such as fluvial-deltaic sandstones versus wave-dominated deltaic rocks. The Appalachian Oil and Natural Gas Research Consortium (AONGRC), a partnership of Appalachian basin state geological surveys and West Virginia University, is studying two heterogeneous reservoirs; the Lower Mississippian Big Injun sandstone in West Virginia, and the Upper Cambrian Rose Run sandstone in Ohio and Pennsylvania. The ongoing research is multidisciplinary and has been designed to measure and map heterogeneity at various scales, and to develop tools and techniques to predict heterogeneity in existing fields and undrilled areas. The main goal is to develop an understanding of the reservoir sufficient to predict, in a given reservoir, optimum drilling locations versus high-risk locations for infill, outpost, or deeper-pool tests.

The Big Injun sandstone is a major oil producer in West Virginia, and has been for more than 100 years. Oil is being, or has been, produced from 58 fields in the state, and gas from another 124. However, within the Big Injun oil fields, 70-80% of the original oil in place (OOIP) typically remains in the reservoir. Some of this oil may be mobil oil trapped in untapped compartments. Therefore, better knowledge of the internal makeup of the reservoirs is essential for more efficient recovery of oil.

The Big Injun is being studied at two scales: the regional scale and a local, or field scale. The regional study area included 21 counties, in which 43 Big Injun oil fields are present. Two of these fields, Granny Creek (also Granny Creek-Stockly) in Clay and Roane counties, and Rock Creek (also Rock Creek-Walton) in Roane County, were chosen for detailed geologic and engineering study.

Oil has been produced from Cambrian-age rocks in Ohio since 1909, although the initial Rose Run discovery well was not drilled until 1965. Following the discovery in Ohio, exploration activity moved eastward into Pennsylvania. Higher prices in the 1980's increased interest in the Rose Run in both states. Today the Rose Run play in Ohio is very active, but in western Pennsylvania the Rose Run is a frontier area.

The interval of the Rose Run exhibits heterogeneity on three scales: (1) megascopic, that is, it varies over a wide areal extent from limestones to dolostones to quartz and feldspathic arenites; (2) mesoscopic, in the sense that within a single well or outcrop there is considerable variation from bed to bed, with thin arenites interbedded with dolostones exhibiting highly variable characteristics; and (3) microscopic, due to local- to regional-scale variations in diagenesis. In Coshocton County, Ohio, four sandstone lenses separated by dolostone can be correlated on geophysical logs. Detailed log analysis of this interval will be tied into cores to better understand the heterogeneous nature of this reservoir. The Rose Run study is essentially a regional study of heterogeneity created by sandstone deposition and facies distribution with detailed study in producing areas.

Research Objectives

Although the two studies are being conducted separately, common objectives are shared by both, and knowledge gained is distributed to both the Big Injun and Rose Run research teams. Sandstone bodies are being mapped within their regional depositional systems, and then sandstone bodies are being classified in a scheme of relative heterogeneity to determine heterogeneity across depositional systems. Facies changes are being mapped within given reservoirs, and the environments of deposition responsible for each facies are being interpreted to predict the inherent relative heterogeneity of each facies. Structural variations will be correlated both with production, where the availability of production data will permit, and with variations in geologic and engineering parameters that affect production. A reliable seismic model of the Big Injun reservoirs in Granny Creek field is being developed to help interpret physical heterogeneity in that field. Pore types are being described and related to permeability, fluid flow and diagenesis, and petrographic data are being integrated with facies and depositional environments to develop a technique to use diagenesis as a predictive tool in future reservoir development.

Another objective in the Big Injun study is to determine the effect of heterogeneity on fluid flow and efficient hydrocarbon recovery in order to improve reservoir management. Graphical methods will be applied to Big Injun production data and new geostatistical methods will be developed to detect regional trends in heterogeneity. Geologic and engineering data on Big Injun reservoirs will be used to construct facies maps and compute the probability that new, infill wells will encounter favorable reservoir rock.

Acknowledgements

Two research teams were responsible for the production of the Big Injun and Rose Run sections of this report. A. Donaldson, assisted by X. Zou, wrote the chapter on Big Injun stratigraphy which incorporated petrologic work by R. Smosna and K. Bruner. B. Shumaker wrote the chapter on Big Injun structural geology, which included computer-generated maps prepared by G. He. T. Wilson and L. Zheng wrote the chapter on geophysical characterization. M. Heald and J. Britton wrote the chapter on Big Injun petrology. Several professors and graduate

students at West Virginia University are responsible for the chapter on petroleum engineering. K. Aminian wrote the chapter and was responsible for data collection and analysis, computer simulation, and, with T. Meloy, pore modeling research. H. Abidi and A. Rulke were responsible for data collection analysis and pore modeling research. S. Ameri, assisted by T. Gaines, was responsible for well log interpretations. H. Bilgesu was responsible for core analysis and core-log correlations with assistance from J. Garner. F. Ziaie was responsible for data collection and simulation studies, with help from W.E. Abbit, D. Zhoe, and G. Haid. J. Wasson assisted with collected data and modeling, and D. Durham assisted with data analysis and report preparation. The final Big Injun chapter, geostatistics and modeling, was written by M. Hohn and R. McDowell. L. Avary, A. Vargo and D. Matchen validated data in the West Virginia Geological Survey database, collected new data, correlated and digitized logs, described cores, and created the revised project database that is being used in the geostatistics and modeling task.

The Rose Run section of the report was written by J. Harper, C. Laughrey, and R. Riley. As with the Big Injun report, numerous individuals assisted in this research effort, including the following: A. Bailey and P. Nicklaus; database entry of well completion data; M. Baranoski and R. Riley, log correlation and digitization, data entry, and construction of cross sections and maps; G. Yates, slabbing Rose Run and Beekmantown cores; D. Carlton, petrographic study of thin sections; W. Kite, petrographic study of well cuttings; and B. Randall, correlation of the Silurian "Packer Shell" marker to be used in mapping shallow structure. The report was edited and assembled by D. Patchen and K. Gazsi.

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THE BIG INJUN SANDSTONE IN WEST VIRGINIA

Stratigraphy

Objectives

The purpose of this stratigraphic analysis is to determine lithologic characteristics that affect reservoir heterogeneity of Big Injun sandstones, specifically in Granny Creek and Rock Creek fields, and generally in the region of western West Virginia. The analysis is designed to: map the geometry of sandstone bodies within a regional depositional system and classify these bodies in a scheme of relative heterogeneity, thus determining the heterogeneity across the depositional systems; and map the facies changes within the given reservoirs, interpret environments responsible for each facies, predict the inherent relative heterogeneity of each facies, and integrate these results within depositional and reservoir models developed by project petrologists and petroleum geologists, respectively.

Regional Stratigraphy

In the regional-scale study, which includes 21 counties in West Virginia (10,528 sq. miles), 1161 wells with geophysical logs were located on a computer-created base map (Figure 1) and are the basis for analyzing the stratigraphy of the interval between the Berea Sandstone and Little Lime, which includes the Big Injun sandstones and the Greenbrier Limestone (Big Lime). Fifteen regional stratigraphic cross sections were constructed; 13 east-west trending and 2 north-south trending. The spacing between wells on the cross sections is about 2.25 miles, whereas the spacing between cross sections (north-south spacing for east-west cross sections) is 4.5 miles in the southern area, and 7 miles in the northern area. Additional cross sections planned in the northern area will make the spacing uniform throughout the 21-county area. On figure 1, the locations of 12 to these stratigraphic cross sections are indicated.

A generalized stratigraphic cross section (Figure 2) resulted from the correlation of rock units in the regional study area along profile RI-RI' (Figure 1). The Big Injun interval consists of a lower and upper Big Injun, with oil production in the Granny Creek, Rock Creek, and Blue Creek fields occurring from the lower Big Injun sandstone. The regional study indicates that the lower Big Injun sandstone pinches out toward the east as a result of the pre-Greenbrier unconformity, and to the west as a facies change to shale. Using the base of the Greenbrier Limestone (Big Lime) as the datum, the regional dip of the Big Injun and other Pocono sandstones is to the west in the study area, accounting for the progressive erosional truncations of these units eastward toward the center of the West Virginia/Pocono Dome (Donaldson and Shumaker, 1981), a growing structure during Early Mississippian time that influenced the sedimentation and preservation of Pocono Group deposits. The lower Big Injun sandstone (Figure 2) is subdivided into informal A, B, and C members by using geophysical logs in the Granny Creek field (Clay 1960 well). These subdivisions will be described in more detail in the discussion of the stratigraphy of the field.

Regional stratigraphic cross sections were constructed from digitized tracings of the gamma-ray and density logs for the stratigraphic interval of the Sunbury Shale to Little Lime. Figure 3 shows cross section RO-RO' extending about 80 miles from Jackson County eastward across the study area to Lewis County. This profile is nearly 20 miles north of the Granny Creek field (RI-RI' cross section; Figure 2), and also shows the lower Big Injun sandstone pinching out to the west as a result of facies change, and pinching out to the east due to erosion that resulted in the pre-Greenbrier unconformity. Sandstone/shale baselines are superimposed on the digitized gamma-ray logs for lithologic determinations, and the digitized density logs show superimposed baselines associating density with estimations of porosity. These relationships will be discussed later.

For a 13-county area, that includes Granny Creek field (G), Rock Creek field (R), and Blue Creek field (B) (Figure 1), sandstone isolith maps (not included in this report) were contoured for the upper and lower Big Injun and upper Weir intervals using data from 200 wells. The maps show areas where these sandstones were totally eroded, partially eroded or non eroded by the pre-Greenbrier unconformity. These sandstone isolith maps represent a "first generation" of maps, and suggest southwestward progradation of the shoreline, which migrated through what is now Clay, Roane, and Kanawha counties during deposition of the lower Big Injun sandstones.

The regional stratigraphic analysis of the Big Injun sandstones shows factors that control the position, geometry and trends of sandstone reservoirs. The next generation of sandstone isolith maps will analyze five-fold more wells from nearly twice the area of the "first generation" maps. It will then be possible to classify the regional types of sandstone reservoirs using the criteria of Donaldson and Boswell (1990).

Stratigraphy of the Granny Creek Field, Clay County, West Virginia

The stratigraphy of the Granny Creek field of Clay County is based on gamma-ray and density log signatures from 459 wells and cores from 10 wells. The field is approximately 3.4 sq. miles in area and the well spacing commonly is 400 feet. Figure 4 is a location map of wells with geophysical log data used in the study, locations of 18 stratigraphic cross sections, including stratigraphic cross section GD-GD' (Figure 5) interpreted in figure 6. This computerized map unifies the northern and southern parts of the field, previously separated into the Pennzoil (northern) and Columbia Natural Resources (southern) tracts. The data for the northern part consist of 309 gamma-ray and 163 density logs, with 150 gamma-ray and 100 density logs in the southern part. The stratigraphic cross sections mainly indicate correlation within the interval from the Squaw sandstone to the

Little Lime (LIT LIME on Figure 5), approximately 400 feet of rock section. In figure 6, the following informal members (formats) of the lower Big Injun are correlated in descending order: A member; B member; and tongues C-3, C-2, and C-1 of the C member. The pre-Greenbrier unconformity resulted in partial, then total erosion progressively eastward across the Granny Creek field such that first the A, and then the B and C-2 tongue of the C member were removed. The C member shows south-westward progradation (forward stepping) of its sandstone tongues with pinch outs of C-1 and C-2 into shales toward the southwest. Within the Granny Creek field C-3 thickens southwestward, again indicating progradation in that direction. A distribution map (Figure 7) of the lower Big Injun C tongues in Granny Creek field shows the successive westward shift of these sandstones due to progradation during deposition.

Preliminary interpretations of the depositional environments for the lower Big Injun sandstone within the oil field are delta front (distributary-mouth bars) for the C member and alluvial channels for the B and A members, based on log signatures and properties observed in cores. Smosna and Bruner (1991) also interpret the lower fine-grained C member to have been deposited in a distributary-mouth bar in the delta-front environment. They also recognized subfacies of the distal mouth bar, which is transitional with offshore prodeltaic shales; the mouth-bar crest, which is strongly influenced by waves and longshore currents; and the back of the bar, which is transitional with coarse-grained fluvial sediments. The upper facies, the A and B members, is very coarse-grained and fluvial in origin. Subfacies include a conglomeratic channel-floor lag, sandy point bar, and coarse-grained chute fills. Additional mapping of the various tongues and members within the Granny Creek field should indicate more about the geometries of these and other subfacies.

We presently recognize the generic offshore-onshore change in subfacies of a river-mouth bar from distal to proximal to bar ramp-channel. We hope that further study in the next year will allow additional distinctions about the river-mouth bar that reveal its internal heterogeneity. For example, are the mouth bars friction or buoyancy types? Were they dominated by fluvial, tidal or wave processes? Was the load suspended, mixed or bed load? Were they deposited in shallow or deep water? How did the tectonic/eustatic controls affect the preservation potential of subfacies? These factors determine the sand-body orientation as strike or dip trending; the preserved thickness of the subaqueous versus subaerial facies; the sand/clay proportions; the spacing and properties of the channel compared with the bar; the type of channel fill during active and abandoned phases; the rate and direction of progradation, the frontal compared with flanking positions; and the frequency of disconformities.

The recognition of three subfacies of the river channel facies by Smosna and Bruner (1991) from study of 6 cores is an important contribution. Additional distinctions within the fluvial facies (the A and B members of the lower Big Injun sandstone) are necessary to establish its suspected complex heterogeneity laterally and vertically. Within the Granny Creek field, are lateral changes in the thickness of the A and B members the result of differential erosion (paleovalleys interpreted from the relief along the pre-Greenbrier unconformity) or facies changes recognized by the subfacies of channel core, channel flank, and interchannel areas? The channel core subfacies seems to dominate, but within it, are clay lenses representing abandoned channels recognized? The proportion of the shale within a channel core subfacies commonly is low for braided streams and increasingly higher for meandering and anastomosing streams, mainly because of the amount of bed load carried. Reservoir properties of ancient river channels show different heterogeneities depending upon whether the river was a bedload, mixed-load or suspended-load type. Therefore, we will analyze the stratigraphic and core data to interpret the stream type. The criteria and evidence to recognize these attributes will become part of the expert systems analysis.

Porosity values were calculated for the lower Big Injun sandstone using the density logs. A table was constructed indicating the thickness of layers with porosity values >10, >13, >16 as well as <7 percent within each of the members of the Big Injun sandstone. These data will be useful in determining the lateral to lateral/vertical continuity of porosity facies between wells spaced approximately 400 feet apart. Production data should help verify the continuity of these porosity facies in three dimensions.

Two calibration experiments involving the geophysical logs were conducted. First, the percentage of sand-size particles determined by thin-section analysis (Swales, 1988) was compared with the sand/shale lines constructed on the gamma-ray logs (Figure 8). The 50% sand line of the log correlated well with the identification of sandstones from thin section analysis for grainstones and low matrix packstones, but less where the packstone contains abundant clay matrix. This analysis validated the positioning of the sand line at 50% on the gamma-ray log. In the second experiment, porosity estimated from density logs was compared with the whole-core porosity measurements reported by Swales (1988) for three Columbia Natural Resources' (CNR) cores (Figure 9). Again, this calibration exercise verified the approach we are using. Both experiments suggest that we can use grain size and porosity estimates from the gamma-ray and density logs, respectively, with confidence.

Ten stratigraphic horizons were identified using geophysical logs from wells in Granny Creek field. These data will be used in drawing structure contour and thickness maps. The ten stratigraphic horizons include the tops and bottoms of the Little Lime, the Big Lime (its bottom is the top of the Big Injun), the Squaw sandstone, and the three members of the Big Injun sandstone interval (A, B, and C). For the structural maps on the regional scale, elevations were picked for 18 different stratigraphic horizons using the tops and bottoms of the following units: Little Lime, Big Lime, Big Injun, Squaw, upper Weir, middle Weir, lower Weir, and Sunbury Shale.

Results

The regional and field stratigraphic studies established the importance of the pre-Greenbrier unconformity in locating the position of pinch outs of the upper Big Injun, lower Big Injun, and upper Weir sandstones. The lower Big Injun can be subdivided into the A, B, and C members and the C member in turn into the C-1, C-2, and C-3 tongues in the Granny Creek field. The reservoir rock in Granny Creek field, the lower Big Injun, increasingly is eroded from west to east across the field, whereas the C member exhibits progradational intertonguing with shales toward the west. The preliminary interpretations of the depositional environments for the lower Big Injun within the oil field are delta front (distributary-mouth bars) for the C member and alluvial channels of the B and A members, based on log signatures and properties observed in the cores. Various experiments verified the accuracy of our estimates of grain size and porosity from the geophysical logs.

Structural Geology

Objective

The purpose of the structural study is to define the structural parameters that affect reservoir heterogeneity in the Granny Creek and Rock Creek fields of West Virginia.

Discussion

To accomplish this objective, it is necessary to study geologic structure and the structural development of the area at both local (field) and regional scales. The basic data required to complete this study are available in several forms: (1) surface geologic maps; (2) drillers' data as reported to the State of West Virginia; (3) geophysical logs; (4) seismic data; (5) fracture data; and (6) core data. All of this information is available in the study area, but not all is of equal quality, or of equal use.

Data quality varies greatly across the study area. Geologic maps, although reliable, provide little useful information in the oil field areas because the surface rocks are only slightly deformed. The most reliable data come from subsurface information in the form of seismic records, geophysical logs and core hole data. Seismic records and core hole data are accurate and critical for the field-scale investigation, but because they only provide limited areal coverage, they are less useful in the regional analysis. Geophysical logs are numerous across the entire study area. They provide accurate information for selecting several lithologic contacts within, above and below the Big Injun reservoir. Wells with reported drillers' tops are numerous, but because several units above and below the reservoir have similar lithology, the tops of units are often misidentified by drillers. These well records are clearly the least accurate but most numerous of all the data.

Because of the nature and distribution of these data, it was decided that structure mapping would be based on seismic data and geophysical logs within the Granny Creek and Rock Creek field areas. A combination of data from drillers' logs and geophysical logs will form the basis of the regional map. It was found that only the top of the Greenbrier Group, the Big Lime, was an accurate pick by drillers, so the regional structure map is contoured on top of the Greenbrier/Big Lime approximately 100-200 feet above the Big Injun sandstone.

A serious limitation to the accuracy of the structure maps is the precision of well locations and datum elevations as reported to the state. Well data in Granny Creek and Rock Creek fields are being validated against well locations and elevations as plotted on U.S.G.S. topographic maps by personnel of the West Virginia Geological and Economic Survey. However, there is neither the time nor resources to check the thousands of wells utilized in constructing the regional map. Therefore, it was decided to simply eliminate anomalous wells from the database. Anomalous wells were identified on structure maps as contoured "bulls eyes" that placed the elevation of the Greenbrier/Big Lime top in that well clearly above or below that of adjacent wells. The overwhelming numbers of wells having nearly the same elevation on the mapped unit in this weakly deformed area made the selection of poor-quality well data quite simple. Minor errors in well elevation can not be identified in this way, so that a few of the low-relief highs and lows on the regional map may not be real.

Preliminary maps based on drillers' reported tops of the Greenbrier Group/Big Lime are shown for the Granny Creek (Figure 10), Rock Creek (Figure 11) and the region (Figures 12 and 13). These maps are considered preliminary because they use drillers' data. They will be replaced or supplemented by structure maps constructed from geophysical log and seismic data. Project Stratigraphers are presently analyzing logs from field wells at the regional scale as a part of their stratigraphic studies. When they have completed that task, we will generate structural maps of the fields and the region using log data.

Results

The results of our structural analyses suggest that there is a degree of structural control on the accumulation of oil in the Big Injun fields even though they traditionally have been considered to be stratigraphic traps. This control is most evident on the regional structural map where all fields are located on the flanks of folds directly adjacent to the synclinal axes (Figure 13). Note, for instance, that the Granny Creek field lies on the east flank of the Mink Shoals anticline, whereas the Rock Creek field lies on the west flank of the Arches Fork anticline. Perhaps the clearest example of flank production occurs on the Warfield anticline where the Hackberry Branch of the Blue Creek field wraps around the plunging end of that structure at about the -600 foot level. Oil production in Rock Creek field is another example of structural heterogeneity and flank production. In Rock Creek field, the narrow productive area wraps around the nose of the

Parkersburg Syncline and then becomes wider near the plungeout of the Milliken Anticline. It is not certain why these relationships exist and further analyses are required to assess the role that structure plays in determining the location of these fields.

Geophysical Characterization

Objectives

The data used in this study consist of surface seismic, borehole vertical seismic profiles, and downhole geophysical logs. These data were acquired to determine whether it is possible to identify stratigraphic or structural heterogeneity within the Big Injun reservoir and surrounding intervals. Deformation at all stratigraphic levels will be mapped to determine the sequential development of the area and whether timing of certain structural features relates in any way to oil production within the field.

The data will be analyzed by reprocessing and modeling. The results will be compared and integrated into the stratigraphic and structural models developed in other tasks from log correlations.

Results

Results and accomplishments of our work during the first year of the project are presented below in terms of specific research topics.

Examination of Existing Seismic Data

During our visits to local oil and gas companies, we were permitted to examine and make limited interpretations of existing company seismic profiles across the Granny Creek field and neighboring areas. This cooperation made it unnecessary to purchase speculative data from geophysical companies as originally planned. Analysis of these lines provides substantial information about the deeper regional scale structural framework of the area. Funds originally budgeted to purchase existing data will be used instead to obtain additional surface seismic and borehole data.

Integration of Seismic and Geologic Data

Stratigraphers and Structural Geologists made joint visits to Pennzoil and Columbia Natural Resources to obtain well log data and to discuss the geological and geophysical characteristics of both the Rock Creek and Granny Creek fields. Well logs collected as a result of these visits have been used to derive pseudo-sonic logs (from nuclear logs only) and to make preliminary seismic models.

A seismic modeling seminar was organized for geologists, and a deconvolution seminar was conducted for geophysicists and electrical engineers in our group. Electrical engineers will be developing a nonstationary approach to deconvolution using the vertical seismic profile data.

Seismic Survey Design

During trips to companies operating in both the Granny Creek and Rock Creek fields, the characteristics of production and the types of production problems that have been encountered in these fields were discussed with company geologists. As a result of these trips, we found that Columbia Natural Resources was drilling four-well program for a water flood in a portion of the Granny Creek field during 1991. Columbia had collected surface seismic data over the area and agreed to let us interpret these lines. Based on the active program being undertaken in this area and the cooperation of Columbia Natural Resources, we planned a set of four lines located in the heart of the field. One of these lines was located to tie into the area where the injection and production wells were located. Western Geophysical was selected to collect 13.6 miles of data over the field.

Data Acquisition

Surface seismic surveys were run in September 1990, at the beginning of the project. The locations of our seismic lines are shown on the structure map of the top of the Big Lime (Figure 14). The data were collected using a Vibroseis source (3-vibrator group) and the sweep was run from 20 to 110 Hz. The receiver layout was 120-channel asymmetrical split spread with a 110-foot group interval. A 24-phone, in-line receiver array was used. Nominal fold in the data is 30, and the sample rate was 2 milliseconds. The quality of the data in the Big Injun interval is excellent and reveals many stratigraphic and possible structural changes in this interval across the field.

Columbia Natural Resources granted permission to enter one of their new wells for the purpose of running a vertical seismic profile and collecting borehole geophysical logs. The contract was awarded to Schlumberger through Columbia Natural Resources, which retained control over the well during the logging operations.

VSP simulations were undertaken in our lab. Based on these simulations a near-well VSP (400 feet) and two long offset VSP's (1400 and 1600 feet) were shot. Schlumberger presented the results of their initial processing of the VSP data during the middle of September (1991). The Big Injun and surrounding intervals are well defined in the near-well VSP. Possible structural and stratigraphic variability can be observed in the offset VSP's. We are currently having Schlumberger undertake additional processing of the offset VSP's to obtain better resolution of these features.

Extensive reprocessing of the data collected over Granny Creek field has been undertaken. Figure 15 shows a final stack section prepared by Strata Search Inc. All lines in the survey have been reprocessed in our lab using the processing stream shown in figure 16. Reprocessing of figure 15 is shown in figure 17 and illustrates improvement in the signal-to-noise ratio and coherence of the shallow data in this area. Reflections from the Big Injun and several other geologic horizons are identified in figure 17.

Generalized Linear Inversion.

Surface seismic data were collected in the vicinity of Columbia Natural Resources' water flooding and production wells. After one of these wells was drilled, the hole was entered to complete VSP and borehole geophysical logging operations. Extensive inversion studies of the seismic data along line GC-2, which cuts across the heart of the field, are now possible.

A seismic line was obtained just south of the Granny Creek field for modeling and interpretation. Sonic and density data were available along the line providing an initial look at seismic characteristics of the Big Injun and surrounding intervals (Zou et al., 1991), and helping to explain many of the characteristics of the data over the Granny Creek field. Subsequently, further model studies were undertaken based on radiation log derived estimates of sonic velocity at several wells along the line. This procedure developed by Zheng (1991) was modified after Corley (1984). A comparison of the radiation log derived sonic log and the actual sonic log from a well in Clay County is shown in figure 18. This procedure also has been used to estimate porosity and yields measurements that are close to the measured values (Table 1).

Logs collected from wells in the field include neutron, gamma-ray and density, and many of those wells lie close to our seismic lines in the Granny Creek field. Hence, we will be able to make ties between the subsurface geology and seismic response at several locations along our seismic data base.

A model was prepared for line GC-2 (Figure 14 and 19), which passes close to the VSP well (Figure 14). The generalized velocity model is plotted in time (Figure 20) and several horizons including the Big Injun sandstone are identified. Differences in arrival time between figures 17 and 20 are due to the presence of a bulk static shift in the seismic model (Figure 20). The synthetic seismic response of this model is shown in figures 21 and 22. Comparison of the synthetic and actual data reveals general agreement along the line, and a correlation between individual reflection events and specific subsurface stratigraphic intervals including the zone of interest.

Petrology

Introduction

Cores were sampled and selected for thin sections. We experimented with different impregnation plastics and found one suitable for detailed studies of diagenetic effects. Additional samples are being selected from cores based on preliminary examination of thin sections that were prepared earlier.

Discussion

Preliminary study of thin sections from the Granny Creek field, Clay County, indicates that the Big Injun is largely a medium to fine-grained sublitharenite. The sandstone is fairly well sorted and initially had high porosity. In the high-quartz sandstone with chlorite-coated grains, good porosity commonly has been maintained (Figure 23). However, in some areas, ductile grains of shale, slate and other argillaceous grains have been compacted into a pseudomatrix, greatly reducing porosity, and locally porosity has been reduced or eliminated by quartz cement (Figure 24) especially where chlorite coatings were thin or absent.

Illite was found to be particularly detrimental in reducing porosity. Even where only small amounts of illite occurred in initially porous sandstone, porosity was commonly eliminated because of compaction attending pressure solution promoted by the illite (Figures 25 and 26). In the process of pressure solution silica was generated for cementation although the actual site of this cement has not been ascertained. The illite generally occurs near the top of the Big Injun in the Granny Creek field. Apparently this was due to infiltration of clay which formed the illite around the sand grains. Although the illitic sandstone zones are thin in the cores analyzed up to this time, thick sections of tight sandstone could occur if there were low-energy areas where fluvial and marine waters intermingled during deposition of the Big Injun.

Carbonate occurs as a replacement of detrital grains and as a pore-filling cement (Figure 27) in parts of the Big Injun. The upper part of the Big Injun sandstone near the overlying Greenbrier Limestone is typically tightly cemented with calcite. Small nodules of iron carbonate (ankerite and siderite) occur sporadically in the Big Injun, particularly in the lower part of the section. Locally, this carbonate lowers porosity to a considerable extent.

Partial or complete dissolution of k-feldspar and plagioclase occurred in most of the Big Injun (Figure 28). The resulting voids generally added 1-3% to the porosity.

Petroleum Engineering

Objectives

Initial objectives were to concentrate on data collection and analysis. Well logs, cores, core analyses, maps, and production records were collected from various sources. Core samples were analyzed to determine permeability and porosity, and logs were interpreted to determine porosity, pay thickness, and water saturations. The results of these analyses were utilized to develop core-log correlations. Modeling and simulation studies were initiated and continued throughout the year, and a network model for flow of fluid through porous rock was developed. The entrainment of solid particles was utilized to investigate fluid flow path in the porous media and pore size distribution.

Development of Reservoir Models

The objective of this subtask is to develop a systematic reservoir model for heterogeneous reservoirs, using rock, fluid, and production data for two Big Injun oil fields in West Virginia (Granny Creek and Rock Creek). Reservoir properties, as well as the results of geological studies, will be utilized for scale-up.

Efforts related to this subtask have been focused on data collection and analysis. An extensive literature review was initiated and has continued in order to document the methods used for reservoir characterization.

Data Collection

Initial effort was concentrated on acquisition of data from various oil and gas companies and geological survey records. The published literature collected, including DOE reports, was searched to compile publicly available data on both fields. Several meetings were planned with company representatives from Pennzoil and Columbia to establish a procedure to gather information from Granny Creek and Rock Creek fields. The data collected consisted of core analyses, logs, maps, and drillers' completion reports. Table 3 lists 34 wells in Granny Creek field for which log interpretations or logs are available, including 18 wells for which core data are available. Table 4 lists 25 Granny Creek field wells for which cores or core data are available. Maps gathered or generated are listed in Table 5.

A limited amount of production data were collected from oil and gas companies and the geological survey for the Granny Creek field. Some of the production records available are shown in Table 6.

Data Analysis

Data from Granny Creek field were studied first. Core analyses data were available for 22 wells, whose locations are shown in figure 29. Analyses for permeability, porosity, grain density, and saturation values were determined by Core Laboratories on most of the cores shortly after they were taken from the wells. Because no information was available for the core sampling procedure, the saturations are believed to represent the surface conditions after samples were brought to the surface. Analysis showed that the directional permeability variations were negligible in most of the wells. Permeability values for wells with permit numbers 1107 and 1130 were plotted as a function of depth and shown in figures 30 and 31. Some of the wells showed relatively good porosity - permeability correlation (Figure 32).

Three wells in Granny Creek field were cored but no laboratory study was performed by the operator for permeability and porosity determinations. After these three cores (permit nos. Clay 1110, 1133, and 1134) were sampled for thin section studies, plug-size cores were taken from the full-size cores. The plug-size cores were cleaned using the centrifuge extractor available in the Reservoir Engineering Laboratory of the Petroleum and Natural Gas Engineering Department of WVU. Porosity measurements were performed on the cores at the designated intervals shown in Table 7. The Helium Porosimeter was used in the determination of the porosity values.

Well logs were interpreted to determine porosity, saturation and formation thickness. Well log analyses were performed only on those wells with available density and induction logs. This was necessary to obtain bulk density and porosity in order to determine water saturation. The following assumptions were made in the log interpretations: water resistivity to be 0.05 ohm-m; fluid density to be 1.0; and matrix density as stated on the Compensated Density Log.

Some of the problems that were encountered included rugose wellbores and the absence of well logs. Some of the density logs did not include the matrix density, and as a result, only partial analysis was possible. In most cases, it was not possible to utilize core analysis results in log interpretation. When using the matrix density from core analysis, a negative porosity value resulted that could not be corrected without a neutron log, and neutron logs were not included in the suite of logs run on the majority of the wells.

The results of the log interpretations for those wells that have a complete suite of logs have been utilized to develop core-log correlations. Porosity values from the cores and logs were studied for a possible correlation. However, porosity values from cores and logs show no significant correlation trend at the present. This is attributed to inclusion of all data points for comparison without delineation of the different zones in the Big Injun sandstone. This conclusion also is an apparent contradiction of the conclusion that in some wells, porosity as measured from whole cores correlates well with porosity estimated from the density log (Figure 9). However, in our core-log interpretations, porosity determined from whole cores or core plugs was compared to porosity determined by evaluating all available logs (density, neutron, etc.) not just the density log which yields only an apparent porosity.

Oil Recovery and Reservoir Management

The objective of this subtask is to study and understand the influence of heterogeneity on hydrocarbon recovery. Specifically, the effect of reservoir heterogeneities on fluid movement and redistribution after long shut-in period (or abandonment) has been under study.

Simulation studies designed to gain better understanding of fluid movement and distribution through a heterogeneous reservoir were initiated and progressed throughout the year. The PC version of BOAST II was obtained and utilized for preliminary simulation studies. This version is a recent release by the Department of Energy that was designed to overcome the limitations of the original BOAST yet fit on a personal computer.

A literature review relative to the capillary effects on fluid movement in porous media was conducted. The results of the literature review were utilized in characterizing heterogeneity in the reservoir models.

A 2-dimensional grid model was utilized to study the effect of areal heterogeneities on fluid movement. Preliminary results of the simulations indicated that relative permeability as well as capillary effects play a major role in fluid movement and distribution. A layered reservoir model is currently under study to evaluate the effect of vertical heterogeneities. The modeling and simulation studies, however, continued at a slow pace due to computer limitations. With the availability of a new computer workstation, simulation studies can be conducted at a much faster pace.

Predicting Porosity and Permeability

The objective of this subtask is to determine the effect of shape on porosity and permeability, and its influence on fluid movement in porous media.

An understanding of the mechanisms and flow paths of fluids in permeable rock is important if greater recovery is to be realized from the reservoir. The complexity of porous rock makes an exact description of its structure impossible. Studies of pore structure for sedimentary rocks by Selley (1985), have revealed that sandstones and limestones often exhibit a network of large pores that are connected through long and narrow connections or, more precisely, ostioles.

Pore Model

In this study, a network of interconnected pores has been developed as a potential model to approximate the porous medium. The model consists of a regular matrix of pores that are connected by different size ostioles (Figure 33). Four ostioles are connected to each pore (Figure 33), yielding a coordination number of four. In an actual porous rock, the ostioles have different shapes and sizes. However, the size of the all ostioles together can be described with a probability distribution. In this model, ostioles were assumed to be cylindrical in shape and have the same length and differ from one another only in radius size. Monte Carlo simulation was utilized to assign the size to each ostiole based on an assumed ostiole size distribution. Four different ostiole size (radius) distributions were considered in this study: rayleigh, lognormal, gauss, and exponential. The distributions are illustrated in figure 34 as a function of dimensionless radius. The different distributions have been normalized such that the area under each distribution is equal to 1.

A 2-dimensional pore network of 20 X 20 pores (Figure 35) was utilized for preliminary evaluations. To avoid edge effects, the two vertical edges were connected, so that the pore model represents the surface of a cylinder. The dimensionless boundary pressure conditions for this model were 100 at the top and 0 at the bottom of the cylinder. The pores are assumed to be considerably larger in size than the ostioles. As a result, all flow resistance lies in the ostioles. The fluid flow conductivity for ostioles is the reciprocal of flow resistance and can be determined from Hagen-Poiseuille's equation. The ostiole conductivity values for an ostiole-size distribution were stocastically assigned to the ostioles.

The fluid-flow rate between two pores was calculated from the pressure difference between the two pores and the ostiole conductivity. The porous rock network model is analogous to a resistor network. The current (fluid flow) was calculated from the voltage (pore pressure difference) and the resistance (reciprocal value of the conductivity). Kirchoff's law was used to calculate the total fluid flow for all serial and parallel ostiole paths in the porous rock.

A point of disagreement between several authors is the question of whether a 2- or 3-dimensional model is to be used for modeling porous rock. Constantinides and Payatakes (1989) stress the use of a 3-dimensional network because of its ability to bypass flow around areas of low permeability. Rege and Fogler (1988), however, encouraged by the agreement of their simulation results of a 2-dimensional model with experimental 3-dimensional data, emphasize the accuracy of their model. During this study, a 2-dimensional model was utilized.

Particle Entrainment in Porous Media

To study and understand the complexity of flow paths, it was assumed during the simulation runs that the fluid entering the pore model contained solid particles. The particles were assumed to be mono-sized and spherical in shape. Two situations may occur when a particle flows through the pore model. First, a particle finds a path consisting of large ostioles. In such a case, the particle flows through this path and leaves the pore model with the fluid. Second, a particle encounters a small ostiole in its path. In this case, the particle plugs the ostioles mechanically (size exclusion). A particle can plug any ostiole that is equal or smaller in size. Once an ostiole is plugged, its conductivity is assumed to reduce to zero. Permeability and consequently the fluid flow rate through the pore model, is reduced with the plugging of an ostiole. With sufficient number of large particles in the fluid, permeability will become negligible.

The plugging of ostioles by particles is referred to as the percolation process. (Kirkpatrick 1973). A more accurate approach to determine the flow path of a particle, introduced by Rege and Fogler (1987), is to use "flow-biasing". A flow-biased model assumes that the probability of a flow path of a particle is stochastic, but proportional to the fluid flow rate.

A Monte-Carlo simulator was developed to simulate the flow of mono-sized particles through the pore network with an assumed ostiole size distribution. The four previously mentioned ostiole size distributions were investigated. The flow path of a particle through the pore network was determined by the "flow-biased" model. The disturbance of the fluid flow pattern within a pore due to particle motion was neglected in the model.

If a particle plugs an ostiole, the conductivity of the ostiole reduces to zero. This is equivalent to removing that ostiole from the network (percolation process). With each plugged ostiole, the pore pressures and the flow rate change and must be recalculated. It is reasonable to express the size of the particles relative to the size of the ostioles in the network in a dimensionless form. This dimensionless form is the percentage of ostioles that are equal or smaller in size than the particle. Per definition, this is referred to in this study as "% small ostioles". In this manner, different ostiole size distributions can be compared with each other. For every ostiole size distribution, the sizes of the particles were chosen such that the "% small ostioles" increases by 5% increments after each run.

Simulation runs were done for different particle sizes. Each series of simulations started with an unplugged network. The simulation runs began with the injection of particles into the network. The decline in fluid flow rate can be translated into network permeability reduction. The permeability reduction was determined as a function of the number and size of the particles. In addition, a percolation threshold for complete flow blockage in the porous media was determined. The injection of particles was terminated when one of two criteria was fulfilled: no more fluid-conducting ostioles that are equal or smaller in size than the injected mono-sized particle were left in the network; or the permeability of the porous rock was reduced completely and the percolation threshold was reached.

A series of permeability reduction curves was calculated for different particle sizes for the ostiole size distributions. All following figures show the average results of 15 simulation runs. This was necessary to obtain reliable average results from the Monte-Carlo simulation. A correlation between number and size of particles and the permeability reduction was found for each ostiole size distribution. The percolation threshold was evaluated in the form of a probability distribution versus the "% small ostioles" as illustrated in figure 36.

Discussion and Results

A number of questions should be considered. First, what percentage of ostioles can actually be plugged by a certain series of mono-sized particles? The answer is obvious for the cases of a dimensionless particle radius of 0 and 1. A particle radius of 0, i.e. "0% small ostioles", cannot plug any ostioles. Conversely, a particle that is larger than all ostioles plugs the first ostiole it encounters. In the case of the 20 X 20 pore network, it is 2.5% of the ostioles. Second, how many ostioles can be closed with particles of a size value between 0 and 1? During the simulation, the percentage of plugged ostioles was calculated and figure 37 shows the results. The curve has a maximum at around 40%. For the "% small ostioles" smaller than the maximum, almost every small ostiole can be plugged. For percentages higher than 40%, the filter effect becomes visible. This is because the density of small ostioles in the network increases. Therefore, the probability for a particle to encounter a small ostiole on its path also increases. Consequently, the plugging of ostioles occurs progressively in the first pore layers. Again, as for the percolation threshold permeability, there seems no influence of the ostiole size distributions on the result. Third, how does the permeability decline versus the percentage of plugged ostioles? This is an important question for forecasting and evaluating formation damage by particle entrainment. Figure 38 shows the permeability for the four ostiole size distributions. The legend presents the "% small ostioles". For example, figure 38 shows the permeability reduction for the Gaussian ostiole size distribution. If particles that are larger than 45% of the ostioles are present in the pore network, they will reduce the permeability to 20%. During the simulation, all data for the permeability were stored as a function of number and size of injected particles. Another form of display for the permeability can be observed in figure 39. These series of curves show the effect of increasing the number of injected particles on permeability. The legend tells the number of injected particles. The first step for a future experiment should be to try to realize the permeability reduction for an infinite number of mono-sized particles.

Finally, figure 36 shows the comparison of the four permeability reduction curves for an infinite number of injected particles. This graph shows very clearly how permeability reduction of the different ostiole distributions varies with particle size. In figure 36, one observes that permeability vanished after the size of the injected particles was larger than about 65% of the ostioles. This was true for every ostiole size distribution. Figure 41 displays cumulative distribution curves of the ostiole size distributions. Comparing figures 40 and 41 provides excellent insight on the impact of different ostiole distribution on permeability. Ostiole size distribution in porous rock has a major impact on permeability reduction.

Geostatistics and Modeling

Objectives

Major goals for the year were to collect pertinent data; perform preliminary analyses of initial potential data; and study historical production and completion trends.

Results

Data Collection

Collection of production data was difficult to complete. We have received cumulative production records and initial potentials for 249 wells on six Pennzoil leases within the central and northern parts of Granny Creek field. We also obtained cumulative production records for 75 Quaker State wells within the Rock Creek field. Additional production data have been requested from Quaker State. We extracted all initial potential data for the two fields under study from the oil and gas database at WVGES for preliminary geostatistical analysis and software testing. Data collection will continue until all sources of production data have been investigated or exhausted.

All pertinent data in the oil and gas database at the West Virginia Geological and Economic Survey were verified. Locations of all Granny Creek (Figure 42) and Rock Creek wells were plotted as they appear in the WVGES oil and gas database; the map for Granny Creek was compared with base maps received from Pennzoil and Columbia Gas, and well locations were corrected as appropriate. Well locations, permit numbers, and company numbers were distributed to researchers for the other tasks. A base map for Rock Creek field was requested from Quaker State. Information on well completion, owner, oil pays, stratigraphy, and well locations for Granny Creek and Rock Creek wells in the WVGES oil and gas database were checked and updated. Work is complete except for comparison of database well locations and company base maps for Rock Creek field.

Twenty-nine Big Injun cores from Granny Creek, Rock Creek and Blue Creek fields were examined and described, and core logs were distributed to other project members. Porosity and permeability analyses for cores in Granny Creek field were examined, and arrangements were made for the collection of new data from existing cores.

Geostatistical Analysis

Preliminary variogram analysis was performed on initial potential data (open flows) from both the Granny Creek and Rock Creek fields. It was found that the variogram ranges were about two kilometers, which means that initial potentials are statistically uncorrelated beyond this distance. Maps of kriged estimates showed an increasing trend in initial potential from south to north in Granny Creek field. Rock Creek field exhibited scattered regions of higher than average open flows. These results are strictly preliminary, and could change with more or better data.

Reservoir Characterization using Production and Completion Data

Geostatistical modeling of a heterogeneous reservoir requires the use of mathematical equations and computers. Preliminary quantification of heterogeneity is necessary because this dictates boundary conditions, complexity of the model, and computer power required to solve it. One of our goals in this portion of the project is to test methods for preliminary assessment of heterogeneity that can be performed at an early stage of the reservoir investigation (before recourse to conventional stratigraphic techniques). Using the Big Injun as an example, we will analyze petroleum production records and petrophysical and engineering data for the Big Injun; demonstrate heterogeneity of the Big Injun reservoir properties; and investigate the correlation between lithologic/stratigraphic heterogeneity and heterogeneity in production.

We have attempted to follow the lead of the Texas Bureau of Economic Geology (R. Finley, 1989) and the Illinois Geological Survey (Leetaru, 1991) in utilizing field production data to assess reservoir heterogeneity. This technique involves graphing production for the entire field throughout its lifetime. Production data are summed by year (or better, by month) and then plotted against time. One then examines the resulting graph for local maxima or "spikes" representing increases in production that go against the general trend of decline for the field.

The underlying assumption for this type of analysis is that production spikes are the result of some combination of new production/recovery techniques (acidization, fracturing, fluid injection) and the discovery of untapped compartments of production within the reservoir. For this analysis to succeed, it is crucial to have detailed production data for the field throughout its entire lifetime. Furthermore, these data need to be recorded for as "fine" as possible increments of time - yearly values are the minimum, workable samples. Additionally, it is necessary to have knowledge of the history of drilling for the field, especially in regards to the introduction of new techniques that may have led to enhanced recovery or improved success in well completion.

The Granny Creek field is a relatively old field discovered in the early 1900's. It has been under the supervision of various West Virginia agencies throughout most of its lifetime. Consequently, good information is available on well completion and the associated drilling/production techniques used. Unfortunately, detailed production data have not been collected by the State, and we are forced to rely on company production records. Our current database for the Granny Creek field contains approximately 700 wells. Pennzoil has provided us with cumulative, yearly production values for six leases within the central and northern portion of the field. These six leases account for 249 wells, approximately one third of the wells within the field. Ideally, it would be desirable to have production data broken down by well for each year, but unfortunately, the Pennzoil data are cumulative by lease.

Pending the acquisition of additional production data from Pennzoil or other companies operating within Granny Creek field, we have attempted to perform an analysis of heterogeneity using the existing data. Figure 43 shows a plot of total yearly production of the six Pennzoil leases through time. Examination of the figure shows four spikes in production approximately centered at years 1941, 1965, 1971, and 1983. The more recent, local increases in production may be due, at least in part, to the introduction of secondary recovery techniques in the 1960's and 1970's and to increased production from existing wells due to favorable economic conditions in the 1980's. The discovery of previously untapped, productive units within the Big Injun may also contribute to the number an amplitude of spike found on the graph. However, without additional and more complete production records for the field, it is difficult to prove reservoir heterogeneity from this figure.

Two types of information that we do have in abundance are well locations and date of completion. A search of our oil and gas PAYS database yielded 338 wells within the Granny Creek field producing or having produced oil or oil and gas from the Big Injun interval. The distribution of these 338 well completions through time is shown in figure 44. Figure 44a is a cumulative frequency plot of well completions versus year of completion. Examination of this figure shows that it is composed of a series of slopes (indicating the completion of a number of new wells during a specific time period) and plateaus (indicating no or few completions during a specific period). Comparison of figure 43 to figure 44a shows a rough correspondence between the timing of production spikes and the slope regions on the well completion curve. This correlation will be investigated more fully as detailed production data become available.

Figure 44b represents the same data set presented in the form of a frequency spectrum - total number of wells completed in each year. Because the time axes for figures 44a and 44b are identical, it is possible to directly compare the two figures. Note that the periods of increase slope in figure 44a correspond to "clusters" of well completions in figure 44b. Plateaus in figure 44a correspond to low or no activity in figure 44b. Again, we suggest that these clusters of well completions may be comparable to spikes on the production-time graph (Figure 43). Periods of renewed drilling activity within an existing field may be spurred by a number of reasons, not all of which are logical or scientific. Economic conditions, lease situations, rig availability, and the price of oil are only a few of the "intangibles" that may be responsible for increase or decreased drilling. We believe that restricting analysis exclusively to completions of <u>producing</u> wells will minimize the effects of random or "roll-of-the-dice" wildcatting activity which may yield completed wells which are unproductive. In short, we believe that the clusters of well completions seen during the history of the Granny Creek field are the result of the same factors responsible for the spikes in the production-time graph - introduction of new techniques and discovery of new production compartments.

If the Big Injun reservoir in Granny Creek is really a mosaic of compartments, these compartments must be distributed in some fashion in space (geographical location) and depth. Consequently, discovery of a new producing compartment by exploratory drilling should result in a group of well completions clustered in time, space, and depth. We have observed clustering in time. The next step is to examine clustering of well completions in both time and space - checking to see if a group of wells drilled at approximately the same time also are drilled in approximately the same location within the field.

Figure 45 shows the geographical locations of the 338 Big Injun wells completed in the Granny Creek field through time. Each of the six maps shows the locations of all wells drilled during each of the time clusters suggested by figures 44a and b (field discovery: 1920-1936, 1936-1946, 1946-1967, 1967-1974, 1974-1981, 1981-DATE). Examination of each of the maps in figure 45 shows a few wells that appeared to be "scattered" at random throughout the field and a tighter geographic clustering of wells. We suggest that the observed clustering of well completions in both time and space is more than coincidence and probably reflects the heterogeneous nature of the Big Injun reservoir.

The next step in this indirect characterization of heterogeneity will be to examine the same data set for clustering of depths of producing interval. If groups of wells that cluster in time and space are found also to be clustered in depth, this will strongly suggest that production in the Big Injun reservoir is compartmentalized. Application of the same analytical technique to Big Injun wells in the Rock Creek field may prove even more useful because the number of wells is larger than for Granny Creek field. We also would like to try this analysis on data from Texas or Illinois that has previously been analyzed using the production-time method. Such a cross-validation is necessary if the proposed method is to be used as an alternative or adjunct to production-time analysis.

THE CAMBRIAN ROSE RUN SANDSTONE OF EASTERN OHIO AND WESTERN PENNSYLVANIA

Introduction

The purpose of this portion of the annual report is to summarize work accomplished during the first year of the study on the identification and description of the regional stratigraphic, petrographic, and structural relationships of the Cambrian Rose Run sandstone in Ohio and Pennsylvania (Figure 46). The Rose Run sandstone has yielded significant amounts of commercial hydrocarbons from wells in both states, making it a viable target for continued exploitation throughout the region. To date, 99 percent of the drilling activity has taken place in Ohio and, with the exception of two wells in northwestern Pennsylvania, all of the productive wells occur in Ohio. At present Ohio drillers consider the "Rose Run play" one of the most interesting prospects in the Appalachian Basin.

The interval of the Rose Run sandstone exhibits heterogeneity on three scales: 1) megascopic, that is, it varies over a wide areal extent from limestones to dolostones to quartz and feldspathic arenites; 2) mesoscopic, in the sense that within a single well or outcrop there is considerable variation from bed to bed, with thin arenites interbedded with dolostones exhibiting highly variable characteristics; and 3) microscopic due to local- to regional-scale variations in diagenesis.

The typical Rose Run sandstone in the subsurface of eastern Ohio and western Pennsylvania consists of a series of interbedded dolostones and quartz or feldspathic arenites that occur within the Knox Group of Ohio and Kentucky, and within the upper portion of the Gatesburg Formation of Pennsylvania (Figure 47). The Knox Group in eastern Ohio is an Upper Cambrian and Lower Ordovician unit that is laterally equivalent with, from top to bottom, the lower portion of the Beekmantown Group (Lower Ordovician) and the Mines, upper sandy, and Ore Hill members of the Gatesburg (Upper Cambrian). Because the Knox and Gatesburg are not completely correlative, extensive use of these terms can cause considerable confusion (see below). The term "Rose Run", therefore, is a very convenient stratigraphic name to use.

The Knox Group and Gatesburg Formation consist primarily of dolostones but include important beds and facies of sandstone, limestone, and evaporites that occur in various areas of the basin. Throughout much of the Appalachian basin the top of these formations is truncated by a regional erosional surface called the Knox unconformity. It is the juxtaposition of folded and faulted sandstone and dolostone beds beneath this unconformity that creates the Rose Run reservoirs.

Summary of Historical Production

Although oil had been found in Cambrian rocks of Ohio in limited quantities prior to 1900, the discovery of oil near Tiffin, Pleasant Township, Morrow County in 1909 initiated a small flurry of activity throughout much of the central part of the state (Dolly and Busch, 1972). Between 1909 and 1938 Cambrian oil production was characteristically small (IP's of 25 to 100 bbl/day), and accompanied by produced brines. By 1940 the Cambrian section had virtually fallen into disfavor with the Ohio oil and gas industry.

A resurgence of interest in the section occurred in the early 1960's due to significant discoveries in Ontario and Ohio. Discovery of the Gobles oil field in Cambrian sandstones of Oxford County, Ontario again stimulated interest in this portion of the geologic section in 1960. A year later United Producing Co. completed the #1 Orrie Myers well in Canaan Township, Morrow County, Ohio. According to Dolly and Busch (1972, p. 2336), this well was completed in a 123-ft section of vuggy dolostone (2,908 and 3,031 ft.) with an open flow of 200 bbl per day of 39° API gravity oil. Ultimate recoverable reserves for this well were estimated as high as 800,000 bbl. This discovery set off such an understandable flurry of interest in the Cambrian rocks of Morrow County and adjacent areas that between 1961 and 1964 1,610 wells were drilled in search of exploitable reserves; 1,340 wells were drilled in 1964 alone. So many wells were drilled, many at such close spacing and with so little regard for conservation, that the Ohio Division of Mines (regulatory predecessor of the Ohio Division of Oil and Gas) had to adopt new oil and gas regulations.

The discovery well for the Rose Run sandstone in Ohio, the Kin-Ark #1 Reuben Erb well, was drilled in 1965 in Clark Township, Holmes County. It penetrated 110 ft of the "Rose Run" and was completed with an initial daily production rate of 2.7 MMcfgpd. After the first six years of production, this well had produced approximately 831 MMcfg (Janssens, 1973).

During this period, the excitement of the Ohio Cambrian play spread out into neighboring states. In northwestern Pennsylvania the Cambrian had been tested as early as 1941, but without success. Sporadic drilling between 1941 and 1963 resulted in thirteen wells in western and central Pennsylvania, but none of these had more than an interesting show. With the excitement over Cambrian production in Ohio as a spur, Pennsylvania's oil and gas industry, particularly Transcontinental Petroleum Corp. and James Drilling Co., initiated drilling programs that eventually resulted in 22 wells being drilled between 1963 and 1966. Of these, two wells produced hydrocarbons and several others had significant shows.

The first successful well, the Transamerican Petroleum #1 Scull, drilled in Spring Township, Crawford County in 1964, had an untreated open flow of 2.59 MMcfgpd and 6 bbl/MMcfg of condensate from the interval 6,308 to 6,311 ft. The well was produced with high back pressure for 18 months. The well was then shut in for two months, and when it was reopened the flow of hydrocarbons had been replaced by water. The total production from the well was 190 MMcfg and 1,100 bbl of condensate (Harper and others, in press).

Since 1966, only 18 additional Cambrian tests have been drilled in Pennsylvania with only two successes (both produce from the Beekmantown Group). Three or four of these wells were drilled in central and eastern Pennsylvania as unsuccessful tests of the Eastern Overthrust Belt.

Interest in Cambrian production occurred once again in the late 1970's and 1980's as a result of higher prices for both oil and natural gas, and the discovery of some very high-reserve wells. This interest continues today as Ohio drillers put down record numbers of holes. From 1980 until 1990 the increase in drilling for Cambrian prospects has been three fold (Coogan, 1991; Figure 48). Of 387 wells drilled to the Rose Run in Ohio during the period 1987-1990, 107 (28 percent) were considered productive. Unproductive Cambrian wells are commonly plugged back and treated in either the Lower Silurian Clinton sandstone (= Medina Group) or the Lower Mississippian - Upper Devonian Berea Sandstone. During that same period, only five Cambrian tests were drilled in northwestern Pennsylvania, and all wells were plugged back and completed in the Medina Group. Cambrian (and Lower Ordovician) fields and pools discovered so far in the study area are shown in figure 49.

Exploration techniques vary among operators. Many drillers simply lease enough land to drill a well, knowing full well that if the Cambrian proves unsuccessful the well can be plugged back and completed in the Lower Silurian Clinton/Medina section. The more serious investigators use all the means at their disposal, including subsurface mapping, seismic surveying and other geophysics, and modeling, to actively explore for the subtle reservoirs and traps that can mean good production and high reserves. These techniques have worked successfully in Ohio during the past decade, and some operators are beginning to apply the same techniques in Pennsylvania.

Previous Work

The Cambrian and Ordovician rocks of the Appalachian Basin have been studied and described in outcrop for over 150 years, beginning with the first geological surveys of New York, Pennsylvania, and Virginia. However, these rocks have remained virtual enigmas until only recently. Stratigraphic studies dominated earlier works, but they tended to confuse, rather than enlighten because nomenclature was drawn from many different areas, some as far away as the Mississippi Valley area (for example, Fettke, 1948). Summaries of older work can be found in Calvert (1962) and Janssens (1973) for Ohio, Wagner (1966b, 1966c, 1976) for Pennsylvania, McGuire and Howell (1963) for Kentucky, Flagler (1966) and Rickard (1973) for New York, and Markello and Read (1981, 1982), Mussman and Read (1986), Pfeil and Read (1980), and Read (1980, 1989) in Virginia.

Freeman (1949) first used the name Rose Run sandstone; she placed this unit in the Elvins Group of the Ozarks, and correlated it with the Davis Member of the Elvins. Later, McGuire and Howell (1963) used the Rose Run to subdivide the Knox Dolomite Group into the Copper Ridge Formation below and the Beekmantown Formation above. They considered the Rose Run to be the oldest submember of the Chepultepec Dolomite Member (lowermost dolostone of the Beekmantown Formation).

Wagner (1961) attempted to establish a workable nomenclature for

Cambrian and Ordovician sequences in northwestern Pennsylvania where different nomenclatures used in Ohio, New York, and central Pennsylvania seemed to converge. He eventually (Wagner, 1966a-c, 1976) adopted the central Pennsylvania nomenclature of Kay (1944), Wilson (1952), and others for the majority of rocks in western Pennsylvania.

Calvert (1962) correlated the Sauk sequence (Mt. Simon Sandstone to Knox Dolomite interval) where it crops out in the Rose Hill district in Virginia and eastern Kentucky to a well drilled to the Precambrian in Fayette County, Ohio. Based upon these correlations, he adopted the stratigraphic nomenclature used in Tennessee, Kentucky, and Virginia (Figure 50).

Janssens (1973), in a detailed stratigraphic study of the Cambrian and Lower Ordovician rocks in Ohio, recognized the Rose Run as a mappable unit in the subsurface in eastern Ohio, but did not attempt to name it formally (Figure 50). He recognized the Beekmantown, Rose Run, and Copper Ridge as informal units within the Knox Dolomite.

More recently Shearrow (1987) conducted a study of the Cambrian and Lower Ordovician focused in northwestern Ohio. He correlated his work into Michigan and agreed with Fettke (1948) in the use of Upper Mississippi Valley terminology for the Cambrian and Lower Ordovician section (Figure 50).

Geologic Setting

Paleogeography and Tectonics

During the Late Precambrian and Early Paleozoic, Ohio and Pennsylvania were part of a large crustal plate, called Laurentia, that occupied a position straddling the equator. Laurentia (as illustrated in figure 51) included the continental shelf and parts of the continental slope and rise. The major land mass of Laurentia included what is now called the Canadian Shield and, according to some reconstructions, the Transcontinental Arch. In figure 52 the Transcontinental Arch is shown as a peninsula and a series of islands.

The probable configuration of the Late Cambrian-Early Ordovician crustal plates is shown in figure 51. The Iapetus Ocean seems to have originated in the Late Precambrian, between 650 and 570 Ma, when the northwestern margin of the Baltic plate rifted away from the southern margin of Laurentia (in terms of modern cardinal directions, the southern margin of Baltica and the eastern margin of Laurentia - Scotese and McKerrow, 1991; Figures 53, 54). At that time the southern margin of Laurentia, including the continental shelf area that would eventually become Ohio and Pennsylvania, became a passive continental margin.

During the Early and Middle Cambrian the Grenville rocks in much of what is now the study area of eastern Ohio and western Pennsylvania remained exposed to erosion. Sedimentary and metasedimentary rocks lithified from Early Cambrian clastic sediments occur only in central and eastern Pennsylvania, and most of the Middle Cambrian rocks lie in the eastern three-fourths of Pennsylvania. Deposition of basal orogenic sands on the Precambrian unconformity in Ohio and western Pennsylvania began late in the Middle Cambrian as sea level rose and/or the southern margin of Laurentia subsided in response to the weight of increasing amounts of sediment.

During the Early or Middle Cambrian an aulacogen, the Rome trough, formed along the southern margin of the exposed land mass of Laurentia. Harris (1978) described the Rome trough as the failed arm of a triple junction, extending from the Mississippi embayment through Kentucky to Pennsylvania, and into New York. The aulacogen probably originated on incipient Precambrian crustal-block faults derived from stresses during opening of the Iapetus Ocean.

Recycled orogenic sands continued to be deposited throughout much of the Late Cambrian, but by that time they were mixed with the shelf carbonates that eventually dominated sedimentation on the shelf. Sandstone suites from the central and eastern United States are mostly quartzose, reflecting their origin from tectonically stable portions of the craton (Dickinson and others, 1983; Figure 54). Some of the sandstones are quite feldspathic, however, and indicate a continental block provenance (Figure 54). The latter sandstones include portions of the Rose Run sandstone in Ohio and Pennsylvania. These feldspathic sandstones suggest that some basement uplift, with greater relief than land areas of the craton, also supplied sediments to the passive margin of southern Laurentia.

Much of the sand apparently accumulated around the land mass, whereas most of the carbonates accumulated in the shallow waters of the shelf (Figure 51). Mixing of these sediments occurred during cyclical sea level changes. Movement within the Rome trough continued, thereby continuing to affect deposition (see Rose Run Structure below). By the end of the Cambrian, deposition of quartz sands had almost ceased, whereas the deposition of carbonates continued unabated.

The Iapetus Ocean continued to widen by mid-ocean rifting until sometime during the Early or Middle Ordovician (Figures 53C-E). According to Scotese and McKerrow (1991), a former transform boundary in the ocean converted to a subduction zone and the Iapetus began to narrow. Previous workers (for example, Dewey and Bird, 1970) indicated that subduction was to the southwest, with Laurentia overriding the oceanic crust of Gondwana. More recent investigations, however, suggest that subduction actually occurred when the oceanic crust at the northeastern margin of the Avalonian belt, itself a fragment of the Gondwana plate, broke off and began to override the southern margin of Laurentia (Figure 52), forming an island arc (Rodgers, 1987; Scotese and McKerrow, 1991).

The continental shelf of Laurentia buckled during the initial period of plate collision (Figure 53). It was block faulted, folded, and regionally uplifted (Mussman and Read, 1986), initiating a period of erosion that beveled progressively older rocks and sediments from south to north (present east to west). This regional erosional surface, called the Knox unconformity, is characterized by erosional relief (subtle to modest paleotopography, with some monadnocks), and localized structural relief as well in the form of anticlinal flexures and block faulting. This surface was subsequently drowned during a higher stand of sea level in the Middle Ordovician. Deposition of post-Knox sediments include basal clastics and carbonates deposited on the margin of the foreland basin, toward the continental interior (Mussman and Read, 1986).

During the later Middle and early Late Ordovician the continental shelf returned to relatively stable conditions, accumulating shelf carbonates in large quantities. These carbonates mixed with clastic muds and occasional bentonites from recurrent tectonic disturbances originating from the convergence of Laurentia with the island arc, especially during the very early part of the Late Ordovician. These disturbances culminated in the Late Ordovician Taconian orogeny when Laurentia collided with the island arc, forming the first Appalachian mountains.

Paleoceanography and Paleoclimatology

The global configuration of the planet during the Cambrian is speculative because of the absence of a global standard for Cambrian biostratigraphy, lack of reliable paleomagnetic data, and uncertainty about the absolute age of the Precambrian/Cambrian boundary (Scotese and McKerrow, 1991). The global configurations shown in figures 51 and 55 are for latest Cambrian and are based on earliest Ordovician configurations. The following discussion on paleoceanography is derived from an excellent paper by Wilde (1991), and readers interested in a more complete presentation of the subject are urged to consult this reference. The discussion on paleoclimatology is based on interpretation of figure 51 using standard meteorological and climatological concepts.

The oceanic circulation patterns are largely influenced by atmospheric circulation patterns to the point where the two systems commonly coincide. This is because surface oceanic currents are driven by wind. Oceanic circulation patterns during the Late Cambrian, as shown in figure 10, are based on the planetary configuration of Scotese and McKerrow (1991). The oceanic currents that affected the southern seas of Laurentia resulted from several factors. First, the exposed land masses on the equator (Laurentia, Siberia, and portions of Gondwana) probably fragmented the global oceanic low pressure systems, with the major systems south of the high pressure centers that occupied the embayments in the northern ocean. Within these systems water currents flowed east to west, roughly parallel with the equator. Second, the other equatorial continents of Siberia and Kazakhstan broke up the circulation pattern of the relatively small southern ocean into high pressure centers. Third, a seaway on the southwest side of Laurentia connecting the northern and southern oceans would have produced a high pressure center in the southern hemisphere. All of these factors combined to move warm water along the southwestern margin of Laurentia.

Climatic and meteorological patterns are influenced by the distribution of land masses and oceans. During summer months temperatures tend to be higher and pressures lower on land; the opposite is true in winter. Heated air rises over land and cooler air flows in from the ocean to replace it, bringing moisture and wet monsoons to subtropical and warm temperate areas. In temperate areas northern and southern air masses come into contact and, at great altitude, create jet streams that may affect the weather patterns for an entire season.

The distribution of landmasses and oceans suggested for the Late Cambrian (Figures 51 and 55) would have affected global seasonal weather patterns essentially the same as we experience today, but with the northern and southern hemispheres switched. During summer large landmasses develop centers of low pressure into which considerable amounts of moist air flows (monsoons). Because land was concentrated in the southern hemisphere during the Late Cambrian, monsoons would have been almost restricted to southern hemisphere summers. Anti-trade monsoon winds would have been generated along the coast of Gondwana, driving warm water eastward and poleward through the seaway between Gondwana and Kazakhstan (Wilde, 1991). The effect of this would have been to counter the flow of cool water from northern midlatitude high pressure systems. In northern hemisphere summer months the lack of large landmasses probably negated the development of monsoon winds there.

Because the southwest-facing coast of Laurentia, where the Rose Run and adjacent rocks were formed, lay between 0° and 30° south latitude (Figure 55) the dominant wind pattern would have been trade winds similar to Recent winds, with some variation due to the configuration of landmasses and oceans. These southeasterly winds must have carried warm maritime air from the moist western side of the high pressure center in the Iapetus Ocean (Figure 55). Along the east coast of Laurentia this air movement would then have provided abundant rainfall in a narrow zone between 15° and 30° south latitude. Although at least part of the east coast of Laurentia must have been abundantly wet during the summer, the position of the continent most likely would have created completely opposite conditions along the southwest coast. Continental west coasts in latitudes 15° to 30° (north or south) are extremely dry, generally with less than 10 inches of rainfall annually. Oceanic subtropical high-pressure cells are inherently dry on the east side because as the air moves downward and equatorward it warms to the point where it reduces relative humidity. On the west side of these cells, the air cools by moving upward and poleward, thereby taking on moisture. Thus, in the trade wind zone the continental coast west of a subtropical high pressure cell tends to receives heavy rainfall, whereas the coast east of that cell tends to be dry. Such conditions are termed West Coast Desert Climates. The principal difference between west coast and continental interior deserts is that the former tend to be relatively cool, with a mean annual temperature of 65°F due to oceanic upwelling along the coast, whereas temperatures average 10oF higher inland. Upwelling along the southwestern coast of Laurentia (Wilde, 1991), coupled with a high pressure system in the Iapetus to the west or southwest, suggests that this region experienced climatic conditions similar to those of Morocco, Baja California, and Western Australia, to name a few representative examples from the Recent.

Stratigraphy

Introduction

The Rose Run sandstone was first described by Freeman (1949) from the Judy and Young #1 Rose Run Iron Co. well in Bath County, northeastern Kentucky. In that well the unit consists of about 70 ft of poorly sorted sandstone approximately 330 ft below the Knox unconformity (Figure 56). McGuire and Howell (1963) considered the Rose Run to be an informal member of the Chepultepec Dolomite, the upper unit of the Knox Dolomite and a correlative of the lower Beekmantown of Pennsylvania and New York. They used it to define the boundary between the Chepultepec and the subjacent Copper Ridge Dolomite (equivalent to the Ore Hill Member of the Gatesburg Formation of Pennsylvania). The name Rose Run was later applied by operators to similar rocks in Ohio and Pennsylvania during the drilling spree of the mid-1960's (see Summary of Cambrian Production above).

The regional stratigraphy of the Upper Cambrian in the study area has been delineated by a series of cross sections using both geophysical logs (mostly gamma-ray) and sample descriptions where they existed, and on the isopach of the Rose Run sandstone. Discussion of the results of these studies is presented below.

Problems of Nomenclature

As in any regional study that crosses state boundaries, there are problems of nomenclature that must be ironed out to the agreement of all parties involved. This study is no exception. Most of the stratigraphic names from the Middle Ordovician[1] to the Precambrian do not conform between Ohio and Pennsylvania (see Figure 47). For example, in Ohio the dolostones and sandstones of the Lower Ordovician and Upper Cambrian are called Knox Group, a name derived from Knox County, Tennessee. In Pennsylvania the Ordovician portion of the correlative sequence is called Beekmantown Group (or Formation) and the Cambrian portion is called Gatesburg Formation (in part), names derived from eastern New York and central Pennsylvania, respectively. The type Knox comprises, from bottom to top, blue, oolitic, often fossiliferous dolostone; dark-gray, granular dolostone; and light-gray, cherty dolostone (Safford, 1869). The type Beekmantown comprises interbedded limestones, magnesian limestones, dolostones, and sandstones (Clarke and Schuchert, 1899). The type Gatesburg consists of thick-bedded, steely-blue,

[1]Chronostratigraphic (particularly series) designations are based on global usage, rather than standard North American usage, as recommended by Palmer, 1983.

coarsely crystalline dolostone with many interbedded layers of quartzose arenite, oolitic chert, and some limestone (Butts, 1918). It is obvious that the only lithologic similarities among these three formations is the use of the term dolostone.

Some of the names currently applied in Ohio come from as far away as Georgia (Conasauga Formation) and Wisconsin (Mt. Simon Sandstone), whereas all of the names applied in northwestern Pennsylvania originated either in central Pennsylvania or in an adjacent state or Canadian province. There has not been a concerted effort in Ohio to establish the validity of much of the stratigraphic nomenclature that has accumulated over the last 100 years. Many of the names were brought in by geologists and drillers from outside the region without regard for accuracy or consistency (drillers, especially, are notorious for using names that have no basis in real geology). Similarly, some of the Cambrian and Ordovician formation names used in the subsurface of western Pennsylvania were applied by correlation of gamma-ray signatures and well cuttings over 100 miles or more with little regard to lithologic differences between that area and the type sections (see Wagner, 1966c).

Under the pre-1960 rules of stratigraphy, it was common practice to name and correlate formations on the basis of fossil content. Since 1960, however, the Code of Stratigraphic Nomenclature requires a formation (a lithostratigraphic unit) to be described and correlated only through lithologic criteria. Geologic age and biostratigraphy cannot be used as descriptive factors. Therefore, if Lower Ordovician rocks in Pennsylvania are called Beekmantown it should be because, lithologically, they are similar or identical to Beekmantown rocks in New York, not because they share the same chronostratigraphic or chronologic position.

It is unfortunate that in a work of this scope issues such as this can only be stated in generalizations. The problem is larger than the study can allow; therefore, the problem must be set aside until some future work. For this study, in lieu of addressing the situation further, two steps are taken to simplify matters. First, the name Rose Run sandstone is used for the dominant unit of interest (the middle arenaceous dolostones of the Knox Dolomite and the upper sandy member of the Gatesburg Formation). Second, all other discussed stratigraphic units between the Precambrian basement and the Upper Ordovician Black River limestones are designated by the two disparate names, separated by a slash (e.g. Mt. Simon/Potsdam).

Regional Cross Sections

Figure 57 shows the locations of the regional cross sections completed during the early phase of this study. Wells from both Ohio and Pennsylvania were tied together in a cross section whenever possible. Figure 58, a representative log suite from a Rose Run well in Ohio, has been included as an example of the type of information used in constructing these cross sections. Figure 59 is an example of cross section A-A′ which is indicated on figure 57.

In constructing the cross sections in both states, the entire interval from the top of the Late Ordovician Trenton Limestone to the Precambrian basement was included. However, because of the time and space constraints, only the interval from the lower portion of the Late Ordovician Black River Limestone to the Precambrian has been included in figures 58 and 59. The cross sections proved very useful for establishing consistency in determining formation tops, interval thicknesses, and structural datums.

Regional Rose Run Subcrop

The regional subcrop map of the Rose Run (Figure 60) is based on the Ohio and Pennsylvania databases of wells that penetrate the Cambrian and Ordovician carbonates in the study area. These include 1,056 wells in the Ohio database, of which approximately 30 are from Kentucky, Pennsylvania, and West Virginia. Sixty-six wells constitute the database in Pennsylvania, of which nine from New York, Ohio, Ontaire, and West Virginia were used as control points beyond the limits of the mapped area.

The Middle Ordovician Wells Creek/Shadow Lake clastics lie directly on the Rose Run sandstone in a narrow belt in eastern Ohio and northwestern Pennsylvania (Figure 60). West of the western edge of this belt the Knox unconformity has truncated strata down to the Copper Ridge/Ore Hill level. In contrast, to the east of the eastern limit of the subcrop belt the Wells Creek/Shadow Lake lies upon progressively younger rocks until the formation disappears by facies change somewhere over the Rome trough in western Pennsylvania. The exact position of this change is uncertain because of the dearth of well information southeast of the western edge of the Rome trough. It is also uncertain whether or not seismic surveying could delineate this change.

The sinuous nature of the subcrop belt is interesting. This is probably a reflection of local, as well as regional structural controls on the formations above and below the unconformity, as suggested by Dolly and Busch (1972). The western edge of the belt in northeastern Ohio appears to coincide with the Wooster Arch, which Coogan (1990a) described as an anticlinal feature in the subsurface. He suggested that the arch may reflect the location of a down-to-the basin growth fault, or series of growth faults, at the edge of the Appalachian basin that controlled sedimentation throughout the Paleozoic. The depositional pattern of the Rose Run in south-central Ohio and northern Kentucky suggests control by the Waverly Arch, a north-south trending feature that was first identified and named by Woodward (1961). Isopach maps of the Knox Dolomite by Janssens (1973), and of the Prairie du Chien Group by Shearrow (1987), indicate thinning over this feature. This thinning is coincident with the westward limit of the Rose Run. McGuire and Howell (1963) also recognized the influence of the Waverly Arch on Rose Run depositional patterns in northern Kentucky. Control of Rose Run deposition may also have been influence by the West Hickman Creek-Bryan Station Fault, a basement fault that crosses and offsets the Rome trough in Kentucky.

Offsets in the western edge of the subcrop belt in southeastern and south-central Ohio may reflect offset of structural controls along reactivated basement wrench faults. For more discussion of these basement structural features and their relationship to the Paleozoic cover, see Structural Geology below.

Regional Rose Run Isopach

The well databases used to construct the isopach map of the Rose Run sandstone (Figure 61) are the same ones used to construct the subcrop map.

The Rose Run interval thickens gradually from 0 ft at the western limit of the subcrop (Figure 60) to about 200 ft throughout the area of eastern Ohio and northwestern Pennsylvania (Figure 61). Work done in Ohio indicates that the sand-to-carbonate ratio within the Rose Run interval decreases to the east and southeast, suggesting a source to the northwest. East of this broad zone the contours are considerably narrower. Part of the reason for this steepening is that the regional Cambrian and Ordovician surface had been buckled during initial plate convergence in the Early Ordovician, with the western edge of the Rome trough acting as a hinge between the subsiding eastern basin and the more stable western craton. Thus, when the area was uplifted and exposed, erosion proceeded to expose older strata on the craton than in the basin. The broad zone of 0 to 200 ft-thick Rose Run mostly contains an incomplete section of the unit. Another reason for the rapidity of thickening (about 5 ft of thickening per mile) may be depositional. According to structural studies (see below), the Rome trough was an actively subsiding graben complex during Rose Run deposition. This fault movement resulted in formation of a basin within the continental shelf that allowed large amounts of clastic sediment to build up. Deposition during the Late Cambrian, as evidenced by the Amoco Production Co. #1 Svetz well in Somerset County, Pennsylvania, for example, resulted in more than 800 ft of Rose Run sandstone in the deepest part of the trough in Pennsylvania. The well penetrated about 700 ft of Rose Run before drilling was stopped at 21,460 ft.

The irregular nature of the isopach map in the area between the western limit and the 200-ft contour is due to erosion. Various embayments, promontories, and erosional remnants (monadnocks) are present along the subcrop trend as a result of paleodrainage. Monadnocks represent small outliers along the subcrop trend where ancient streams carved channels around the more resistant sections, leaving small isolated bodies of preserved "Beekmantown" and Rose Run strata. These monadnocks are primary targets for exploration along the subcrop trend. Erosional remnants are characterized by a thinning of the Wells Creek/Shadow Lake, and draping at the level of the Trenton Limestone.

The detailed paleotopography developed on the Rose Run in this area is impossible to see in figure 61, yet some larger-scale features can be discerned. For example, some of the V-shaped contours in eastern Ohio suggest major river systems draining the higher lands to the west. The isolated closures in various parts of the map suggest large monadnocks.

Paleotopography is of major importance in Rose Run exploration because it helps provide a trapping mechanism for the reservoirs (Coogan, 1990b). It is unfortunate that at the scale of figure 61 it is difficult to see the paleotopography in all its complexity. Until more detailed work has been done, readers are referred to Dolly and Busch (1972) for discussion and illustration of this paleotopography on a local level.

Petrology and Depositional Environments

Introduction

Petrologic studies of the Rose Run sandstone, and portions of other members of the Gatesburg Formation, include the examination of both cores and outcrops. Because studies of the outcrop are not completed, for this report only the core data are presented. The Ohio Geological Survey has 12 cores of the Rose Run, whereas the Pennsylvania Geological Survey has four whole-diameter cores of portions of the Gatesburg Formation (Appendix 1 and Figure 62). The Pennsylvania cores are the only ones that have been studied in any detail thus far.

Three of the cores from Pennsylvania were recovered from the Hammermill Paper Co. #2 Fee well (Figure 54), a basement well in the city of Erie, Erie County drilled in 1964. Pennsylvania's fourth core was recovered from the Shell Oil Co. #1 Shade Mountain Unit well drilled in Juniata County in 1964. The Gatesburg Formation crops out in western south-central Pennsylvania (Figure 63).

Work completed to date on the petrology task is mostly preparative and descriptive. Ohio investigators have slabbed and described the Rose Run cores, sampled selected intervals for thin sections and X-ray diffraction, and completed cursory microscopic examinations of some Rose Run sandstone intervals. In Pennsylvania, all of the pertinent cores have been slabbed and described, preliminary interpretations of the cores have been made, and additional samples for thin sectioning, X-ray diffraction, and SEM analyses have been prepared. Some outcrop descriptions and sampling were completed in Pennsylvania during the summer, and more will be done in the fall. Because the discussion below pertains to more than just the Rose Run sandstone portion of the Late Cambrian sequence, the name Gatesburg is used for all core samples.

Petrography of Gatesburg Sandstones (Northwestern Pennsylvania)

Work completed in Pennsylvania to date clearly reveals the extreme heterogeneity of the rocks in the Gatesburg Formation. The four Pennsylvania cores contain rocks that represent deposition at two extreme ends of a rimmed shelf during Late Cambrian time (Figure 64). The three cores from the Hammermill Paper Co. #2 Fee well (Figure 54) comprise rocks deposited on the inner shelf, between the Rome trough and the platform hinge. These rocks are mostly sandstones and peritidal dolostones. The core from the Shell Oil Co. #1 Shade

Mountain Unit well contains rocks deposited on the outer shelf. Outer shelf sediments were dominated by thick grainstones, cyclic ribbon carbonates, algal bioherms, and subtidal, non-cyclic carbonates (Read, 1989).

Much of the heterogeneity in the Gatesburg Formation is a direct inheritance from the original rimmed-shelf setting. The rocks originated through facies mixing on the rimmed platform (Figure 65). The rocks reflect a spectrum of mixed siliciclastic and carbonate lithologies. Facies mixing was process-controlled along somewhat diffuse interfaces between paralic siliciclastics, peritidal carbonates, and subtidal carbonates. The depositional setting influenced the geometry of reservoir and non-reservoir rock bodies within the Gatesburg interval, as well as the nature of the depositional boundaries of the rock bodies. The resultant mosaic of various facies, finer-grained interbeds, diastems, and erosional surfaces are baffles to fluid flow and create fluid-flow compartments. Sedimentary structures and grain size distributions impart fluid flow anisotropy and diagenetic variability to the rocks. These features were inherited from the process acting in the original depositional medium.

Rose Run Sandstone (Upper Sandy Member)

Cores 1 and 2 from the Hammermill Paper Co. well contain rocks of the Rose Run sandstone. Core 1 (Figures 66 and 67) cut the Knox unconformity at 5,103 ft and contains 28 ft of interbedded sandstone and dolostone, with subordinate amounts of limestone and shale (Figure 67). The sandstones are medium light gray to very light gray, well sorted, fine- to medium-grained quartz arenites. The quartz grains are mostly monocrystalline and are rounded. Small amounts of feldspar consist of microcline and perthite. Rare lithic grains are composed of chert. Accessory grains include tourmaline, zircon, and muscovite. Shale chip conglomerate occurs at the base of some fining-upwards sequences. Chlorite grain coats, secondary quartz overgrowths, and dolomite cement bind the sandstones. Apparent sedimentary structures are lacking in the sandstones. Porosity in these quartz arenites is very low (Table 8), and both horizontal and vertical permeability are less that 0.1 md.

Core 2 (Figures 66 and 67) contains 12 ft of white to light gray, fine- to medium-grained, well sorted subarkose and arkosic arenite. Quartz is mostly monocrystalline; the larger grains exhibit moderately strong undulose extinction. Grains are rounded to well rounded. Feldspars are abundant and consist of orthoclase and microcline; some microcline is perthitic. Lithic grains include rare chert and sedimentary rocks fragments. Very small amounts of muscovite, zircon, and tourmaline also occur in the sandstones. The rocks are cemented by chlorite grain coats, secondary quartz overgrowths, and dolomite. Patches of sandstone are replaced by dolomite. X-ray diffraction (Figure 68) confirms the simple mineralogy of the sandstones; lower intensities of some dolomite peaks, however, suggest the presence of iron, i.e., the dolomite may be ankeritic. The sandstones are crossbedded and contain basal rip-up clasts of shale and dolostone rock fragments. Porosities range from 2.6 to 13.9 percent. Horizontal permeability ranges from less than 0.1 md to 192 md. Vertical permeability ranges from less than 0.1 md to 53.2 md. Capillary pressure data (Figure 69) reveal that the pore throats are well sorted. Irreducible water saturations in the sandstones are low (Figure 69).

Lower Sandy Member

Core 3 in the Hammermill well contains rocks of the lower sandy member of the Gatesburg Formation (Figure 70). The Lower Sandy correlates with the Conasauga and Kerbel formations of Ohio (Figure 47, column 4). Core 3 contains 18 ft of mostly sandstone, with minor limestone, siltstone, and shale. The sandstones are very light gray, well sorted, fine-grained to medium-grained arkosic arenites. The quartz grains are mostly monocrystalline, of high sphericity, and subrounded to rounded. Feldspars are composed of orthoclase, microcline, and some pethrite. Untwinned orthoclase grains are partially altered to sericite and display considerable vacuolization. Microcline and perthite show similar alteration. Accessories include zircon, tourmaline, and apatite. The sandstones are cemented by dolomite, feldspar and quartz overgrowths, and some clay. Sedimentary structures include low-angle and high-angle crosslamination and bedding. Shale rip-up clasts are common, particularly near the bases of fining-upwards sequences. Figure 71 illustrates the X-ray diffraction scan of the Lower Sandy Member in Core 3. Porosities are between 9.4 and 13.4 percent. Pore throat sorting is good, although the pore throats are quite small (Figure 72). The smallest pore throats yield higher irreducible water saturations. Horizontal permeability ranges from 0.4 to 5.2 md; vertical permeability ranges from 0.19 to 6.34 md.

Much work remains to be done on these cores, including study of the interbedded carbonates and integration of that data with information concerning the sandstones to develop a reasonable depositional model. This effort will include integrating the Pennsylvania data with that of the Ohio investigation. The principal intention for the coming year will be to define the diagenetic history of the sandstones and characterize the porosity and permeability of the rocks. This information will be utilized to develop useful log interpretation schemes for "Rose Run" targets, something that is very much needed (Figure 73).

Further work will also include finishing the work on the outcrop in central Pennsylvania. Data from the outcrop should help to improve understanding of the middle platform environments during Late Cambrian time, and provide additional knowledge of the geology of Gatesburg targets in the central Pennsylvania Ridge and Valley Province (Eastern Overthrust Belt).

Petrography of Gatesburg Carbonates (Central Pennsylvania)

The Gatesburg Formation was tested in central Pennsylvania by Shell Oil Co. in 1964, when they drilled the #1 Shade Mountain Unit well in Juniata County.

This well was drilled on the Shade Mountain anticline where it penetrated duplex thrust sheets. Shell encountered only a show of gas, but they recovered a small core of the Gatesburg Formation from between 10,010 and 10,035 feet (Figure 74). The recovered rocks consist of dolostone and anhydrite. Porosities are very low and permeabilities are less than 0.1 md.

The core contains stacked shallowing-upward carbonate sequences (Figure 75). One complete sequence consists of subtidal shelf-lagoon sediments overlain by intertidal and supratidal sediments respectively. Evaporites cap the sequence and these are of special significance. The individual facies recognized in this core are described below.

Subtidal Shelf-Lagoon Facies

These rocks consist of mixed-fossil dolopackstones and dolowackestones. Fossils include algal remains and shell material, including brachiopods. Horizontal laminations and crosslamination occur sporadically in the core. Some of the bedding is nodular. Some birds-eye structures, tepee structures, and pull-apart structures are present too. Trace amounts of feldspar are scattered throughout the rock. The dolostones are mottled and well-burrowed. This facies also contains minor anhydrite and chert.

Subtidal Shoal or Channel Flank Facies

This facies consists of mixed ooid-peloid dolograinstones and dolopackstones and peloid-mixed fossil dolopackstones. The fossils are undifferatiated shell material. The rocks contain scattered quartz and feldspar, and minor amounts of anhydrite. Rip up clasts occur in some of the rocks. Horizontal laminations and nodular bedding are present and the rocks are bioturbated.

Shoal or Levee Bank Facies

This facies consists of ooid dolograinstones which grade downwards into the mixed ooid-peloid dolograinstones of the shoal flank or channel flank facies.

Sabkha and Subaqueous Evaporite Facies

This facies contains nodular and laminated anhydrite, along with rippled and lenticular dolostone and stromatolites. This facies also contains an interbank lagoon or "pond" subfacies comprised of oolitic, mottled and burrowed, fossiliferous dolostones. The evaporites are interpreted as having formed along the high portion of carbonate banks as normal subkha successions (nodular anhydrite) or in the interbanks ponds and lagoons as subaqueous evaporites (laminated anhydrite and stromatolites). Figure 76 illustrates the appropriate model.

Hardie (1986) suggested that the climate during Gatesburg time was, "...dry enough to produce some growth of evaporite minerals within the supratidal sediments but not arid enough to accumulate a cap of sabkha evaporite deposits", which agrees with the discussion of paleoclimate given above. Read (1989) suggested a semiarid climate, with an overall evaporative depositional setting. The recognition of evaporite minerals in the Gatesburg Formation and its equivalents has, to date, been indirect. Hardie (1986) discussed displacive calcite nodules that originally might have been supratidal gypsum. Folk and Pittman (1971) suggested that length-slow chalcedony in the Gatesburg was evidence for vanished evaporites. The Gatesburg Formation rocks recovered from the Shell Oil Co. #1 Shade Mountain Unit well provides unequivocal evidence of evaporite deposition in central Pennsylvania during Late Cambrian time.

Structural Geology

Introduction

Harding and Lowell (1979) described two major modes of structural styles, basement involved and detached, that Harper (1989) documented or speculated on in the subsurface of western Pennsylvania. Although these structural styles also exist in Ohio (Figure 77), detached structures are limited to extreme eastern Ohio. Basement involved structural styles, often called "thick-skinned tectonics", include extensional fault blocks, compressive fault blocks and basement thrusts, wrench fault assemblages, and basement warps. Detached structural styles commonly have been referred to as "thin-skinned tectonics". They include decollement thrust-fold assemblages, detached normal-fault assemblages (growth faults), salt structures, and shale structures. Wrench fault assemblages separating adjacent detached zones should be added to this list. Recurrent movement along basement involved structures have been shown to have directly affected many of the detached structures, as well as the distribution of sedimentary facies, hydrocarbon development, source and reservoir rocks, and traps (Harper, 1989).

Extensional basement faulting includes down-to-the-east normal faulting initiated during the opening of the Iapetus Ocean in the Late Precambrian, and development of the Rome trough during the Cambrian. Compressive block faulting cannot be documented with any degree of reliability, but probably occurred during the Cambrian as evidenced by the amount of feldspathic sandstones in the Mt. Simon/Potsdam, Rome/Warrior, Conasauga/Gatesburg Lower Sandy, and Rose Run intervals. Also, plate margin convergence during the Early Ordovician may have initiated a reversal of movement on old rift faults (Read, 1989), which would have created compressive fault blocks near the margin. Wrench faults probably originated as transform faults during Precambrian rifting (Thomas, 1977), and later became zones of crustal instability between adjacent crustal blocks (Lavin and others, 1982). In the study area the Tyrone-Mt. Union lineament, the Pittsburgh-Washington lineament (= Highlandtown fault zone of Ohio), and the Cambridge cross-strike structural discontinuity are the best examples. Basement warping may have occurred in the Rome trough area after the faults locked up, probably in the Middle Ordovician.

Detachment structures may not be nearly as recognizable in the Cambrian and Ordovician section of the study area as they are in younger strata. The only detached structures that can be documented are growth faults, wrench faults, some of which may have substituted vertical movement for the original horizontal movement sometime during the Late Cambrian or Early Ordovician, and thrust faults that developed during the Alleghanian orogeny in the Late Permian. These detached structures commonly developed in imitation of their basement counterparts. For example, the Cambrian growth faults described by Wagner (1976) occur over basement normal faults of the Rome trough. Also, several of the basement wrench fault assemblages, most notably the Tyrone-Mt. Union lineament, have influenced structure and deposition in western Pennsylvania throughout geologic time (Rodgers and Anderson, 1984), and may be active still (Canich and Gold, 1985). The Cambridge cross-strike structural discontinuity in eastern Ohio (Figure 77) has been interpreted by Baranoski (1989) as a similar basement wrench fault.

Many of these features may be recognizable in the subsurface with the aid of seismic surveying. At this stage of the study, however, there has been very little accomplished in the way of seismic studies in either Ohio or Pennsylvania, aside from determining what is available and making arrangements for obtaining more data. In Pennsylvania, planning for future interpretation of seismic lines involved testing a commercially available synthetic seismogram program for the PC. The result, based on velocity log data from the Peoples Natural Gas #1 Robert Temple well in Mercer County, is shown in Figure 78. Use of this technique in the interpretation of available non-proprietary seismic lines will be attempted in future research.

Influential Structural Features

Rome Trough

The Rome trough is a graben structure that runs from the Mississippi Embayment through Kentucky, West Virginia, and Pennsylvania into New York (Harris, 1978; Harper, 1989). The northwestern edge of the trough has been delineated by a series of northeastern-trending gravity and magnetic anomalies (Kulander and Dean, 1978). Mapping by Baranoski and Riley (1988; also in press) indicates that the Rome trough steps up to the northwest into extreme southeastern Ohio from West Virginia and Kentucky. The northeastern termination of the trough is in doubt, but may be at or near the Adirondacks.

The Rome trough exhibits certain characteristics that are typical of aulacogens (Hoffman and others, 1974), including development in the interior of a foreland platform and long life. The Rome trough has been susceptible to reactivation during the entire geologic record (as shown in Pennsylvania by Harper, 1989). The developmental stages of such a structure were described by Harris (1978), as: 1) a graben stage in which subsidence is confined to the graben and displacement occurs penecontemporaneously with sedimentation along block faults; 2) the transitional stage in which the boundary faults begin to lock up or have only minor recurrent movement; and 3) the downwarping stage in which the entire area subsides, thus forming a regional downwarp. From this information, it can be stated that the Rome trough reached stage 1 during the Early or Middle Cambrian (Read, 1989), stage 2 during the Late Cambrian or Early Ordovician, and stage 3 before the Late Ordovician.

Most illustrations of the Rome trough (e.g. Figure 79) show the trough as a relatively simple curved graben running from Kentucky to Pennsylvania. Harper (1989) determined, however, that the trough was offset, at least in Pennsylvania, by a series of basement wrench faults (Figure 79). This "best fit" interpretation was determined by studies of the Paleozoic rock cover. For example, offset of the trough along the Tyrone-Mt. Union lineament had been suggested by Lavin and others (1982) based on aeromagnetic and gravity anomalies. Segmentation of the trough by the Pittsburgh-Washington lineament is suggested by numerous data, including the work of Thomas (1977) who indicated similar offsets throughout the Appalachians and Ouachitas along Late Precambrian-Early Paleozoic transform faults.

Wagner (1976) speculated that the Rome trough affected deposition during the Late Cambrian and Early Ordovician by creating an actively subsiding depositional basin (his Olin basin). He mapped Upper Cambrian rocks thickening from 800 ft in northwestern Pennsylvania to over 1,200 ft within the trough, and Beekmantown rocks thicken from 400 ft to greater than 2,500 ft according to Wagner (1976, Figures 8 and 10). Supplementary work by Ryder and others (in press) and Harper (1991), including two of the regional cross sections prepared for this study, provide additional evidence that the Rome trough affected deposition during the Late Cambrian and Early to Middle Ordovician. Harper's lines C-D and G-I cross the trough in northern and southwestern Pennsylvania, respectively, showing offset along suspected basement and/or growth faults with thickened Rose Run through upper Beekmantown strata on the southeast side of the faults. In the Amoco Production Co. #1 Leonard Svetz well in Somerset County, the Beekmantown includes approximately 3,800 ft of dolostone and sandstone, a much thicker accumulation than in wells farther east and southeast.

Based on gamma-ray log correlations and well-sample control, Wagner (1976) documented a thick sandstone within the Rome trough that he called the Olin Sandstone Member of the Gatesburg Formation. Wagner felt that this sandstone occurred stratigraphically below the level of the Lower Sandy Member of northwestern Pennsylvania, but could be correlated with a portion of the Lower Sandy in central Pennsylvania and northeastern West Virginia. He suggested that a complete reevaluation of the Cambrian stratigraphy of northwestern Pennsylvania was in order because of this discrepancy.

During this investigation it was determined that Wagner had miscorrelated certain gamma-ray markers in his study, and that the Olin Sandstone as originally defined does not exist. This same conclusion has been reached independently by Ryder (1989; also Ryder and others (in press). What Wagner called the Olin Sandstone is, in fact, the Rose Run sandstone, thickened tremendously within the Rome trough. In several of the wells in Harper's (1991) cross sections that penetrate the Rome trough in Pennsylvania and New York, the Rose Run reaches thicknesses in excess of 500 ft. This is especially evident in the Amoco Production Co. #1 Leonard Svetz well in Somerset Co. where the Rose Run is estimated at greater than 800 ft thick.

Wrench Faults (Lineaments)

Several authors have shown evidence for the existence of major basement wrench faults, including the Tyrone-Mt. Union lineament (Canich and Gold, 1977 and 1985; Rodgers and Anderson, 1984; T-M in Figure 79) and the Pittsburgh-Washington lineament (Parrish and Lavin, 1982; Lavin and others, 1982; Harper and Laughrey, 1987: P-W in Figure 79), and the Cambridge cross-strike structural discontinuity (Baranoski, 1989). These and other wrench fault assemblages cross the structural grain of the Appalachians and thus are termed cross-strike structural discontinuities, or CSD's (Wheeler, 1980). Some of these wrench faults probably had a vertical component as well as a horizontal component of movement. For example, the Pittsburgh-Washington lineament, especially well-defined by aeromagnetic anomalies (Zietz and others, 1980), is represented by a magnetic gradient that may be interpreted as differences in basement elevation, difference in basement composition, or both (Harper, 1989). Normal and reverse faulting and anomalous isopach variations have been observed in the Silurian and Devonian on geophysical logs in southeastern Ohio by Baranoski (1989), which strongly suggest strike-slip movement along pre-existing basement faults. Proprietary seismic data in this area indicates structural offset in the basement. Rodgers and Anderson (1984) found no evidence of a strike-slip component in the shallower (i.e. Lower Devonian through Pennsylvanian) rocks associated with the Tyrone-Mt. Union lineament. They suggested instead that, after the Early Ordovician, the rocks northeast of the lineament were uplifted relative to those southwest.

Knox Unconformity

At sometime during the Early Ordovician, a transform boundary in the Iapetus Ocean became a subduction zone, and the passive southeastern margin of the Laurentian plate began sliding down under the adjacent edge of the Gondwanan plate (the Avalonian margin - Scotese and McKerrow, 1991). This change from a passive to a convergent margin initiated several major changes in sea level and in tectonic and depositional controls (Jacobi, 1981; Mussman and Read, 1986; Read, 1989). By the early Middle Ordovician (Whitrockian Stage) much of the southern continental shelf of Laurentia was emergent. The erosional surface developed across the shelf, called the Knox unconformity, is regional in nature; it can be recognized throughout most of the present Appalachians and, perhaps, most of North America (see Mussman and Read, 1986, Figure 17).

Tectonic deformation due to plate collision was modest (no mountain ranges resulted from it), but unmistakable. Read (1989) suggested that older rift faults from the opening of Iapetus were reactivated in reverse direction, causing initial uplift of the shelf margin. As convergence continued, folding and faulting also occurred in various areas of the shelf.

The Knox erosional surface exposed older and older rocks from east to west (present cardinal directions). Based on conodont work in Virginia by Harris and Repetski (1982) it appears that the Knox unconformity occurs within the Beekmantown, rather than at the top as thought by previous workers (as summarized by Twenhofel and others, 1954). In central Pennsylvania the unconformity, if it exists at all (see below) probably would occur within the lower portion of the Bellefonte Formation (upper Beekmantown - Figure 47). About 1,450 ft of pre-Bellefonte Beekmantown strata have been measured in Blair County (Butts, 1918, 1945), and more than 2,200 ft in Centre County (Butts and Moore, 1936; Krynine, 1946). West of the western margin of the Rome trough the unconformity truncates lower Beekmantown strata (based on the Manufacturers Light and Heat #1 Jesse Hockenberry well in northwestern Butler County). In northwestern Pennsylvania and northeastern Ohio, the sub-Knox strata grow increasingly older, from Mines Member of the Gatesburg Formation to Rose Run sandstone. In Ontario the subcrop consists of rocks equivalent to either the Rome/Warrior or Conasauga/Gatesburg Lower Sandy. In northern Kentucky the Rose Run sandstone does not appear to subcrop at the Knox unconformity in northern Kentucky (McGuire and Howell, 1963). In southern Ohio preliminary correlations indicate that the Rose Run sandstone does not subcrop to the west, but changes facies from quartz sand to a more dominant dolostone. These correlations may also indicate a more regional extent of Woodward's (1961) Waverly Arch. Work will be done on these problems during the second year of the project.

Ryder and others (in press) report the occurrence of Chazyan (late Middle Ordovician) conodonts within at least the upper 1,500 ft of Beekmantown strata in the Amoco Production Co. #1 Leonard Svetz well in Somerset County. They tentatively placed the Early-Middle Ordovician boundary at 19,000 ft in this well, indicating that about 1,800 ft of Beekmantown represented Early Ordovician strata and about 3,000 ft represented Middle Ordovician. Because of a seeming lack of evidence for truncation of the Early Ordovician strata, Ryder and others (in press) concluded that the Knox unconformity probably does not exist within the Rome trough. This has not yet been confirmed.

The existence of the unconformity in central Pennsylvania has not been confirmed, either. Chavetz (1969), who considered the Knox unconformity to occur between strata equivalent to the Bellefonte and Loysburg formations (Figure

47, column 7), described the transition of strata between these two units as gradual. Mussman and Read (1986; also Read, 1989) interpreted information such as this, as well as the more regional work of Colton (1971), to conclude that the unconformity passed laterally into a conformable sequence in Pennsylvania. In this scenario, central Pennsylvania was the site of a depocenter that influenced Cambrian and Ordovician sediment thickness and facies distributions on the shelf (Read, 1980, Figure 2). However, the conclusion that the unconformity does not exist in central Pennsylvania is based on a false assumption and should be ignored. Harris and Repetski (1982), in proposing that the unconformity occurs within the Beekmantown, assigned 700 ft of upper Beekmantown (Bellefonte) in Blair County (an area studied by Chavetz) to the Middle Ordovician, but did not specifically state that an unconformity existed in this area.

The suggestion that the central Pennsylvania area continued to be a center of deposition at the same time most of the remainder of Laurentia was undergoing erosion is difficult to accept, given the extent of the Knox unconformity and the fact that central Pennsylvania is situated on what was still the continental shelf. Without further study, however, it may never be firmly established one way or the other. There may be information hidden in studies that could be used to demonstrate or negate the existence of the unconformity. For example, Knowles (1966) and Lees (1967) documented a thick cherty zone near the base of the Bellefonte Formation in Centre and Bedford counties, respectively. Ryder and others (in press) suggested that the top of this zone may coincide with the Knox unconformity in central Pennsylvania. But this evidence is circumstantial at this time.

Regional Structure Maps

Regional structure in the Appalachian Basin tends to follow a standard pattern from the Precambrian basement to the Middle Devonian - subsea elevations increase from northwest to southeast, with a certain amount of curvature due to flexures along the established Appalachian Basin salients and recesses (Colton, 1970 and others). From Middle Devonian through Pennsylvanian and Permian the patterns differ somewhat, mostly because of vertical flexures and faulting as a result of detachment on one or more strata. Most of the structural similarities from horizon to horizon result from commonality of both depositional setting in a broad foreland basin and deformation during the Alleghanian orogeny about 250 ma.

On the local level structures may change rapidly from place to place. Where a regional structure map shows an almost unvarying plane surface gradually dipping eastward into the basin, a local map may show folding and faulting at a magnitude unmappable on the regional level. By and large, this appears to be the case with both the Knox unconformity (Figure 80) and Rose Run sandstone (Figure 81). Throughout eastern Ohio and much of western Pennsylvania the structure contours on the tops of the Rose Run sandstone and the unconformity indicate a gradual decrease in subsea elevation to the east and southeast. Some of the roughness in the otherwise smooth contours are undoubtedly due to the paleotopography developed on the top of the Rose Run in Ohio and northwestern Pennsylvania. However, it is also obvious from both maps that more has occurred to disturb these surfaces than just the Alleghanian orogeny.

The subsea configuration of the Knox unconformity is the simplest and easiest to describe. As Figure 80 illustrates the Knox unconformity currently dips gently to the east and southeast in Ohio and Pennsylvania. Dips range from approximately 50 ft/mi in northeastern Ohio and northwestern Pennsylvania to approximately 100 ft/mi in southeastern Ohio and western West Virginia. Other than for a few local anomalies in the contours that are probably due to paleotopography, the only major disturbances occur in northwestern Pennsylvania. Here, the continuity of the contours has been upset by the Tyrone-Mt. Union lineament, described above as a major basement wrench fault separating crustal blocks (Lavin and others, 1982). The map could have been drawn without acknowledging the lineament, but throughout western Pennsylvania this would have created an enormous departure from the otherwise relatively smooth nature of the contours. Under the circumstances, it appears that the lineament, illustrated as a left lateral strike-slip fault, defines a "best fit" interpretation on the regional level. This interpretation is supported by the structure on the Rose Run sandstone (Figure 81).

An additional disturbance in the structure contours on the Knox unconformity occurs just to the northeast of the Tyrone-Mt. Union lineament in southwestern Warren County, Pennsylvania. This disturbance is defined by closure on the -7,000 ft contour and bending of shallower contours around it to the northwest. The exact nature of this disturbance is unknown, but it appears from the map to be a localized downward flexure of the unconformity surface. It should be kept in mind, however, that there is very little well control in this area, so the feature could be a plunging synclinal structure as well as a closed depression. In addition no seismic surveys of the area have been found, so that any discussion of the anomaly is strictly speculative. It is probable that such information exists and may be made available for further study. Meridian Exploration Corp. drilled a successful Beekmantown test (the #1 Hammermill Paper Co. well) on this anomaly in 1985, and it is likely that the prospect was based as much, or more, on seismic studies as on standard geological mapping.

Structure on the Rose Run sandstone (Figure 81) is much more complex than structure on the unconformity. Besides the Tyrone-Mt. Union lineament, the Pittsburgh-Washington lineament apparently also had an active part in the structural configuration of the surface throughout its length in southwestern Pennsylvania and into eastern Ohio. In addition, numerous growth faults above basement rift faults also occur. These have been offset by movement along the major wrench faults (lineaments).

Wagner (1976) first advanced the idea of Cambrian and Lower Ordovician growth faults in the subsurface of western Pennsylvania, using only gamma-ray log signatures and well cuttings. Since that time much discussion has taken place concerning the numbers and positions, and indeed the existence, of these deep structures. Figure 81 has been constructed to reflect the concept of Wagner's growth faults. Seismic surveys have established the presence of rift faults within fractured basement. However, the existence of the growth faults in the sedimentary cover is, as yet, strictly speculative (though compelling). Such structures must have existed because the "best fit" for both the regional cross sections and regional mapping, which have been supplemented by geophysical studies (Davis, 1980; Chaffin, 1981), demand their existence.

The implications of Figure 81 are obvious. The Rose Run sandstone may thicken to the southeast in Pennsylvania (see Figure 16), which should provide additional potential targets for hydrocarbon exploration, but it also increases in depth to the point where it is unlikely to be drilled by the traditionally small independent Appalachian operator. With subsea elevations exceeding 15,000 ft in southwestern and south-central Pennsylvania, the Rose Run sandstone may be a likely target only for companies with large resource bases, such as the major oil companies.

PRESENTATIONS OF RESEARCH RESULTS

Members of our group presented two professional papers and five posters related to the research being undertaken on this project.

Tom Wilson presented a paper at the annual meeting of the Society of Exploration Geophysicists in San Francisco (Wilson, 1990). Li Zheng presented a paper at the annual Appalachian Petroleum Geology Symposium (Zheng, 1991) in Morgantown, West Virginia. At that same meeting, posters were presented by Alan Donaldson and Xiangdong Zou (1991), Dave Matchen (1991), and Zou, Wilson, and Donaldson (1991a). In September, at the Eastern Section meeting of the American Association of Petroleum Geologists in Pittsburgh, posters were presented by Zou, Wilson, and Donaldson (1991b) and Zou and Donaldson (1991).

Papers Presented

Donaldson, A.C., and Zou, X., 1991, Relationship of the Pocono Big Injun sandstones to the pre-Greenbrier unconformity in West Virginia: Regional stratigraphic considerations for reservoir heterogeneity (abstract): in Program and Abstracts, the 22nd Annual Appalachian Petroleum Geology Symposium, West Virginia Geological Survey, Morgantown, p. 25.

Matchen, D.L., 1991, Seismic modeling of the Lower Mississippian sandstones in southern Kanawha County, West Virginia (abstract): in Program and Abstracts, the 22nd Annual Appalachian Petroleum Geology Symposium, West Virginia Geological Survey, Morgantown, p. 51.

Wilson, T.H., 1990, Nonstationarity in seismic data: A VSP case study (abstract): in Proceedings Volume of the 58th Annual International meeting of the Society of Exploration Geophysicists, p. 1683-86.

Zheng, L., 1991, Seismic stratigraphic study of the Lower Mississippian sandstones - calculation of synthetic sonic log from nuclear logs (abstract): in Program and Abstracts, the 22nd Annual Appalachian Petroleum Geology Symposium, West Virginia Geological Survey, Morgantown, p. 84-85.

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APPENDIX I

Catalogue of Upper Cambrian and Lower Ordovician Cores

1.	COUNTY AND STATE:	Coshocton Co., Ohio
	TOWNSHIP AND LOCATION:	White Eyes Twp., Sec. 17
	CORE NUMBER AND PERMIT:	Core #2716, Permit #2653
	WELL NAME:	Stone Resources #1 Barth
	CORED INTERVAL:	6,590-6,639 ft
	STRATIGRAPHIC INTERVAL:	Wells Creek to "Rose Run"
	CONDITION:	Slabbed
2.	COUNTY AND STATE:	Coshocton Co., Ohio
	TOWNSHIP AND LOCATION:	Virginia Twp., Lot 21, 4th Quarter
	CORE NUMBER AND PERMIT:	Core #2852, Permit #2183
	WELL NAME:	Gallegher #1 McLeod Heirs
	CORED INTERVAL:	5,986-5,999 ft
	STRATIGRAPHIC INTERVAL:	Wells Creek to "Rose Run"
	CONDITION:	Slabbed
3.	COUNTY AND STATE:	Coshocton Co., Ohio
	TOWNSHIP AND LOCATION:	Virginia Twp., Lot 24, 4th Quarter
	CORE NUMBER AND PERMIT:	Core #2853, Permit #2268
	WELL NAME:	Gallegher #1 Vickers
	CORED INTERVAL:	5,967-5,986 ft
	STRATIGRAPHIC INTERVAL:	Wells Creek to "Rose Run"
	CONDITION:	Slabbed
4.	COUNTY AND STATE:	Coshocton Co., Ohio
	TOWNSHIP AND LOCATION:	Adams Twp., Section 2
	CORE NUMBER AND PERMIT:	Core #2713, Permit #4092
	WELL NAME:	Pomstone #1 Oaklief
	CORED INTERVAL:	?
	STRATIGRAPHIC INTERVAL:	Beekmantown
	CONDITION:	Unslabbed
5.	COUNTY AND STATE:	Coshocton Co., Ohio
	TOWNSHIP AND LOCATION:	Adams Twp., Sec. 12
	CORE NUMBER AND PERMIT;	Core #2715, Permit #5962
	WELL NAME:	Stone #1-A Lower
	CORED INTERVAL:	6,736-6,796 ft
	STRATIGRAPHIC INTERVAL:	Wells Creek to "Rose Run"
	CONDITION:	Slabbed

6. COUNTY AND STATE: Columbiana Co., Ohio
TOWNSHIP AND LOCATION: Knox Twp., Sec. 12
CORE NUMBER AND PERMIT: Core #2850, Permit #592
WELL NAME: East Ohio Gas #1-2468 Denny
CORED INTERVAL: 8,097-8,126 and 8,249-8,295 ft
STRATIGRAPHIC INTERVAL: Beekmantown and "Rose Run"
CONDITION: Unslabbed

7. COUNTY AND STATE: Guernsey Co., Ohio
TOWNSHIP AND LOCATION: Adams Twp., Sec. 15
CORE NUMBER AND PERMIT: Core #867, Permit #782
WELL NAME: Lakeshore #1 Marshall
CORED INTERVAL: 6,875-7,045 ft
STRATIGRAPHIC INTERVAL: Wells Creek, Beekmantown, and "Rose Run"
CONDITION: Slabbed

8. COUNTY AND STATE: Holmes Co., Ohio
TOWNSHIP AND LOCATION: Berlin Twp., Lot 12
CORE NUMBER AND PERMIT: Core #2892, Permit #1279
WELL NAME: Amerada #1 Geib
CORED INTERVAL: 6,368-6,419 ft
STRATIGRAPHIC INTERVAL: Wells Creek to Knox
CONDITION: Unslabbed

9. COUNTY AND STATE: Jackson Co., Ohio
TOWNSHIP AND LOCATION: Franklin Twp., Sec. 8
CORE NUMBER AND PERMIT: Core #2892, Permit #102
WELL NAME: Nucorp #1 Trepanier
CORED INTERVAL: 4,488-4,522 ft
STRATIGRAPHIC INTERVAL: "Rose Run"
CONDITION: Slabbed

10. COUNTY AND STATE: Morgan Co., Ohio
TOWNSHIP AND LOCATION: Homer Twp., Frac. 32
CORE NUMBER AND PERMIT: Core #2923, Permit #1249
WELL NAME: Columbia Gas #11125 Kittle
CORED INTERVAL: 6,249-6,343 and 6,401-6,521 ft
STRATIGRAPHIC INTERVAL: Wells Creek to Beekmantown, and "Rose Run"
CONDITION:

11. COUNTY AND STATE: Scioto Co., Ohio
TOWNSHIP AND LOCATION: Green Twp
CORE NUMBER AND PERMIT: Core #2598, Permit #212
WELL NAME: Earlougher #1 USS Chemical Div.
CORED INTERVAL: 3,979-4,009 and 4,254-4,262 ft
STRATIGRAPHIC INTERVAL: Beekmantown and "Rose Run"
CONDITION: Slabbed

12. COUNTY AND STATE: Tuscarawas Co., Ohio
TOWNSHIP AND LOCATION: Clay Twp., Lot 14 N
CORE NUMBER AND PERMIT: Core #2963, Permit #955
WELL NAME: Stocker and Sitler #1 Mizer
CORED INTERVAL: 7,647-7,688 ft
STRATIGRAPHIC INTERVAL: "Rose Run"
CONDITION: Slabbed

13. COUNTY AND STATE: Scioto Co., Ohio[2]
TOWNSHIP AND LOCATION: Green Twp.
CORE NUMBER AND PERMIT:
WELL NAME: Aristech test/monitor well
CORED INTERVAL: 10-5,443 ft
STRATIGRAPHIC INTERVAL: Logan to Rome
CONDITION:

14. COUNTY AND STATE: Erie Co., Pennsylvania
TOWNSHIP AND LOCATION: City of Erie
CORE NUMBER AND PERMIT: Permit #20109
WELL NAME: Hammermill Paper Co. #2 Fee
CORED INTERVAL: 5,102-5,131; 5,154-5,166; 5,547-5,565 ft
STRATIGRAPHIC INTERVAL: Shadow Lake and Gatesburg
CONDITION: Slabbed and unslabbed

15. COUNTY AND STATE: Juniata Co., Pennsylvania
TOWNSHIP AND LOCATION: Fayette Twp.
CORE NUMBER AND PERMIT: Permit #20001
WELL NAME: Shell Oil Co. #1 Shade Mountain Unit
CORED INTERVAL: 10,010-10,035 ft
STRATIGRAPHIC INTERVAL: Gatesburg
CONDITION: Slabbed

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[2]To be donated to Ohio Division of Geologic Survey

APPENDIX II

Availability of Products

Products Currently Available

Ohio Division of Geological Survey Digital Chart and Map Series (DCMS) -Open File Maps

1. DCMS-1 Knox and Deeper Wells in Southeast Ohio; Scale 1:250,000.
2. DCMS-2 Knox and Deeper Wells in Northeast Ohio; Scale 1:250,000.
3. DCMS-3 Knox and Deeper Wells in Portions of Coshocton, Holmes, and Tuscarawas counties; Scale 1:62,500.
4. DCMS-5 Cambrian and Lower Ordovician Stratigraphic Cross Section - Greenup County, Kentucky, to Crawford County, Pennsylvania.
5. DCMS-6 Cambrian and Lower Ordovician Stratigraphic Cross Section - Morrow County, Ohio, to Wood County, West Virginia.

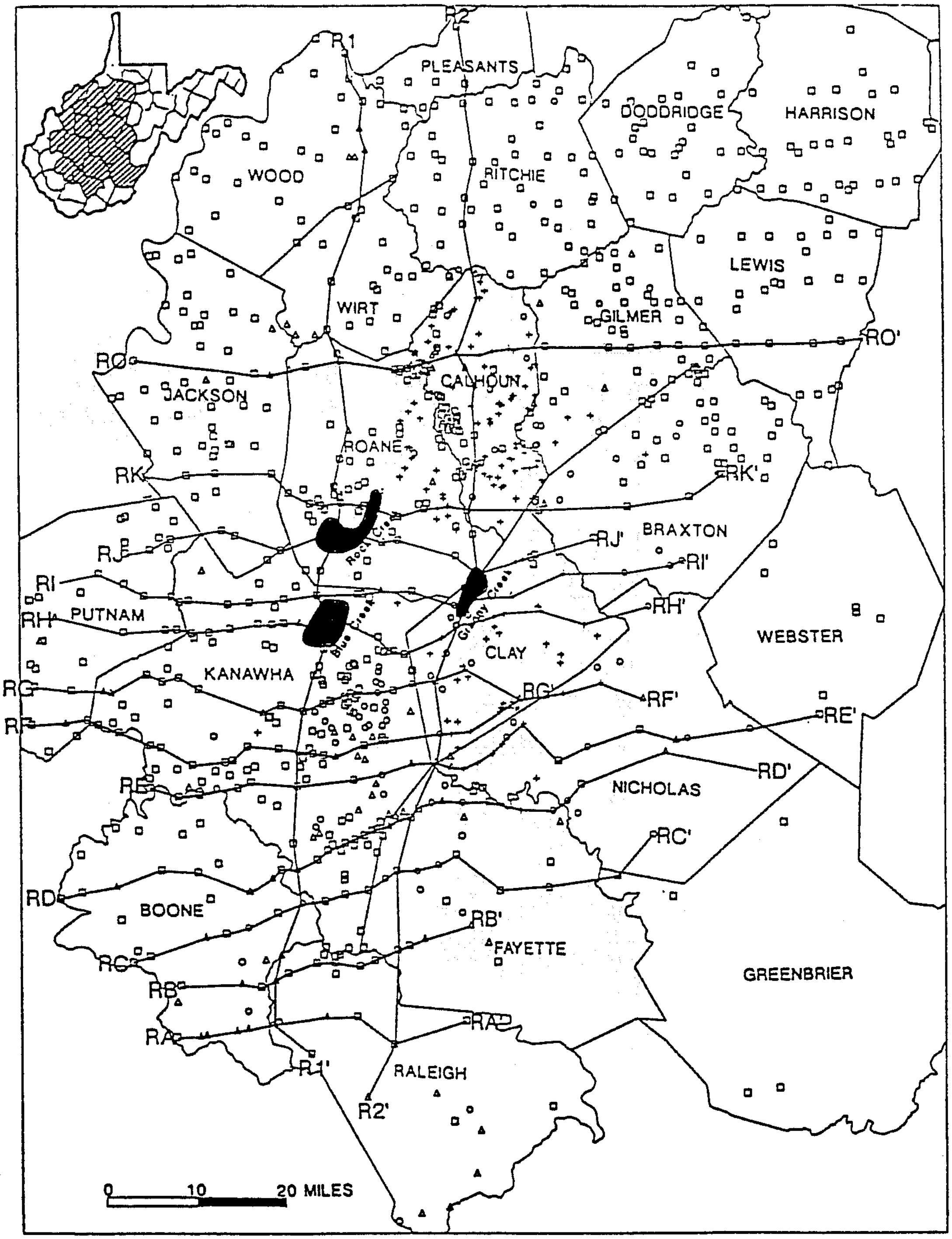
Products to be Made Available in October 1992

Ohio Division of Geological Survey

1. Completion card database for all Knox penetrations in study area.
2. Logtop database for all Knox penetrations from correlations by staff geologists.
3. Production database for Rose Run and Beekmantown.

Pennsylvania Bureau of Topographic and Geologic Survey

1. Formation top database for all wells penetrating top of Middle Ordovician carbonates or deeper.
2. Middle Ordovician to Precambrian cross sections of wells and outcrops in Pennsylvania and adjacent states.



LEGEND

▫ WELL PENETRATING DEVONIAN SHALE △ WELL PENETRATING SUNBURY SHALE OR WEIR SS.

∘ WELL PENETRATING SQUAW SS. + WELL PENETRATING BIG LIME AND PART OF BIG INJUN

Figure 1. Location map showing wells with geophysical logs and profiles selected for stratigraphic cross sections used in the regional study of 21 counties in West Virginia.

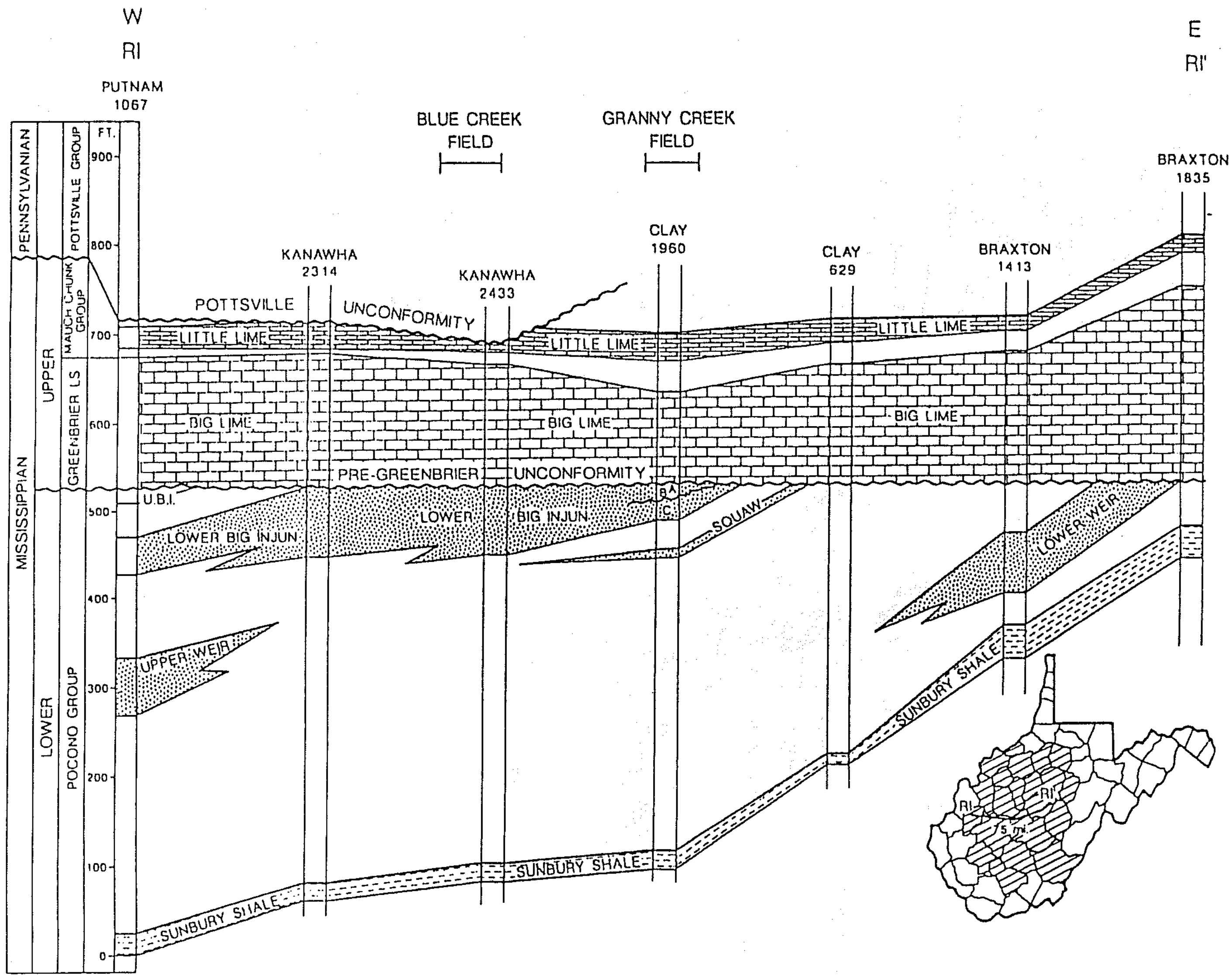


Figure 2. Generalized stratigraphy of rock units in regional area (see insert map) based on 75-mile profile trending east-west (Rl-Rl'). Pre-Greenbrier unconformity (datum) shows increased eastward erosion of the Lower Mississippian rocks. Granny Creek and Blue Creek oil fields are located on the cross section. Informal A, B, and C members of the lower Big Injun sandstone are labeled (Clay 1960). Upper Big Injun (UBI) is shown in Putnam 1067.

FIGURE 3. CROSS-SECTION RO-RO' FROM JACKSON COUNTY TO LEWIS COUNTY OF WEST VIRGINIA FOR THE REGIONAL STUDY

Figure 3. Regional stratigraphic cross section RO-RO' (see figure 1), correlated from geophysical log data, showing relationship of Big Injun sandstones to pre-Greenbrier unconformity. Pre-Pottsville unconformity also is shown.

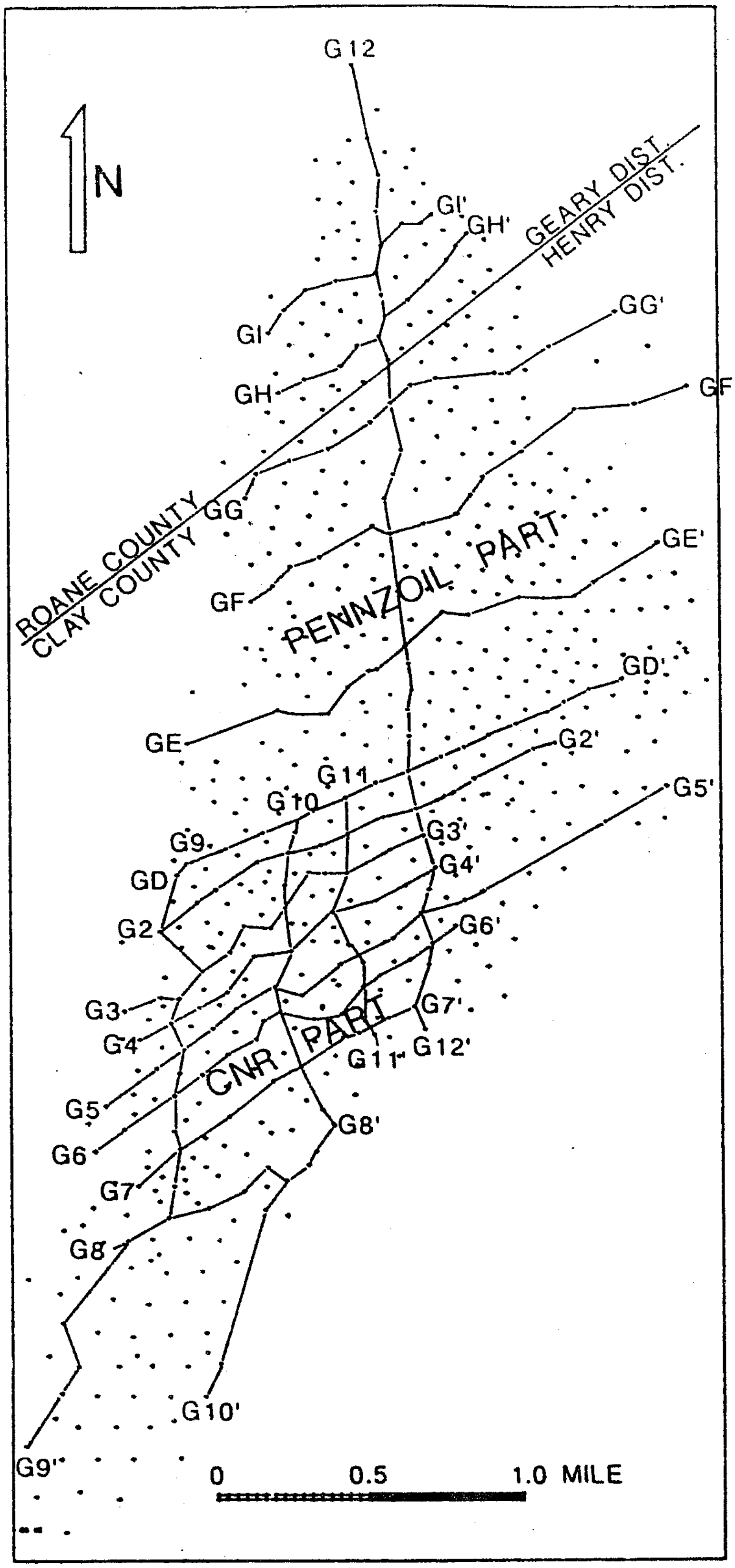


Figure 4. Location map of wells used and cross sections constructed for study of the Granny Creek field in Clay and Roane counties, West Virginia. The numbered cross sections occur in the southern part where CNR operates, whereas lettered cross sections denote Pennzoil leases in the northern part of the field.

Figure 5. Stratigraphic cross section GD-GD' (see figure 4) of the Granny Creek field correlated from geophysical log data, showing the relationship of Big Injun sandstones to pre-Greenbrier unconformity within interval between the Squaw sandstone and Little Lime unit.

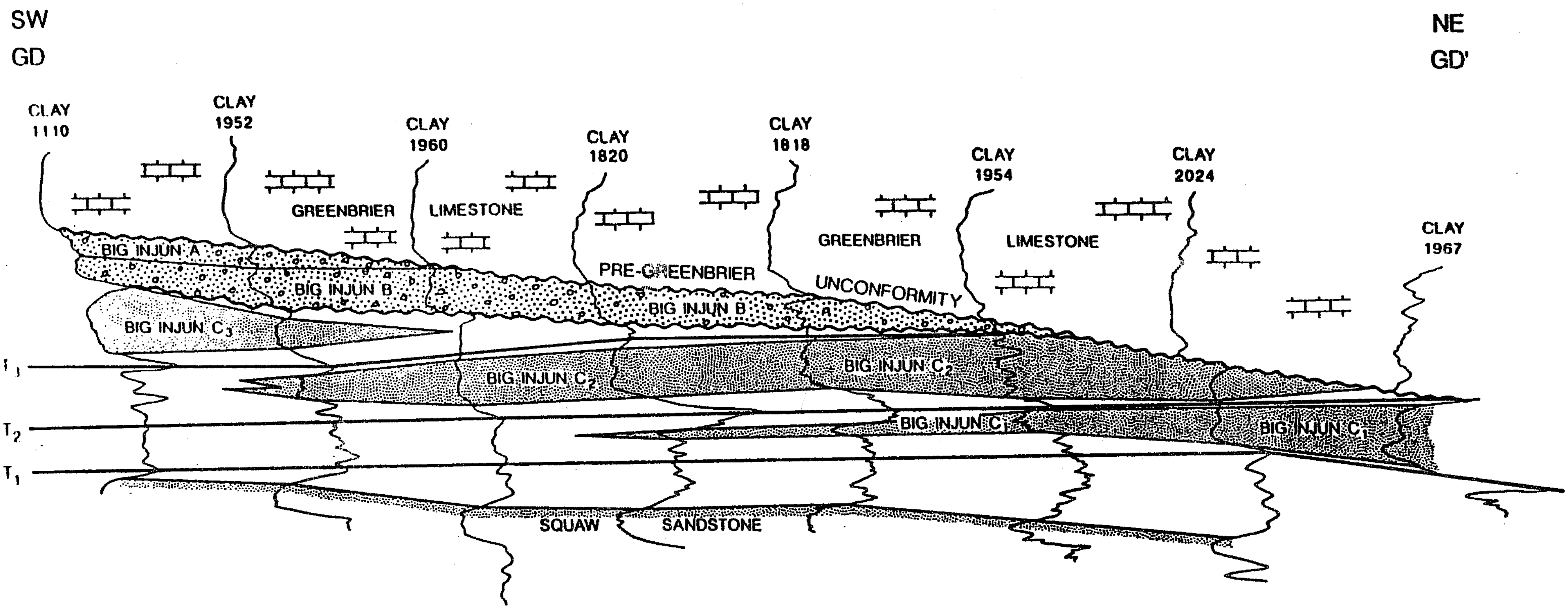


Figure 6. Generalized stratigraphy of the lower Big Injun sandstone based on cross section GD-GD' (see figure 4). The fine-grained sandstones occur as southwestward prograding tongues (C1, C2, C3) of an interpreted ancient river-mouth bar, overlain by pebbly, coarse-grained sandstones (A and B members) representing river channel deposits. The lower Big Injun sandstones pinch out against the pre-Greenbrier (Big Lime) Limestone.

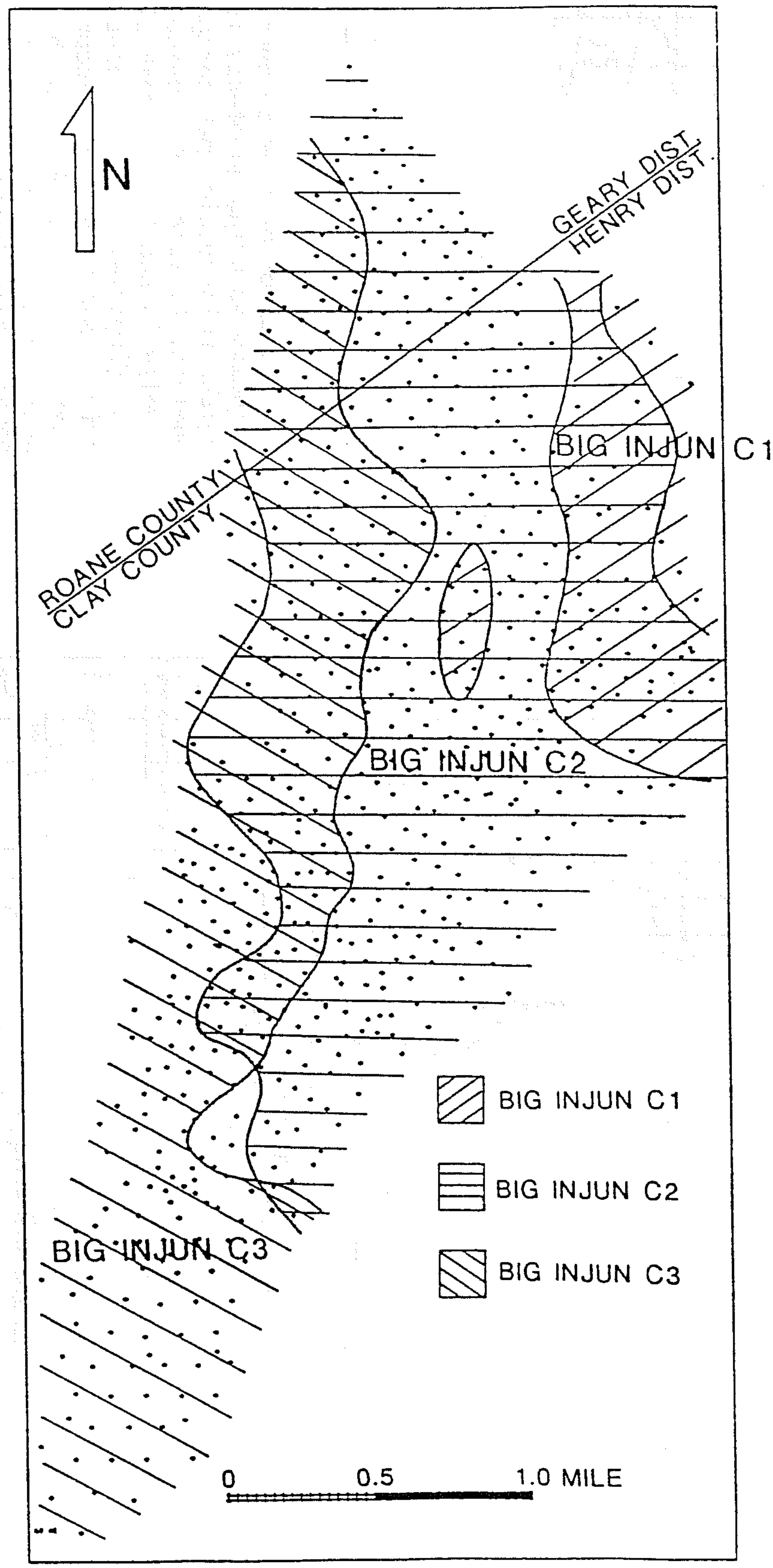


Figure 7. Distribution map of the C1, C2, and C3 tongues of the lower Big Injun sandstone (see figure 6) in the Granny Creek field (see figure 4). The imbricated nature of these members is indicated by the overlapping of units in map view.

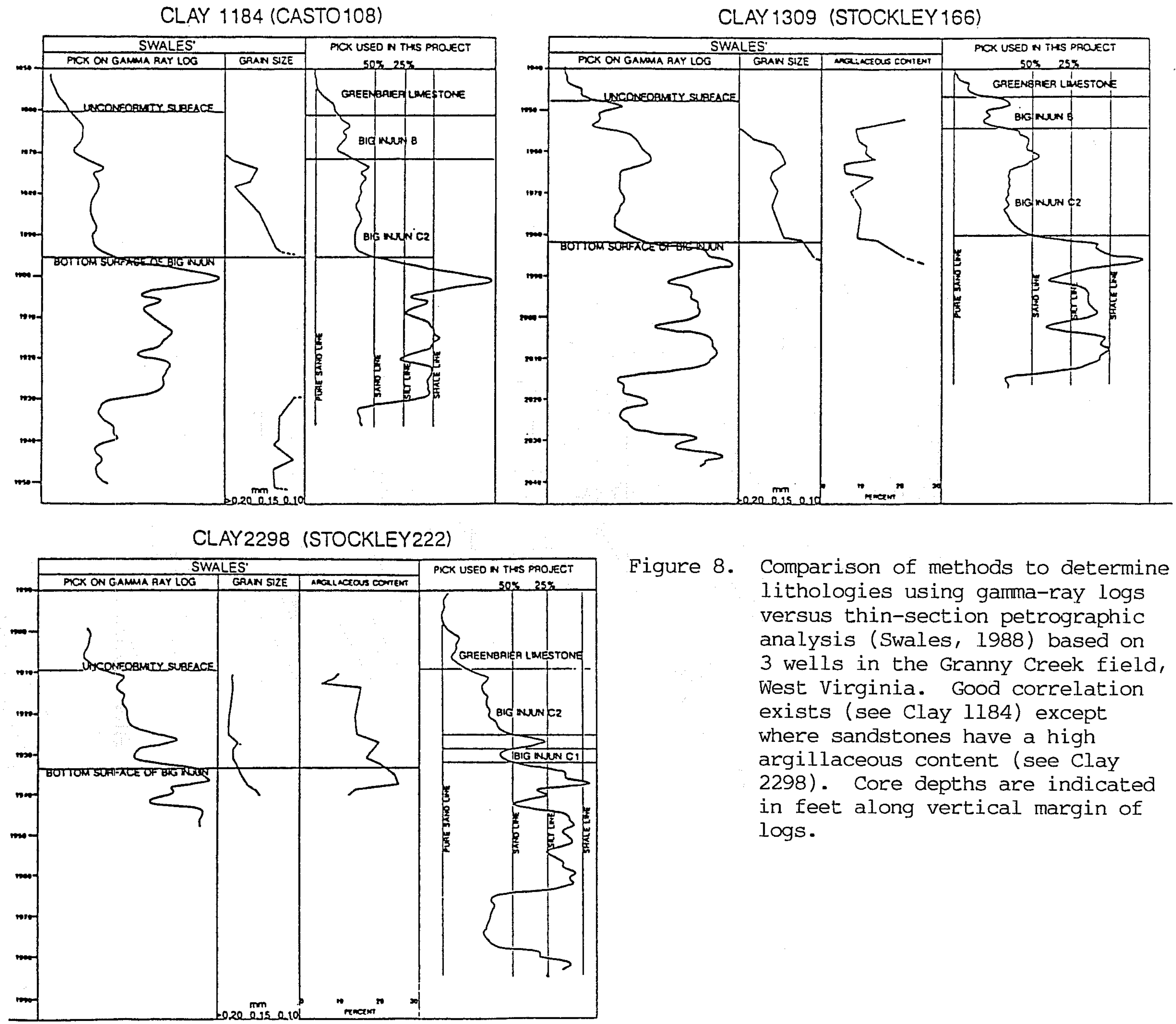


Figure 8. Comparison of methods to determine lithologies using gamma-ray logs versus thin-section petrographic analysis (Swales, 1988) based on 3 wells in the Granny Creek field, West Virginia. Good correlation exists (see Clay 1184) except where sandstones have a high argillaceous content (see Clay 2298). Core depths are indicated in feet along vertical margin of logs.

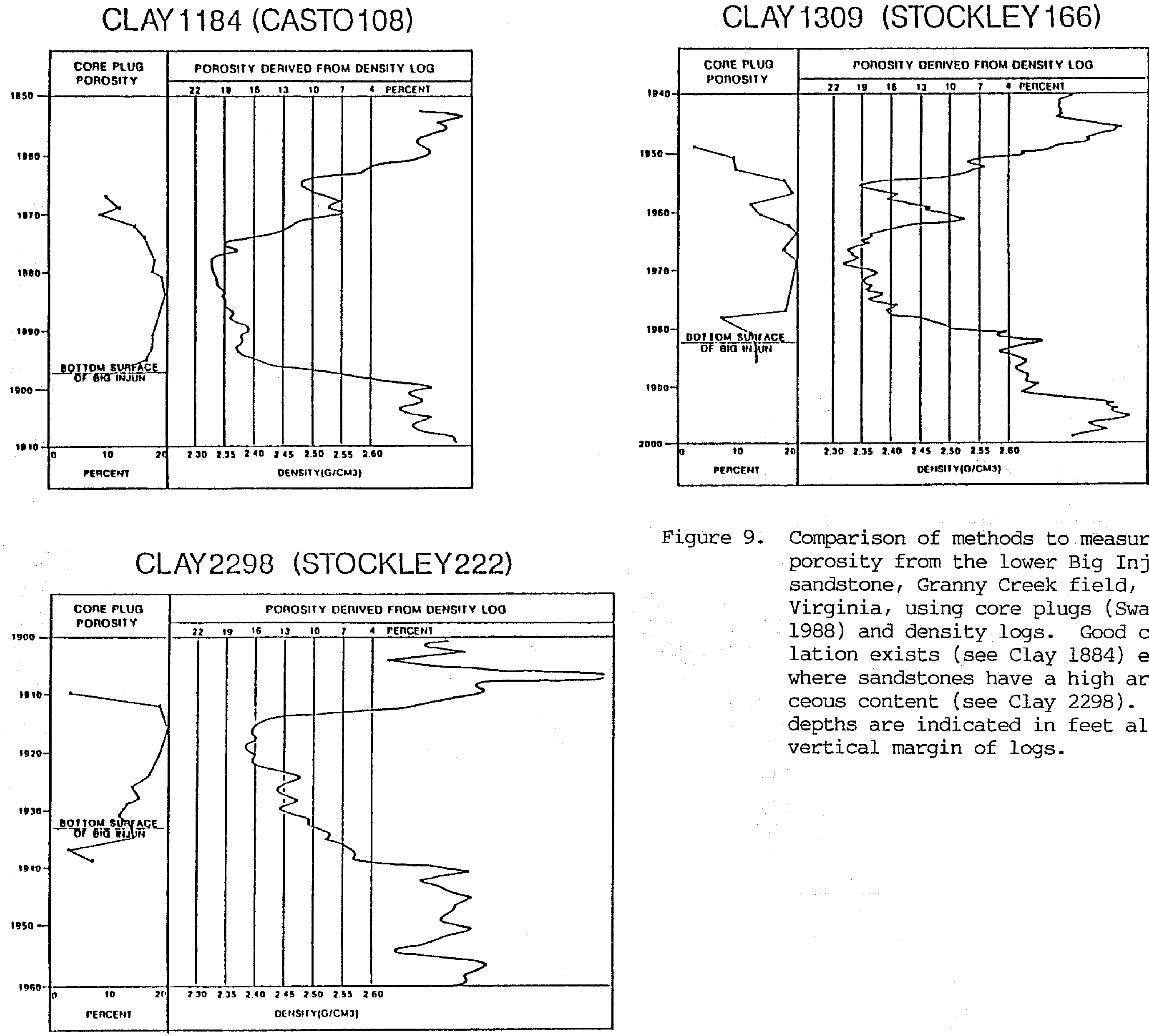
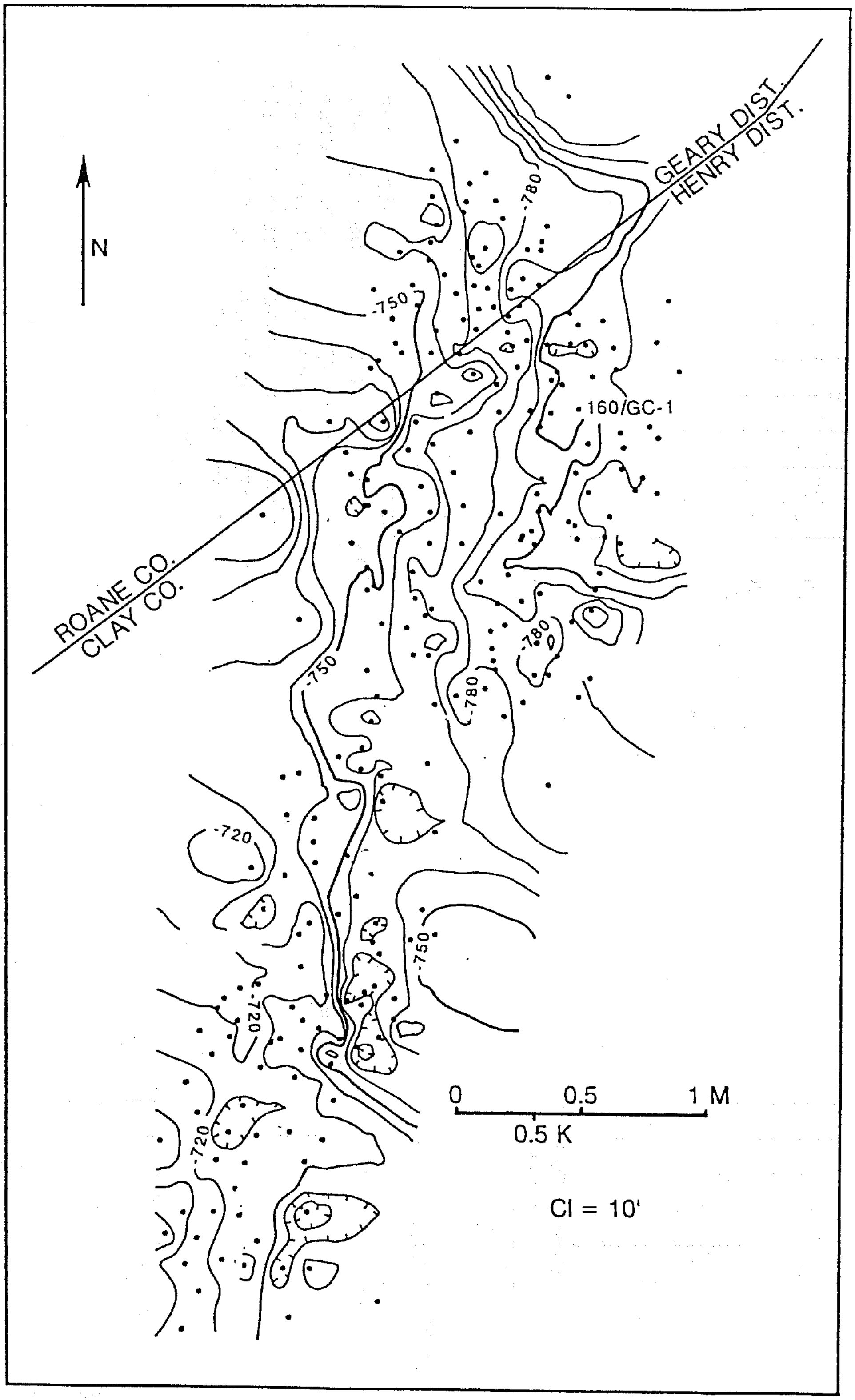


Figure 9. Comparison of methods to measure porosity from the lower Big Injun sandstone, Granny Creek field, West Virginia, using core plugs (Swales, 1988) and density logs. Good correlation exists (see Clay 1884) except where sandstones have a high argillaceous content (see Clay 2298). Core depths are indicated in feet along vertical margin of logs.



GRANNY CREEK FIELD

CLAY & ROANE COS. WV.

Figure 10. Computer-generated subsurface geologic structure map of the Granny Creek oil field, Clay and Roane counties, West Virginia. Contours are drawn on top of the Greenbrier Group (drillers' Big Lime).

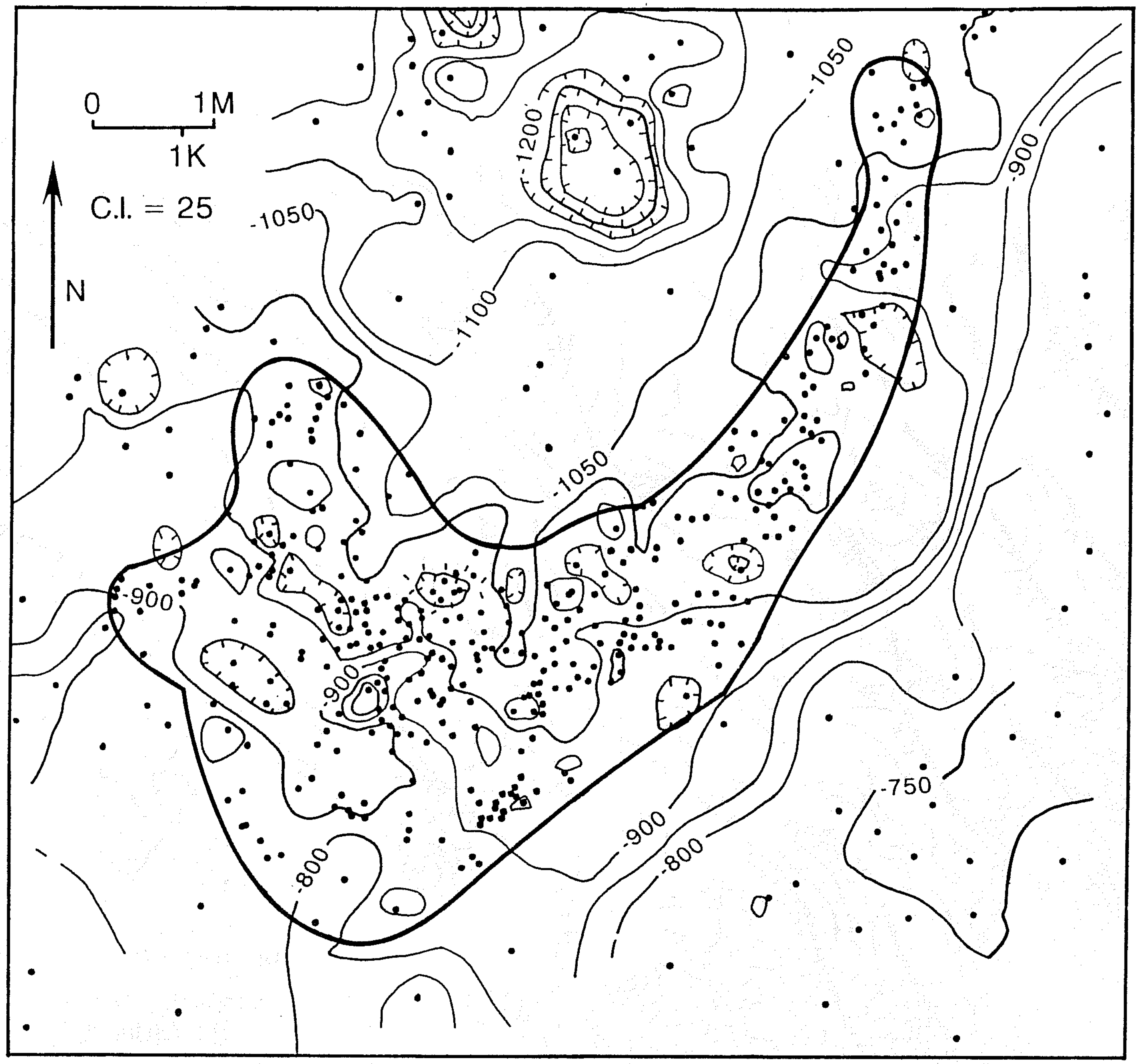


Figure 11. Computer-generated subsurface geologic structure map of the Rock Creek – Johnson Creek oil field, Roane County, West Virginia. Contours are drawn on top of the Greenbrier Group (drillers' Big Lime).

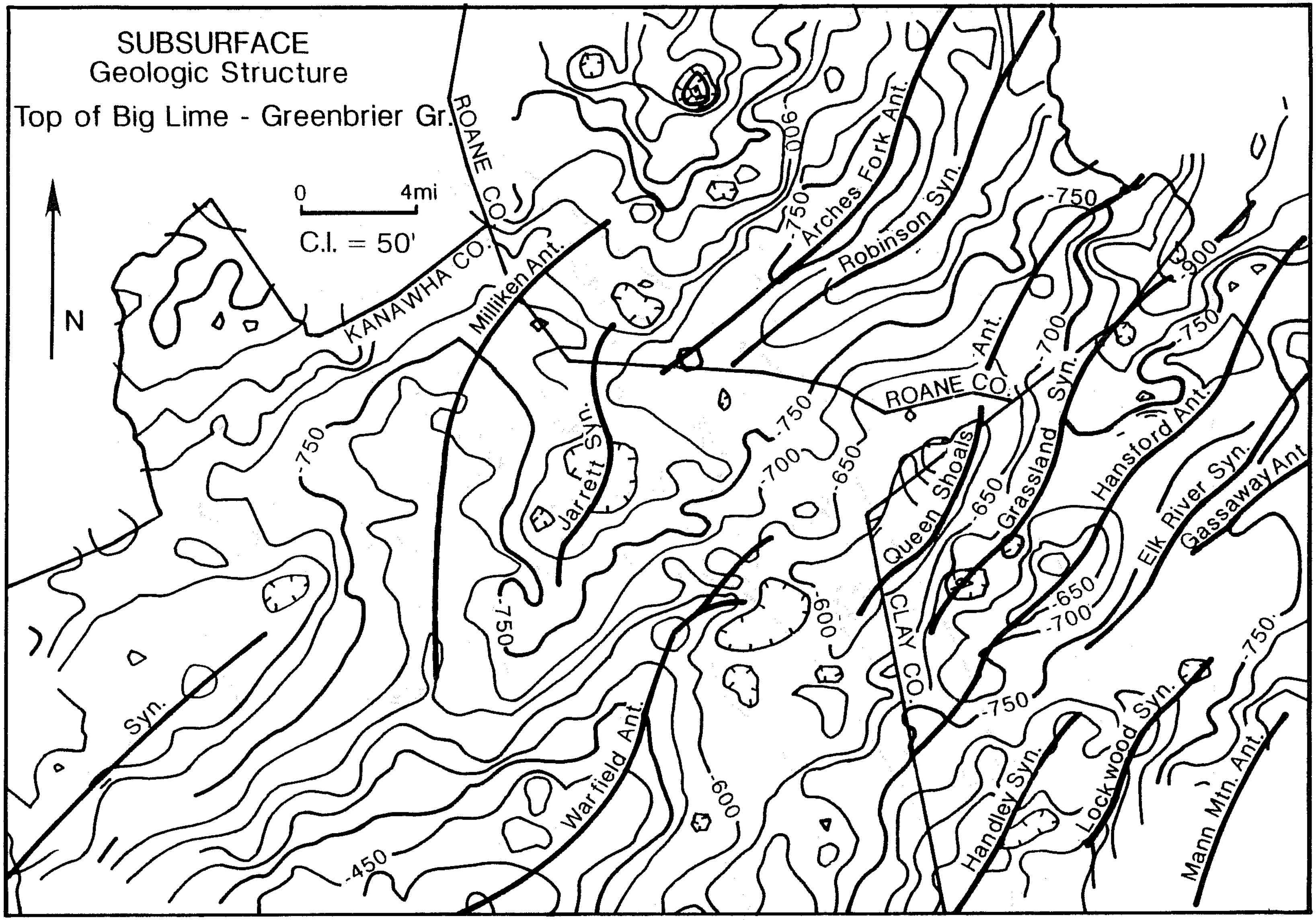


Figure 12. Computer-generated regional subsurface structure map. Contours are drawn on top of the Greenbrier Group (drillers' Big Injun).

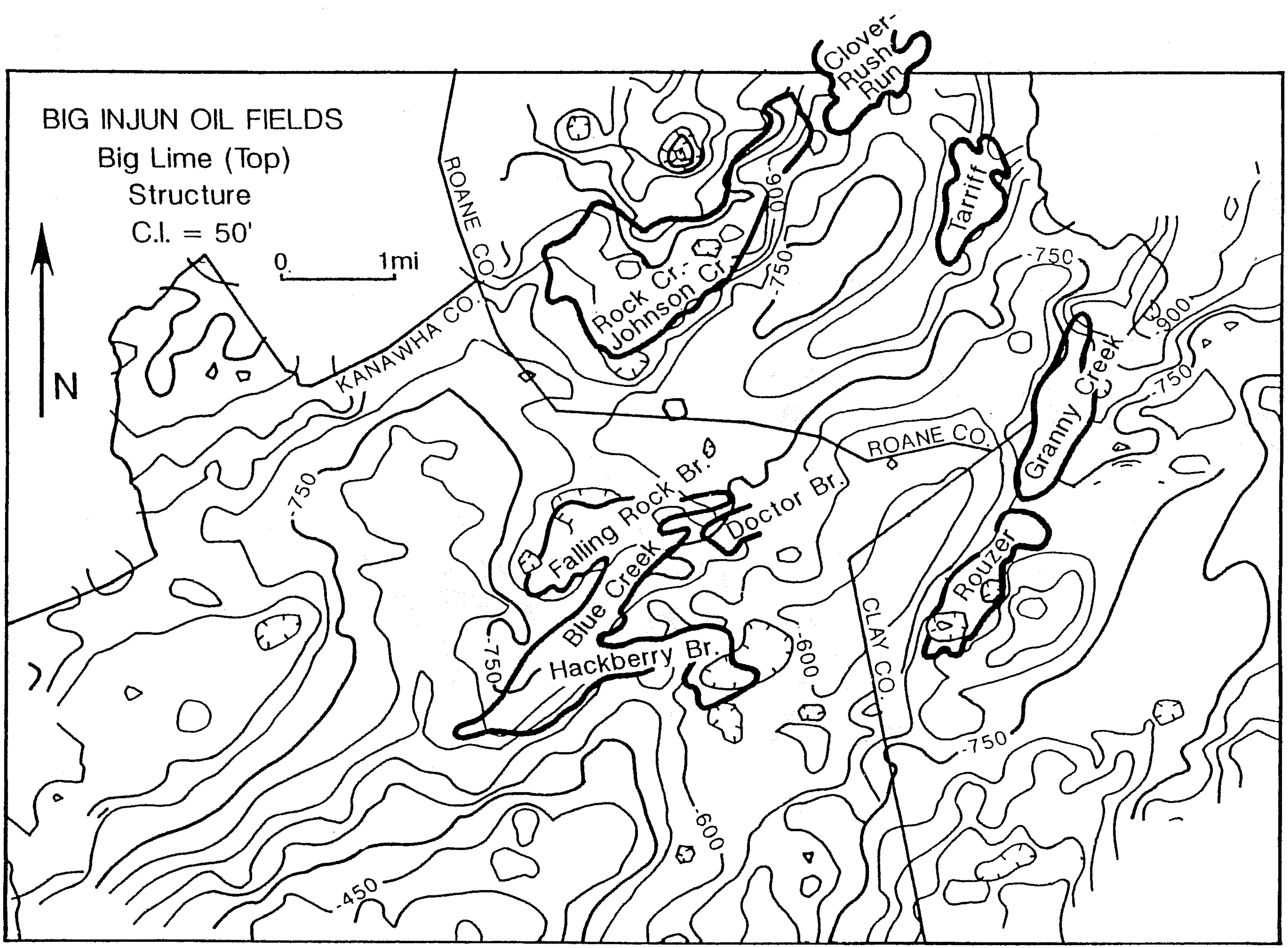


Figure 13. Big Injun oil fields superimposed on regional subsurface stracture map (see figure 12).

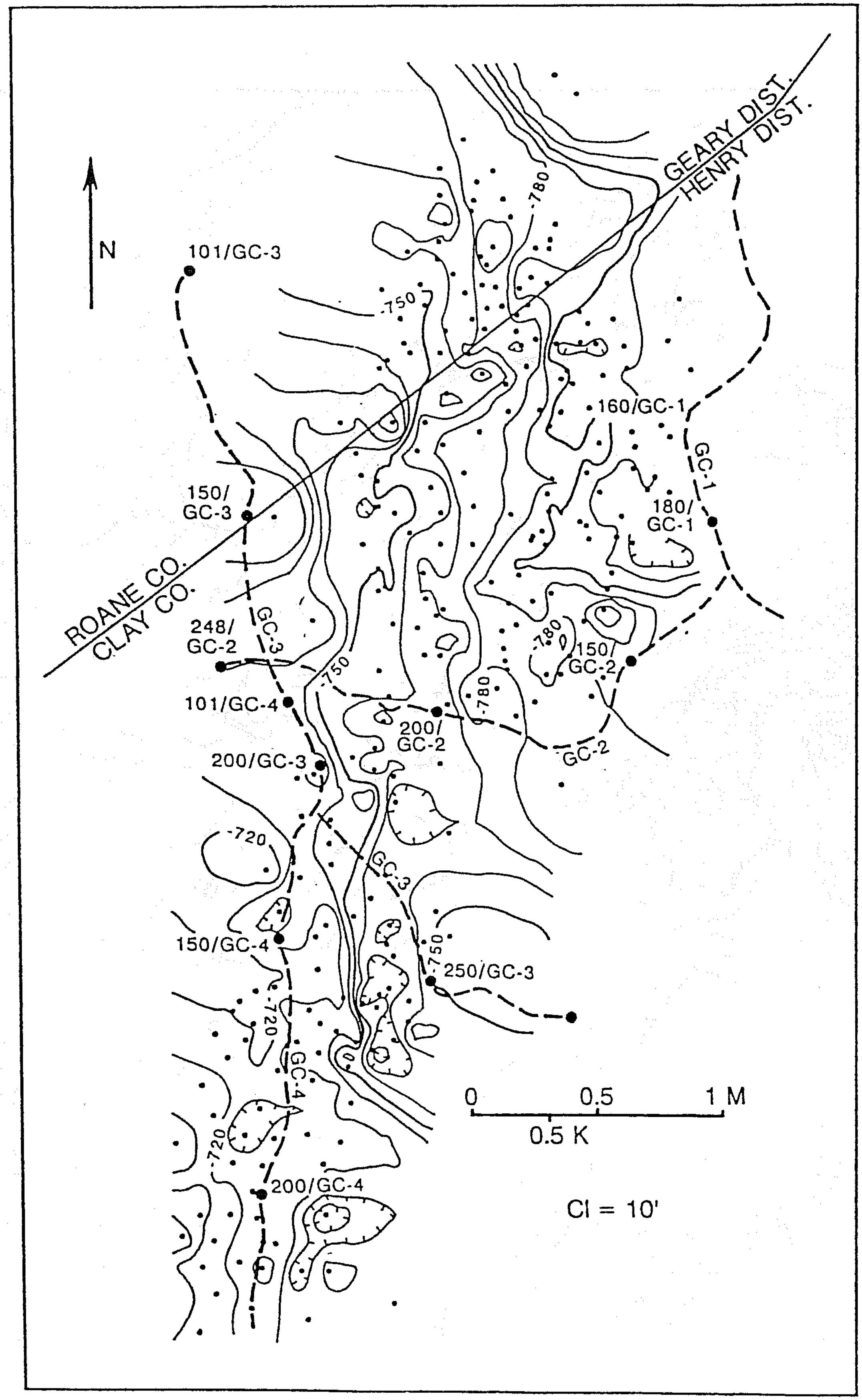


Figure 14. Location of seismic lines on subsurface geologic structure map of the Granny Creek oil field (see figure 10). Large dots with numbers/letters are shot points.

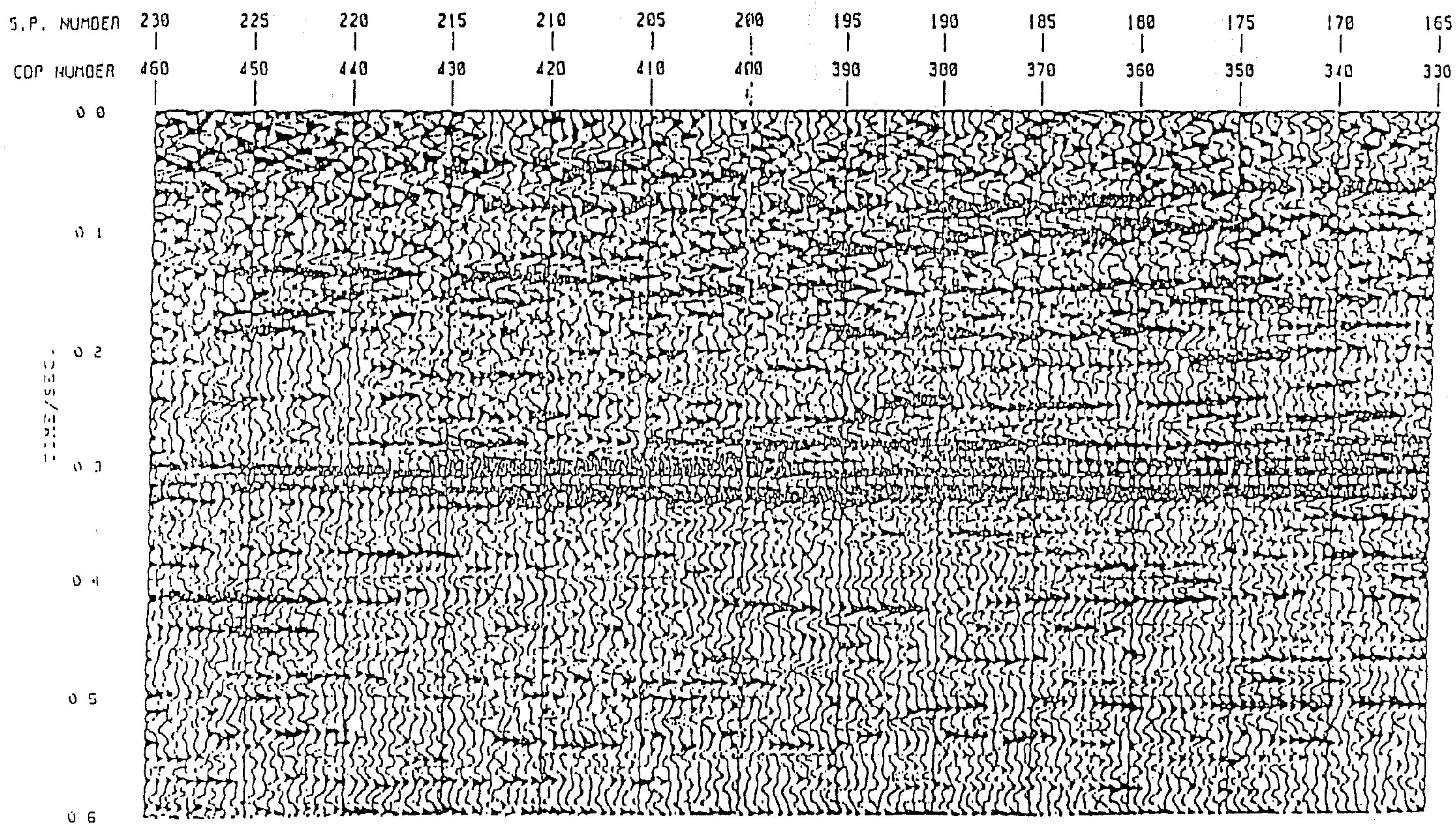


Figure 15. Window of seismic data from seismic line GC-2 through the heart of Granny Creek field. The line was processed by Strata Search, Inc. and is in a zero phase format. The Greenbrier Limestone and the Big Injun sandstone are represented by the large amplitude reflections at approximately 0.3 seconds two-way travel time.

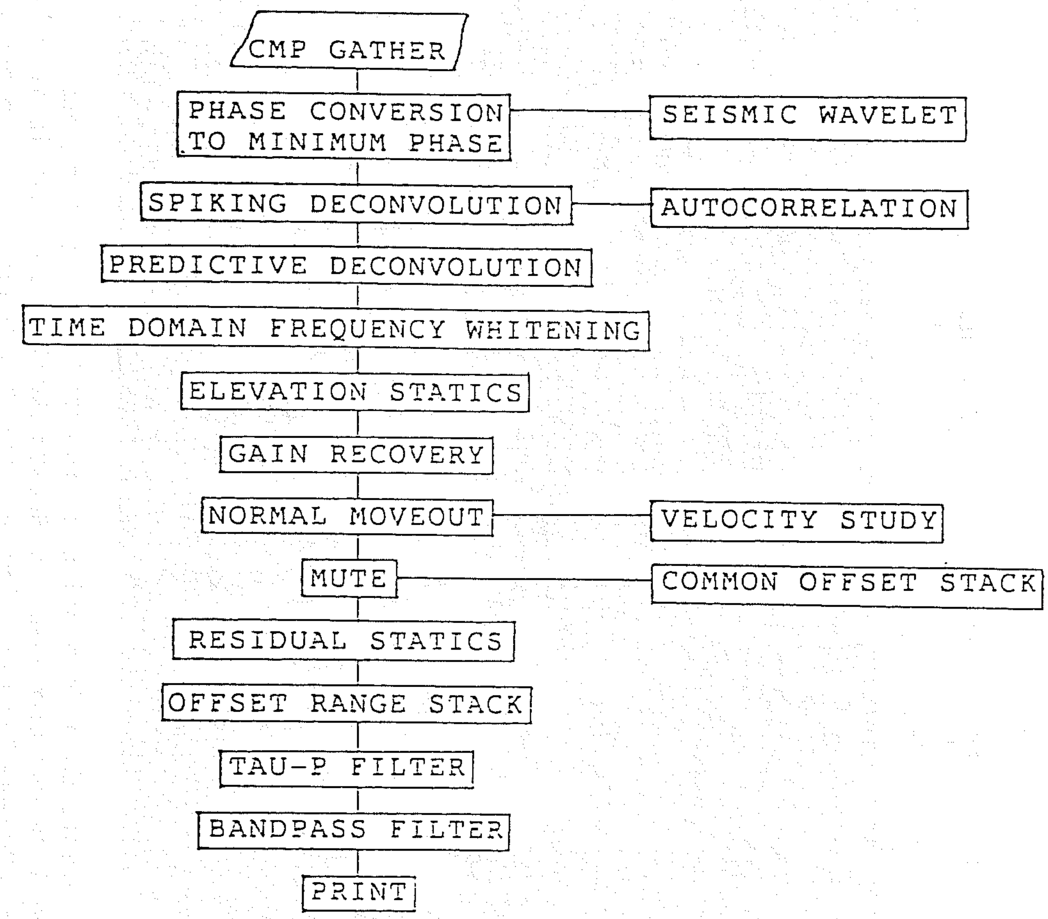


Figure 16. The data processing stream designed in our lab illustrates the sequence of both pre-stack and post-stack reprocessing of the Granny Creek seismic lines.

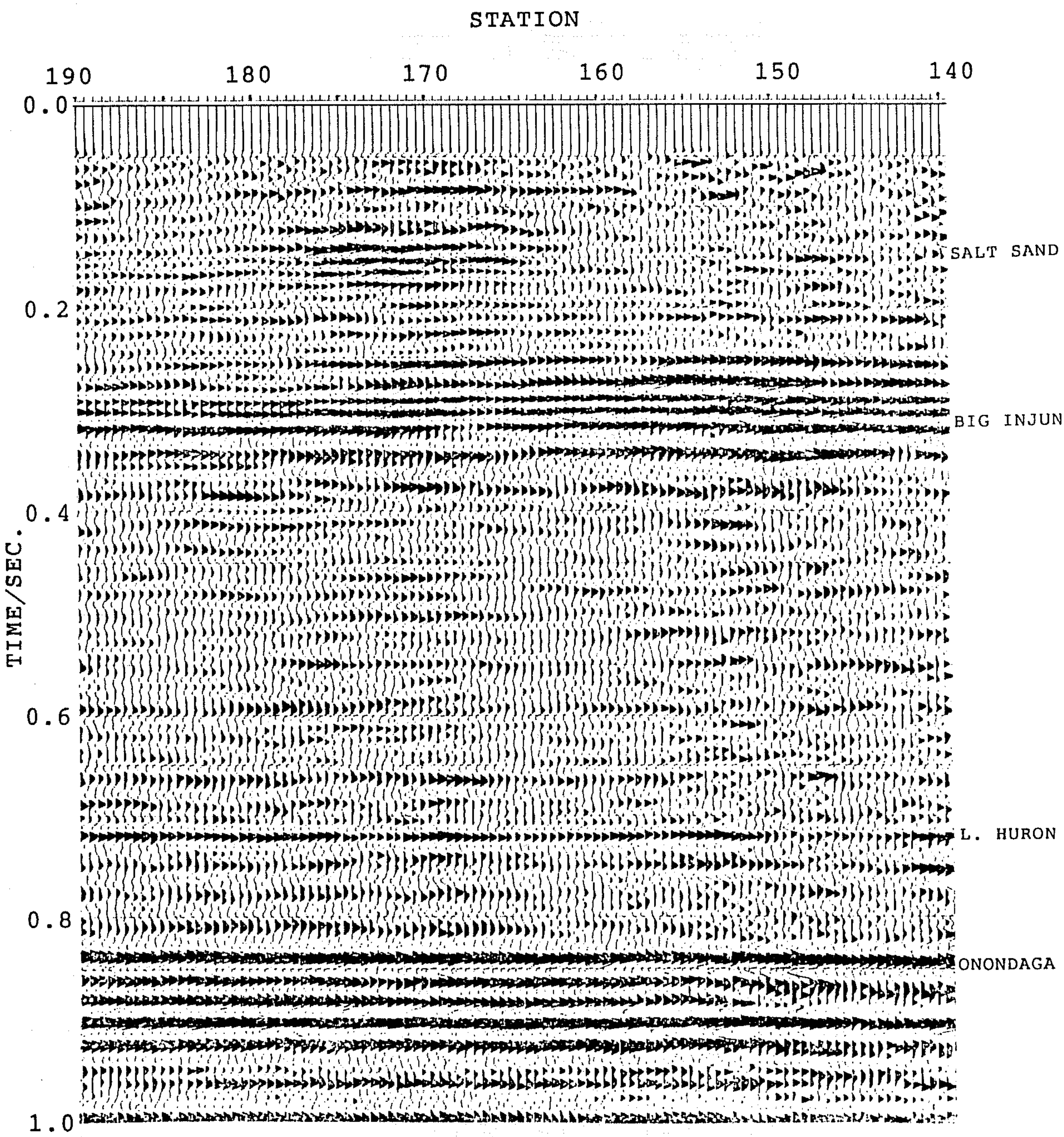


Figure 17. The seismic data along line GC-2 (shown in figure 15) after reprocessing in our lab. An increase in the resolution and coherence of shallow reflections has been achieved.

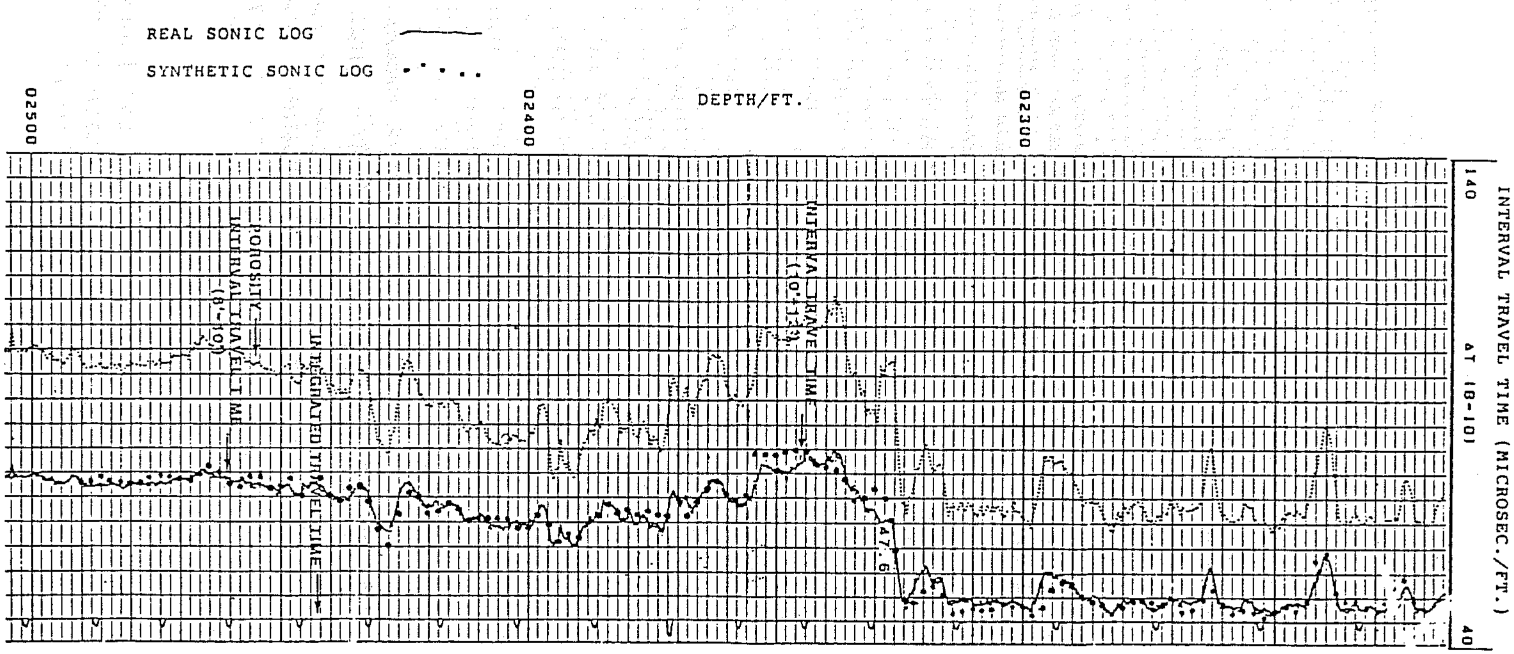


Figure 18. Interval transit times estimated solely from the radiation logs (Calculated Sonic Log) in the Clay 2426 well are compared to actual interval transit times recorded on the sonic log of this interval.

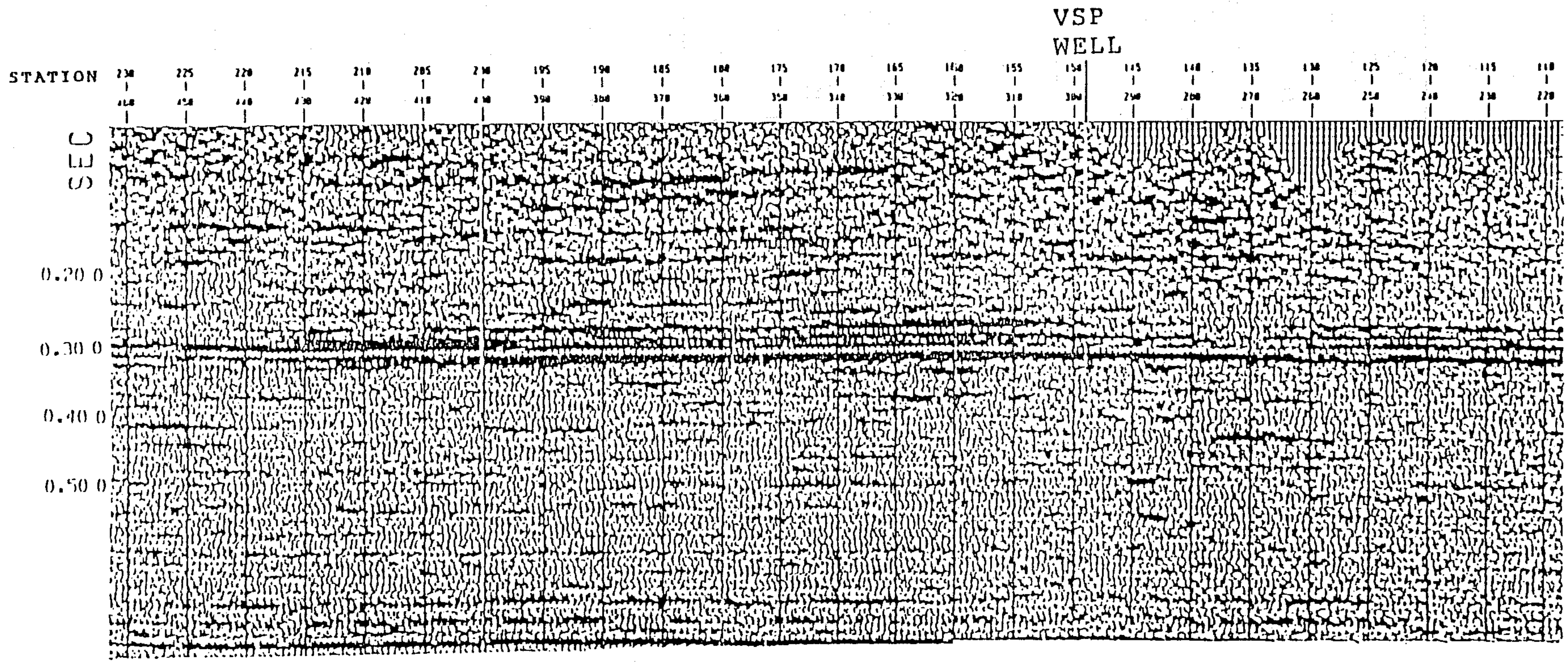


Figure 19. Seismic data along line GC-2 in the vicinity of the VSP (Vertical Seismic Profile) well. This well is located close to Station Number 149 or CMP (Common Midpoint) Number 298. Reflections from the Big Injun and other stratigraphic intervals in the section are labeled.

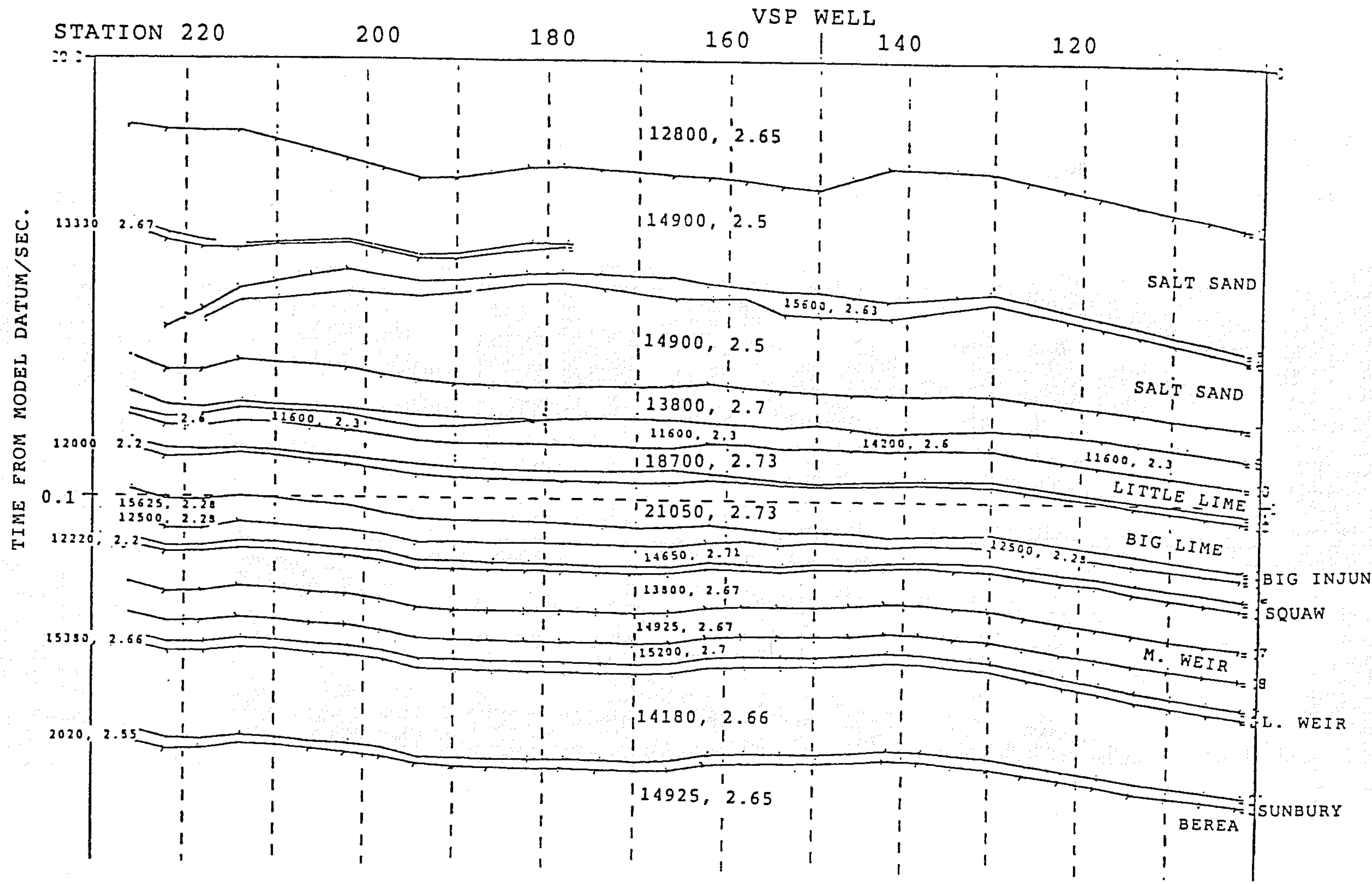


Figure 20. A generalized acoustic model of the subsurface along line GC-2. Layers in the model representing the Big Injun and other stratigraphic intervals in the section are labeled.

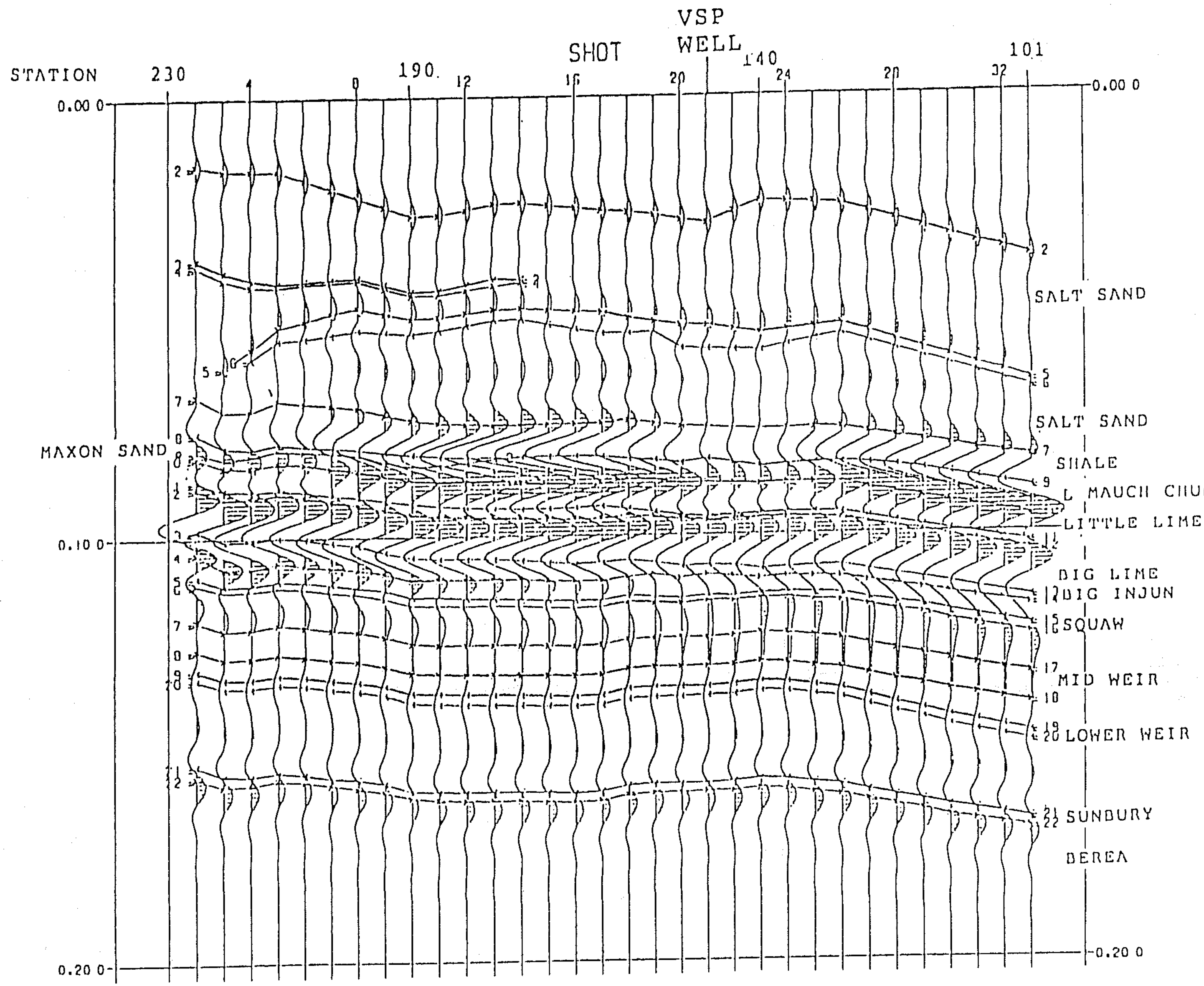


Figure 21. The synthetic seismic response of the acoustic model (see figure 20) forms a basis for identifying reflections in the seismic data over Granny Creek field.

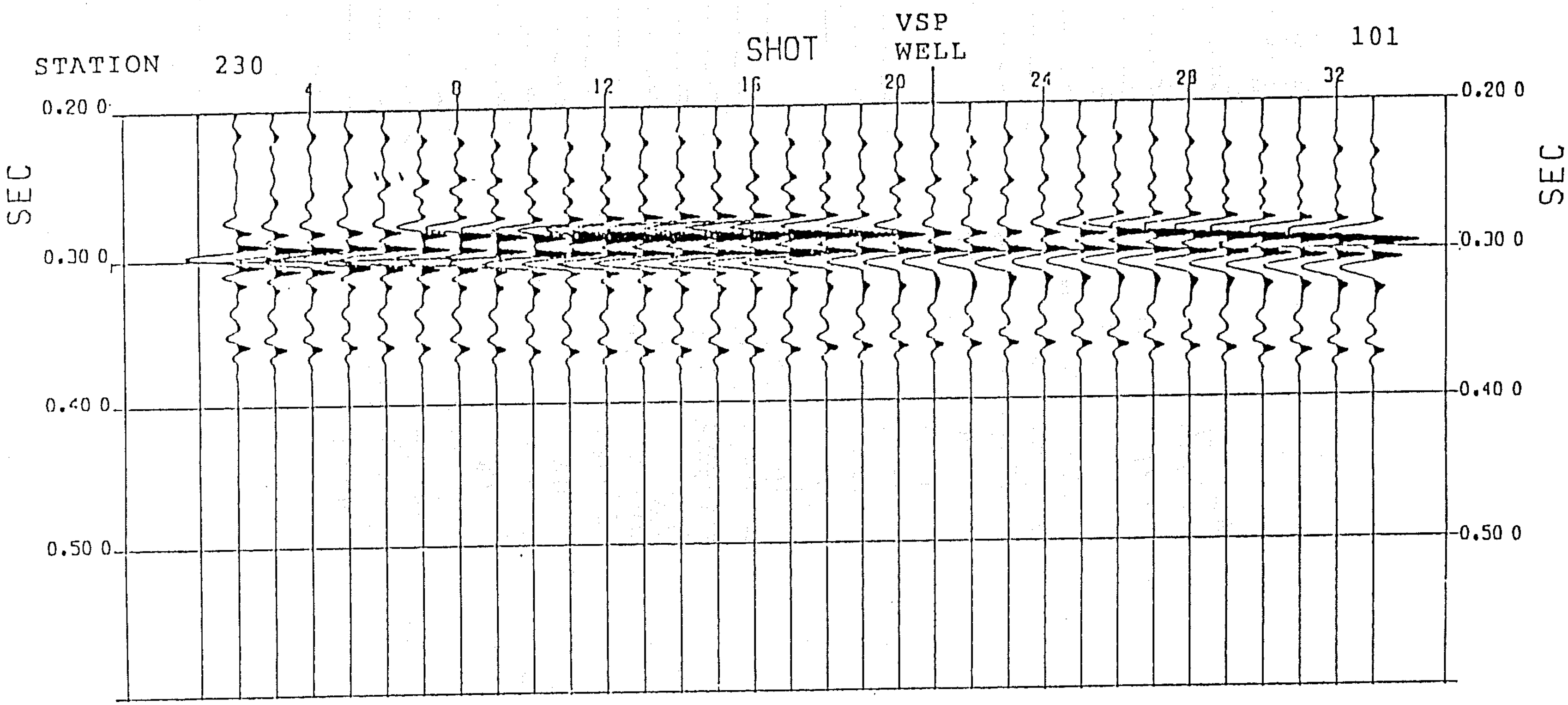


Figure 22. The synthetic data (see figure 21) are replotted in a variable-area wiggly-trace display format for comparison to seismic data shown in figure 19.

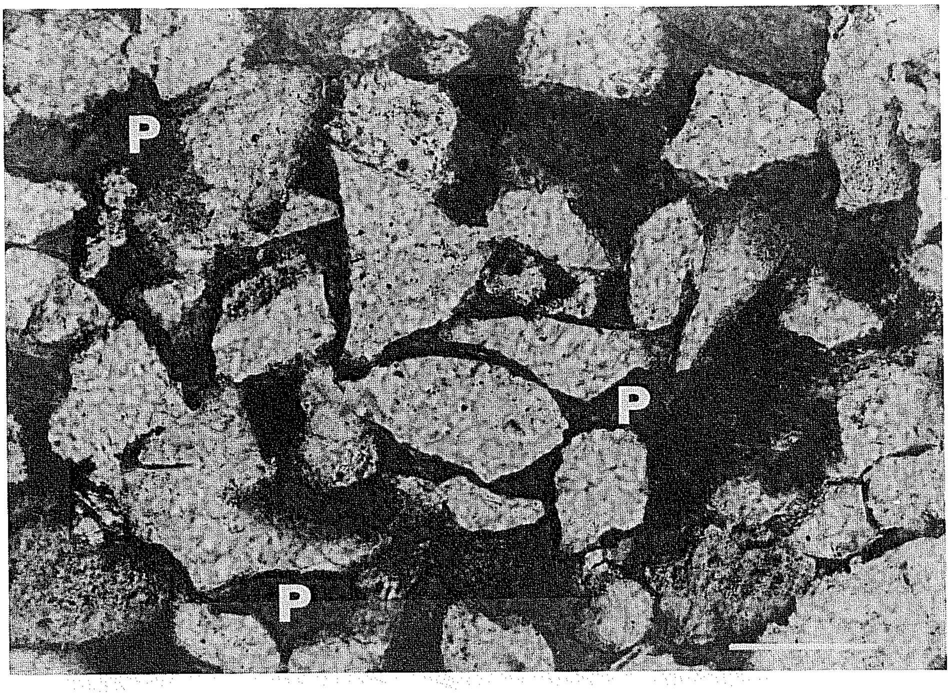


Figure 23. Photomicrograph (plain polarized light) of chlorite-coated quartz sandstone with good porosity. Sample from 1910.3 ft in well Clay 1110. Pores (P). Bar length 0.1 mm.

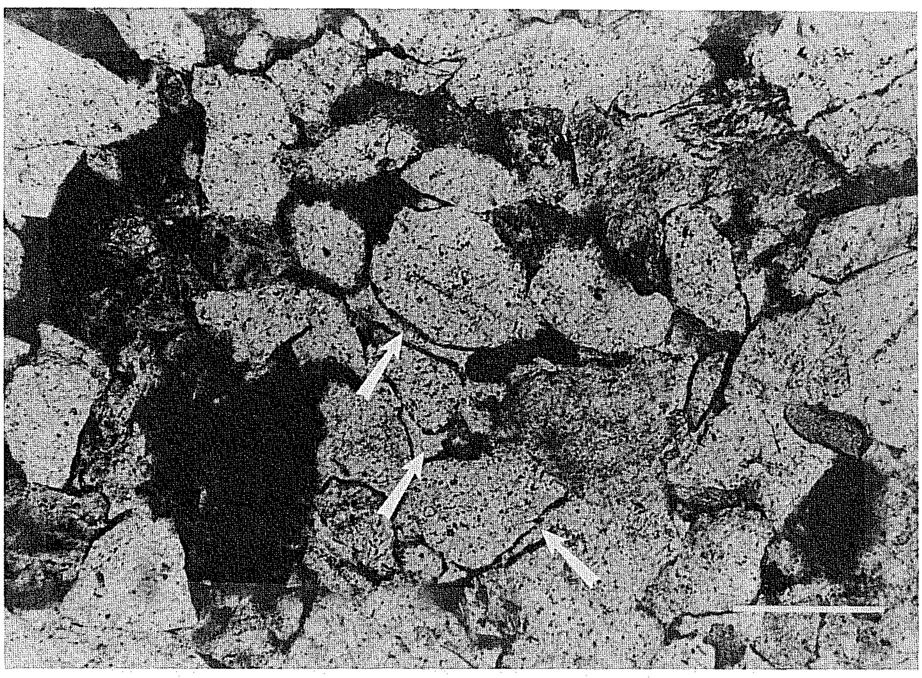


Figure 24. Photomicrograph (plain polarized light) of secondary quartz (arrows) filling pores. Sample from 1899.2 ft in well Clay 1110. Bar length 0.2 mm.

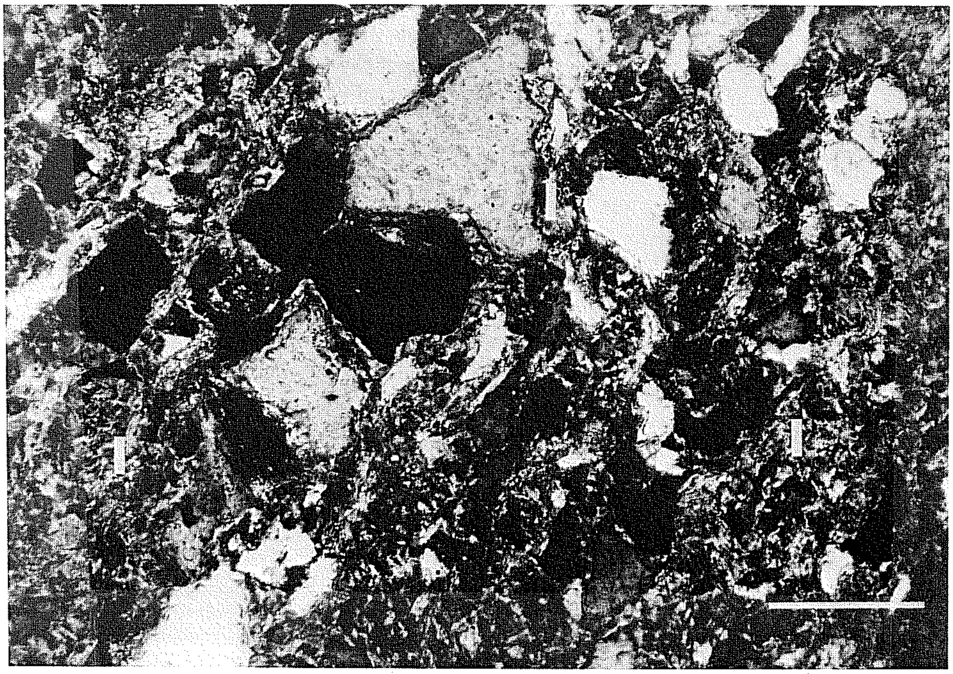


Figure 25. Photomicrograph (crossed nicols) of illite (I) around quartz grains. Sample from 1864.5 ft in well Clay 1130. Bar length 0.2 mm.

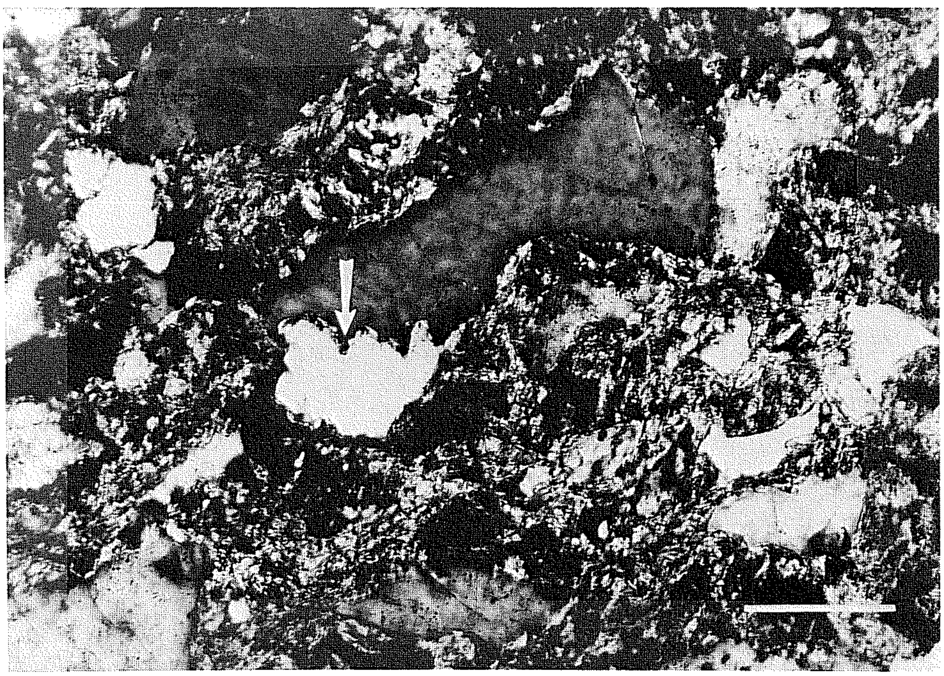


Figure 26. Photomicrograph (crossed nicols) of pressure solution between quartz grains (arrow) in illitic sandstone. Sample from 1864.5 ft in well Clay 1130. Bar length 0.1 mm.

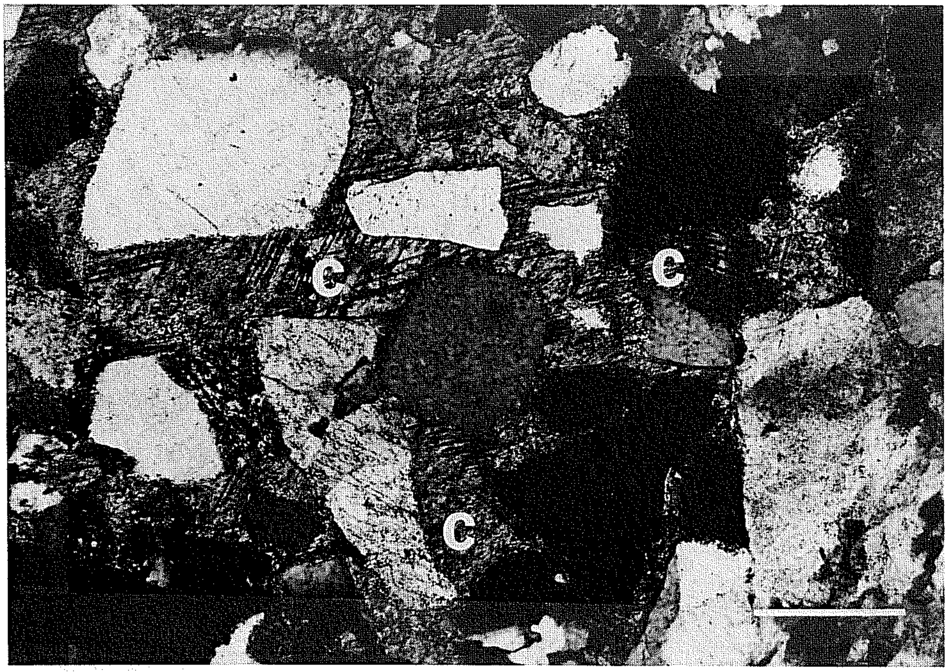


Figure 27. Photomicrograph (plain polarized light) of calcite (C) cemented sandstone. Sample from 1883.3 ft in well Clay 1110. Bar length 0.2 mm.

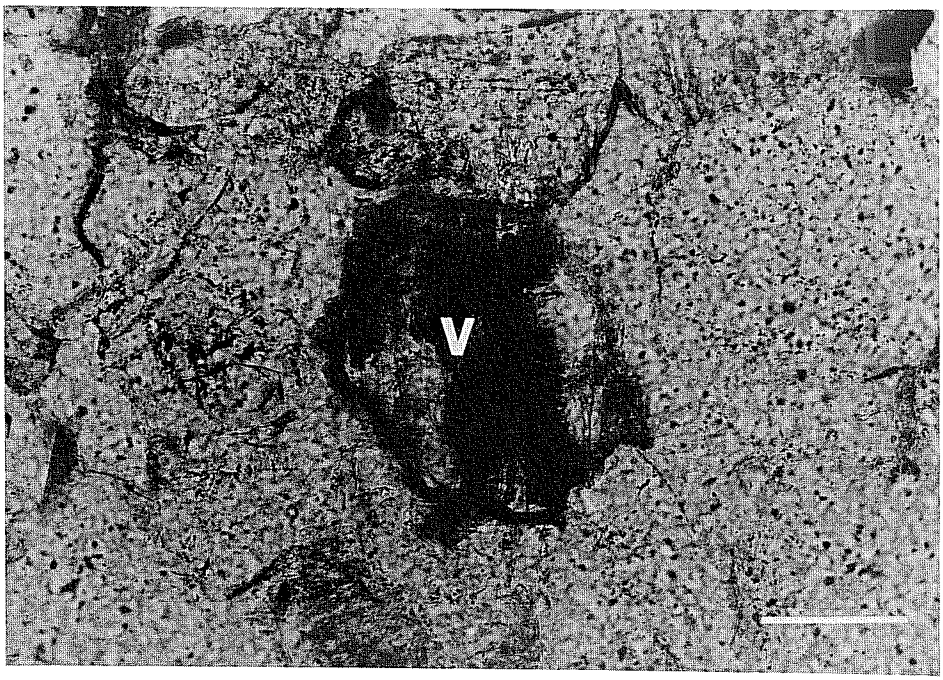


Figure 28. Photomicrograph (plain polarized light) of a void (V) in partially dissolved feldspar. Sample from 1899.2 ft in well Clay 1110. Bar length 0.1 mm.

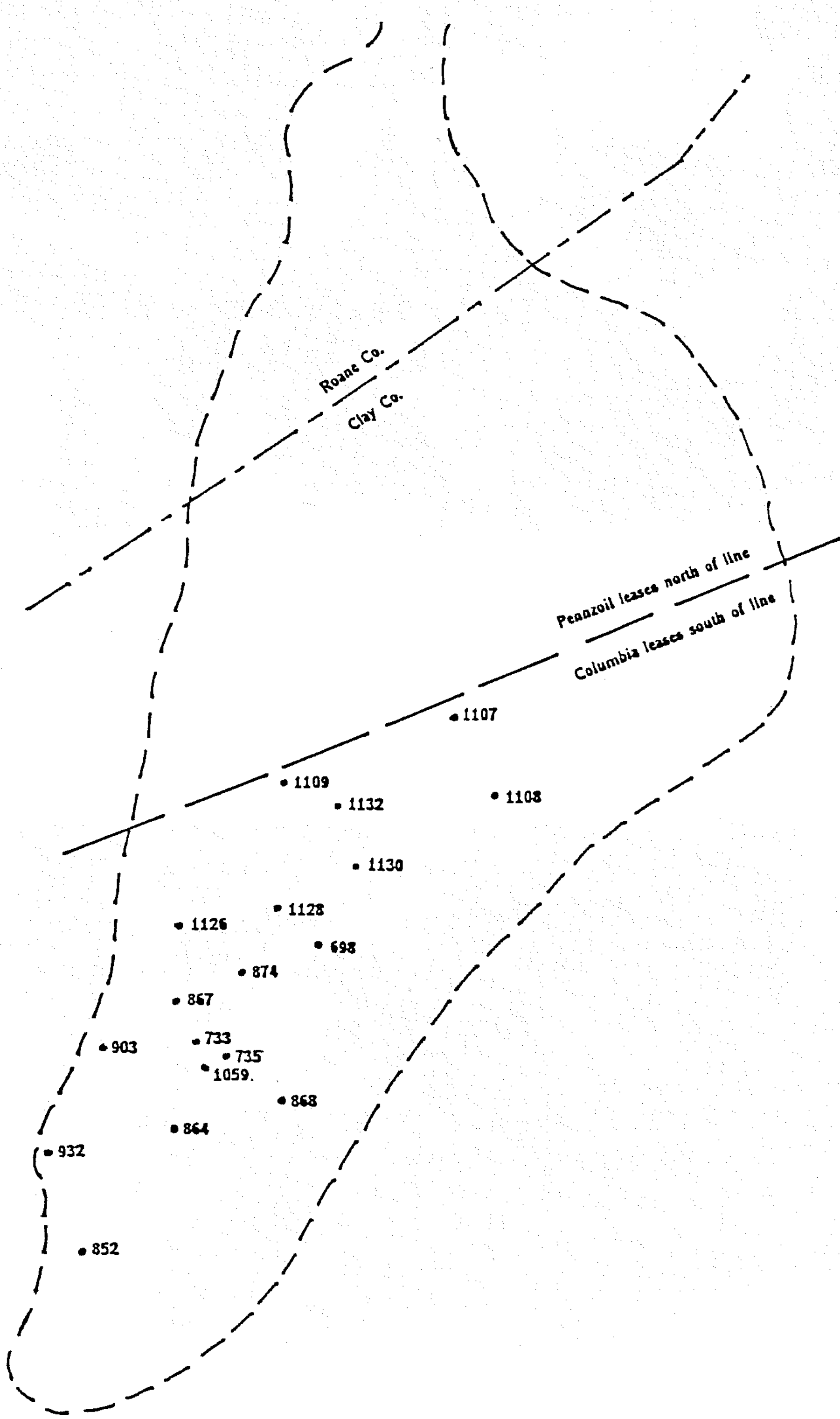


Figure 29. Approximate location with permit numbers for wells with Big Injun sandstone core samples in the Granny Creek field.

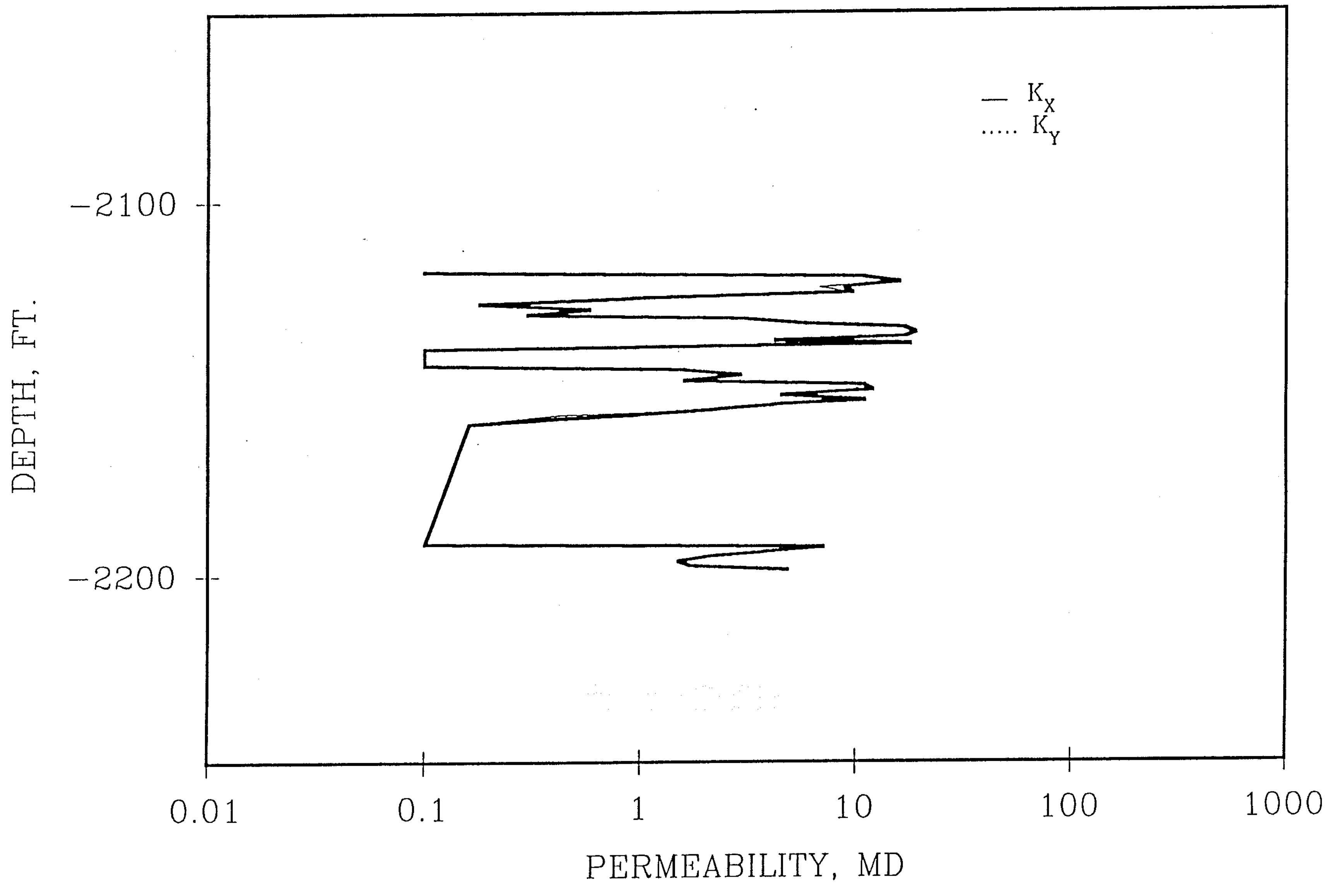


Figure 30. Permeability variation with depth in the Big Injun sandstone, Granny Creek field, CNR well 20310 (permit Clay 1107).

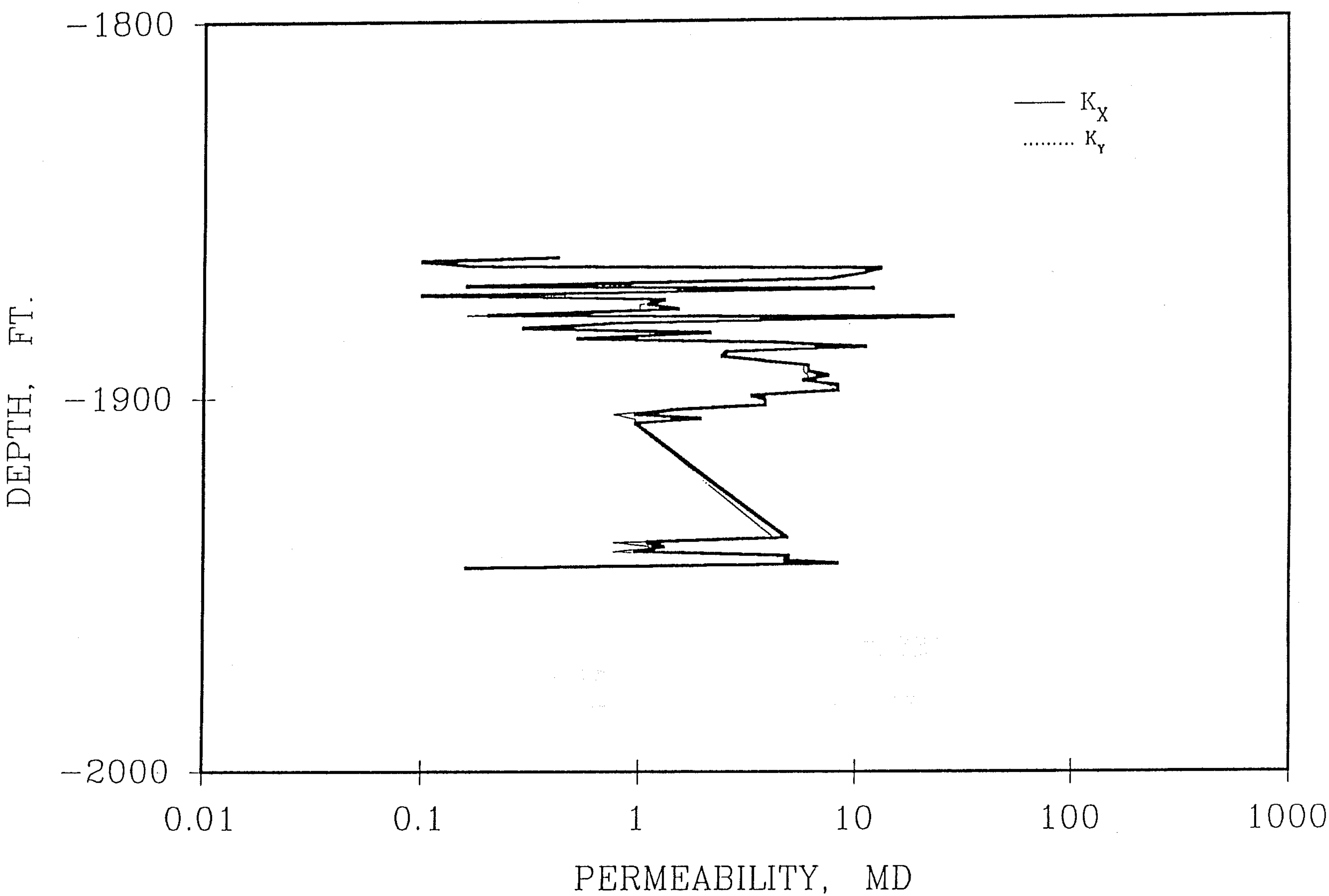


Figure 31. Permeability variation with depth in the Big Injun sandstone, Granny Creek field, CNR well 20313 (permit Clay 1130).

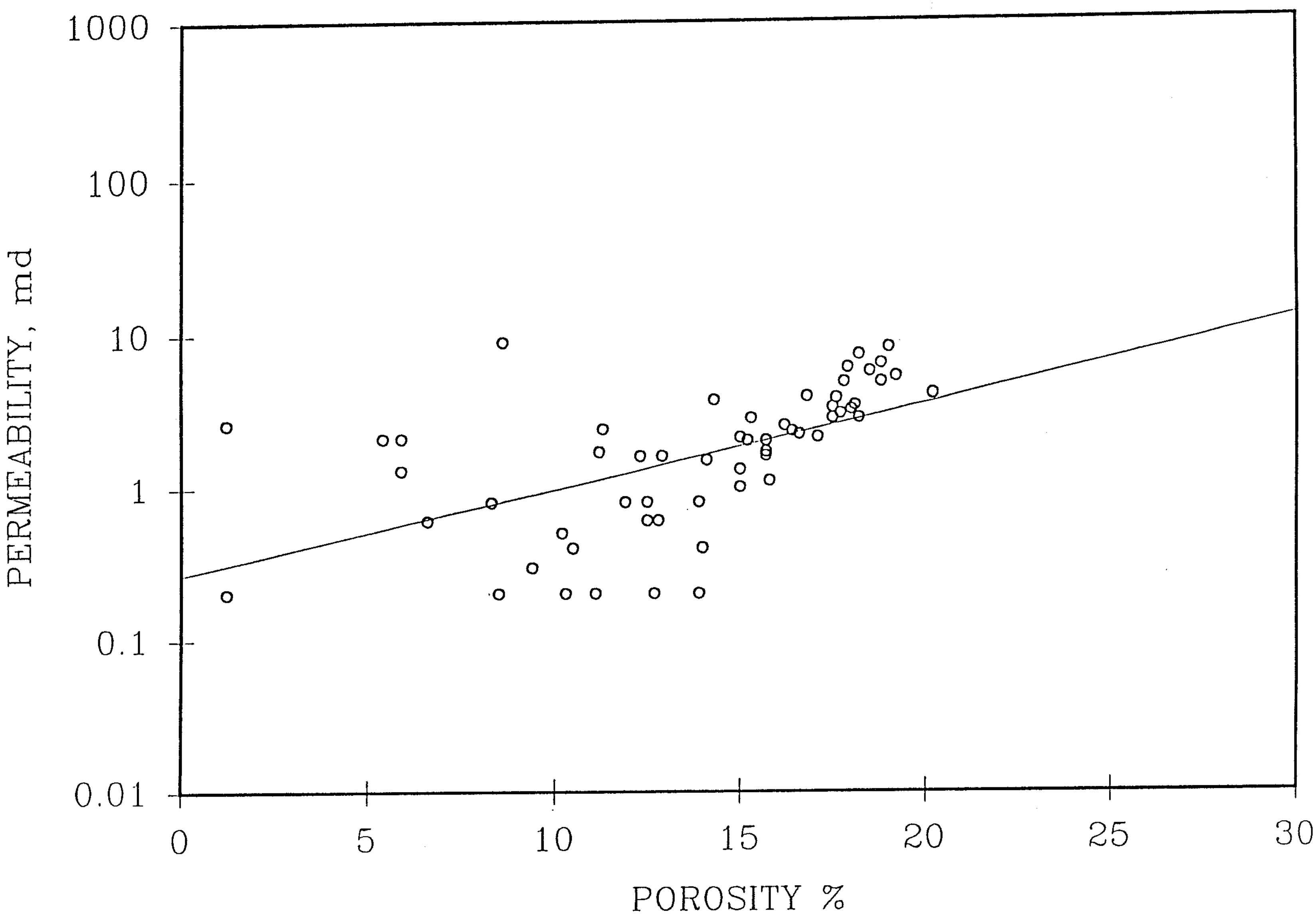


Figure 32. Permeability and porosity correlation in the Big Injun sandstone, Granny Creek field, Pennzoil's J.B. Casto 108 (permit Clay 1184).

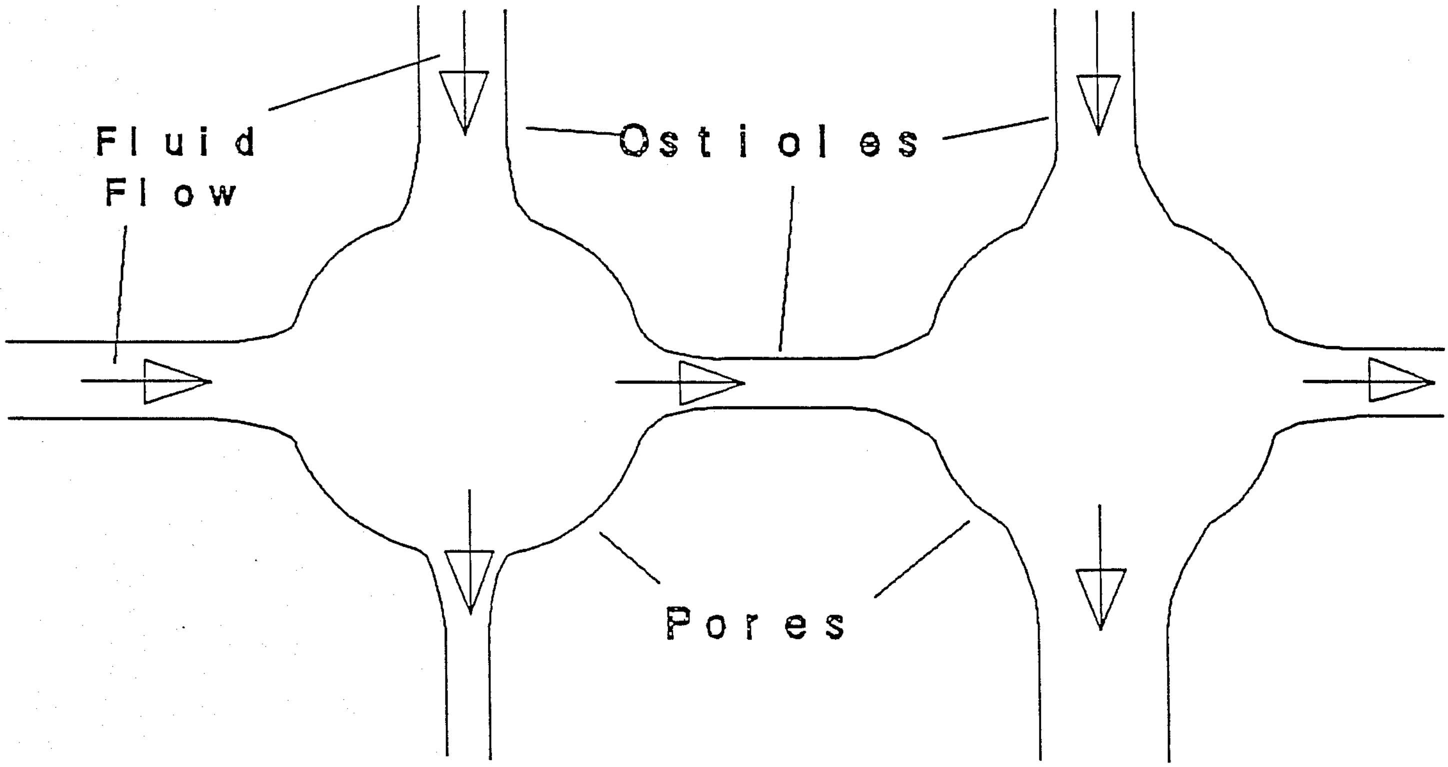


Figure 33. Diagram of ostiole configuration between pores.

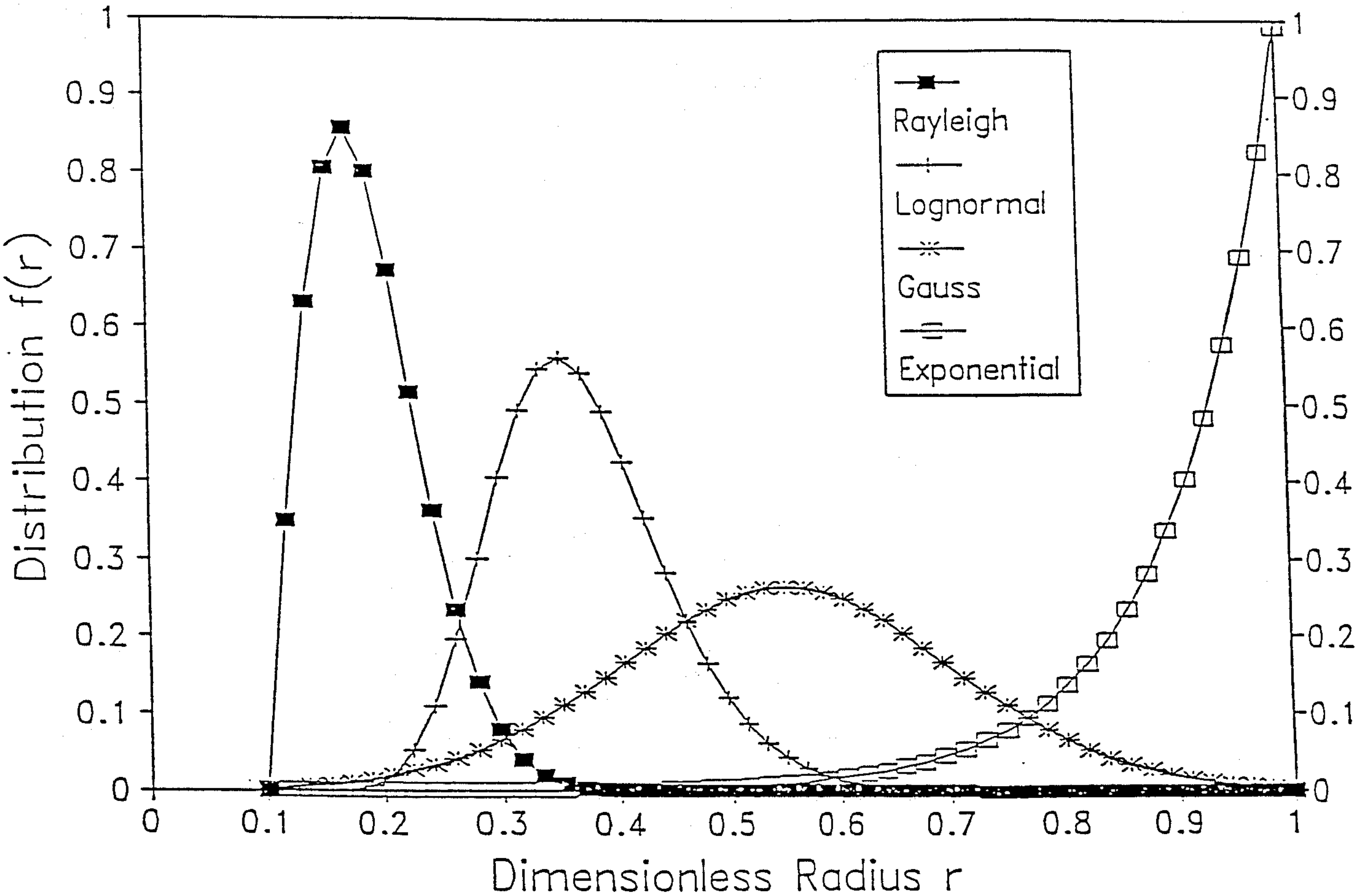


Figure 34. The normalized ostiole size distributions used in the pore network model.

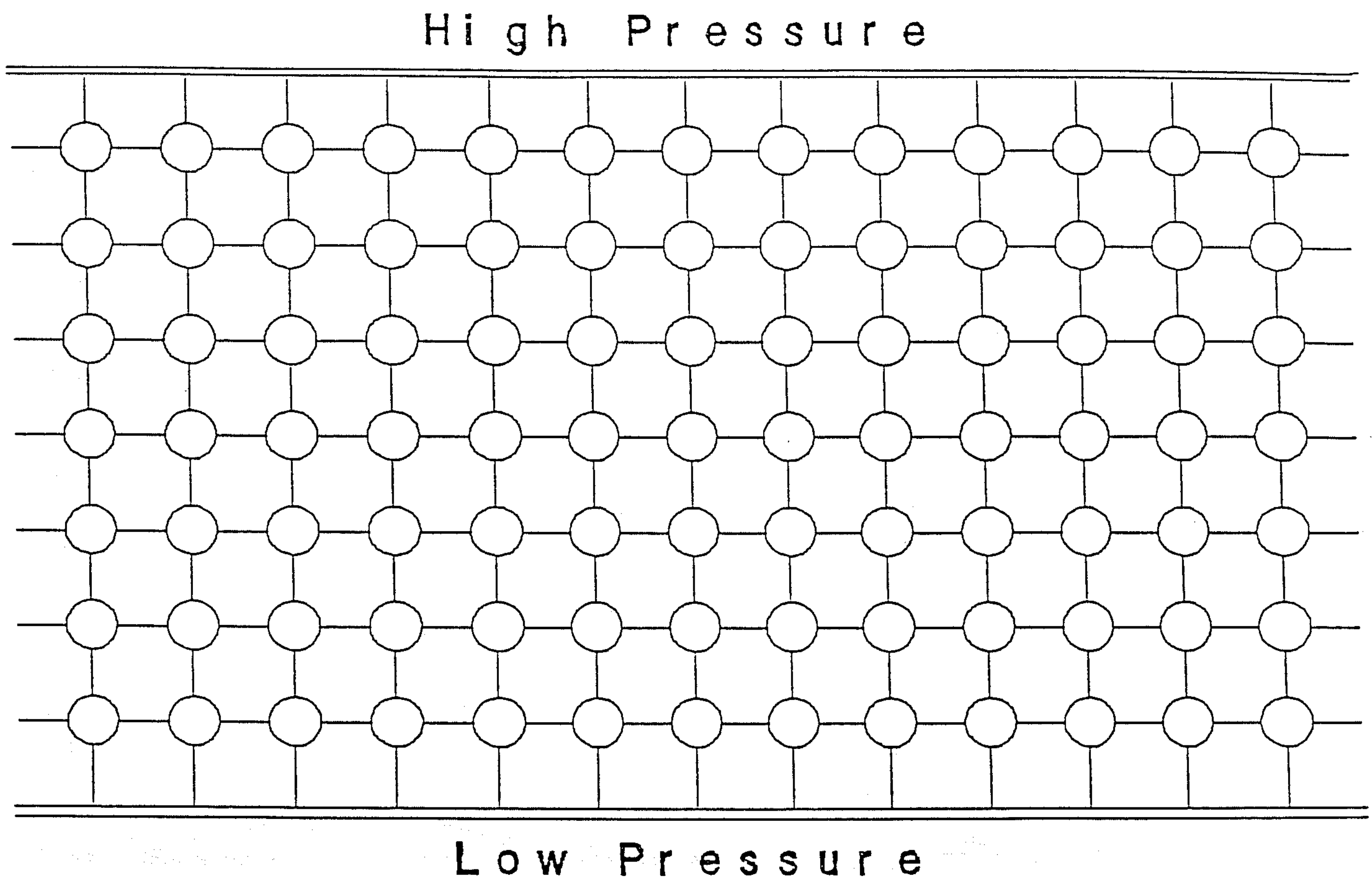


Figure 35. Two-dimensional pore network consisting of ostioles and connections.

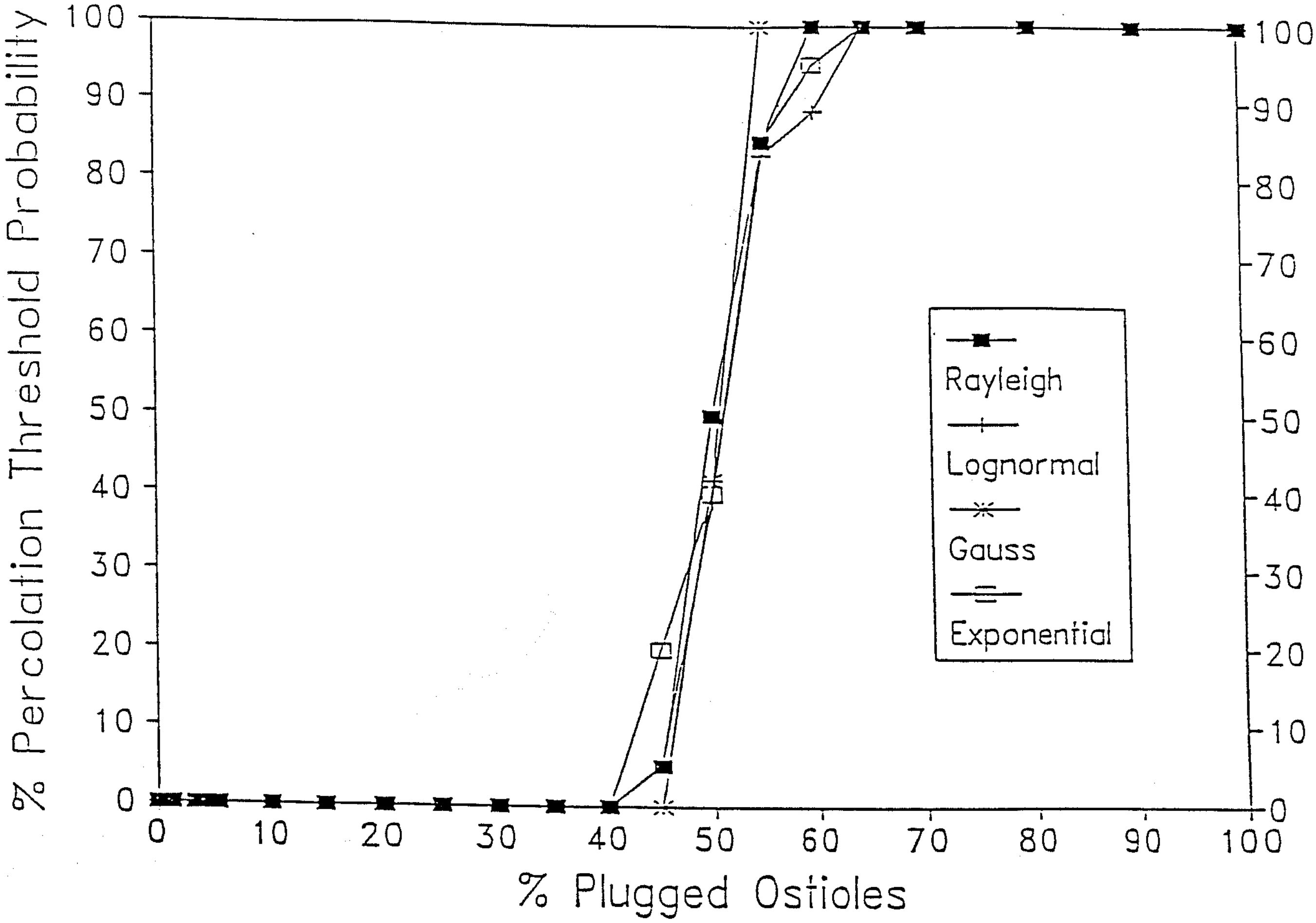


Figure 36. The probability of reaching percolation threshold as a function of percent of plugged ostioles and ostiole size distribution.

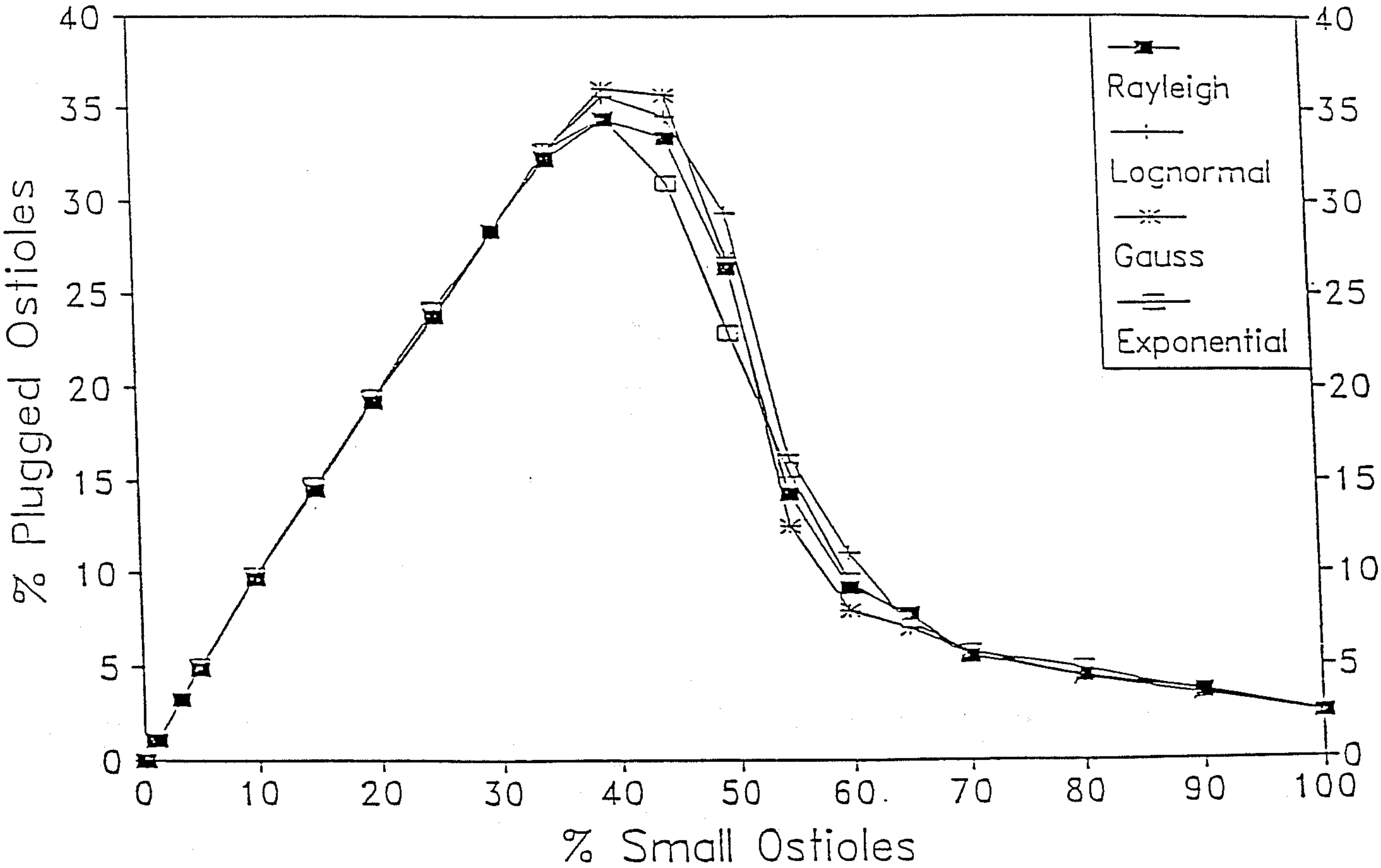


Figure 37. The effect of ostiole size distribution on the relationship between percent of plugged ostioles and percent of small ostioles.

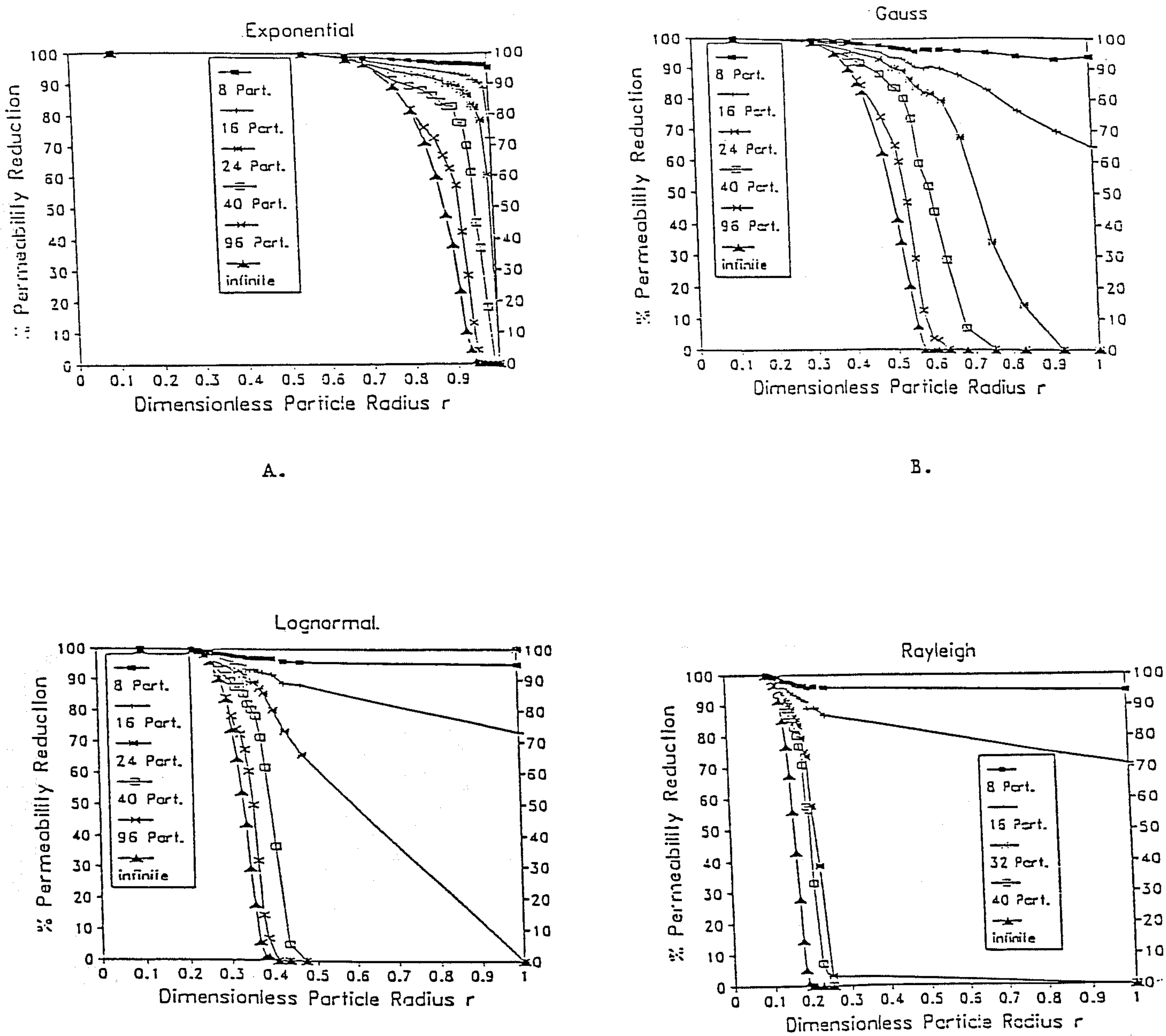


Figure 38. The relationship between permeability reduction and percent of plugged ostioles for four different ostiole size distributions used in the pore network model.

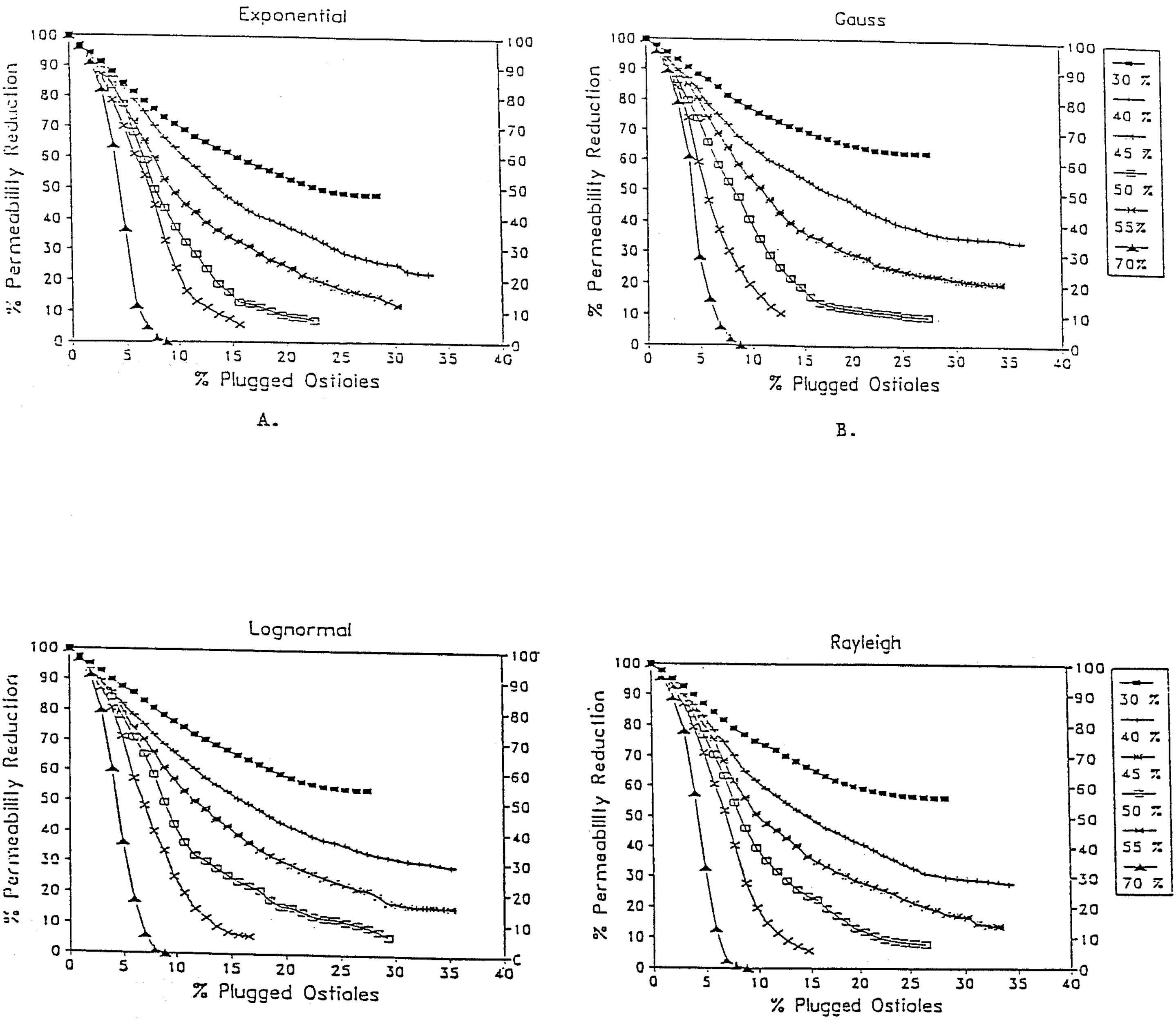


Figure 39. The relationship between permeability reduction, dimensionless particle radius, and number of injected particles for four different ostiole size distributions used in the pore network model.

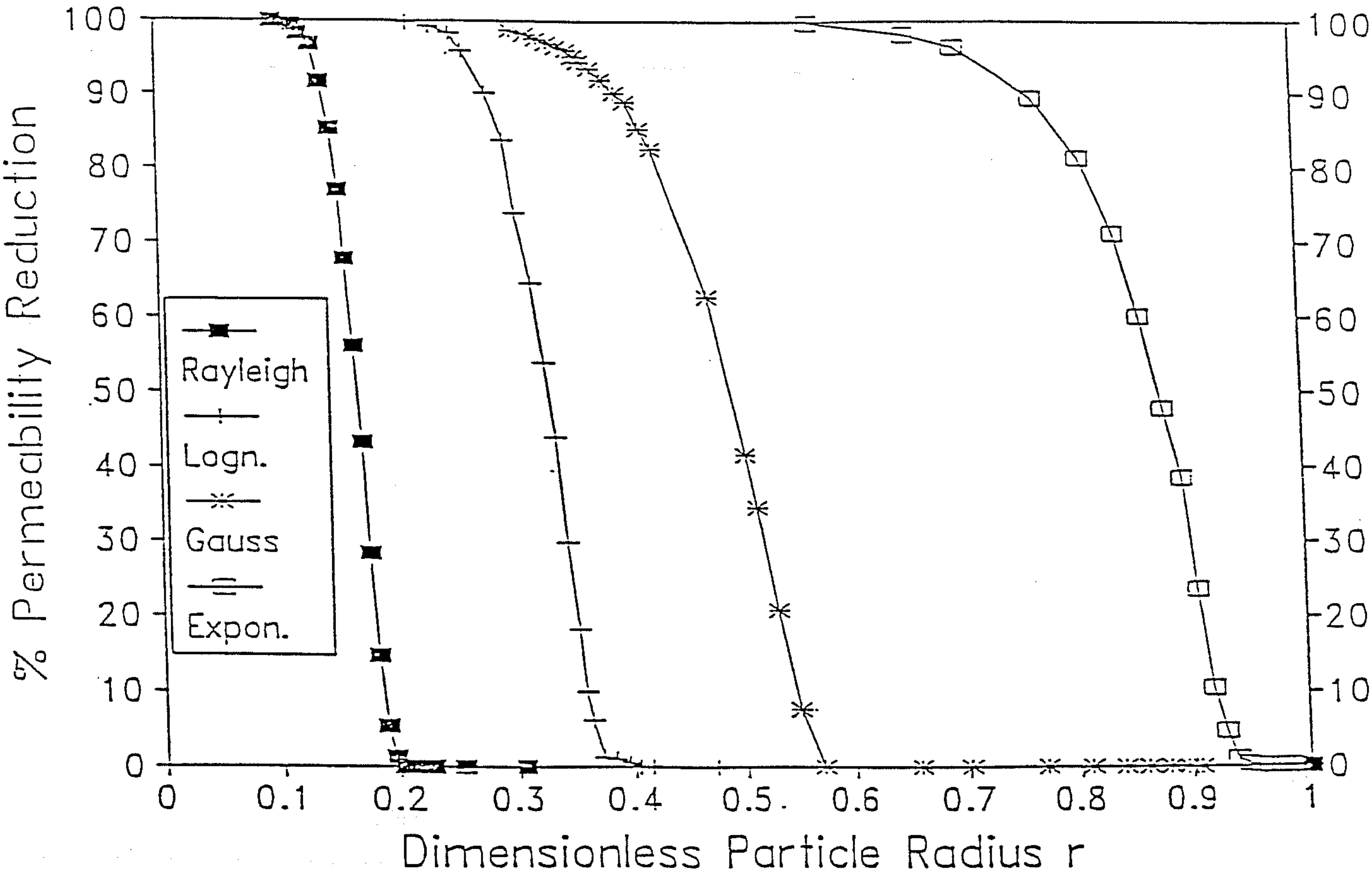


Figure 40. The influence of ostiole size distribution on percent of permeability reduction as a function of dimensionless particle radius using an infinite number of particles.

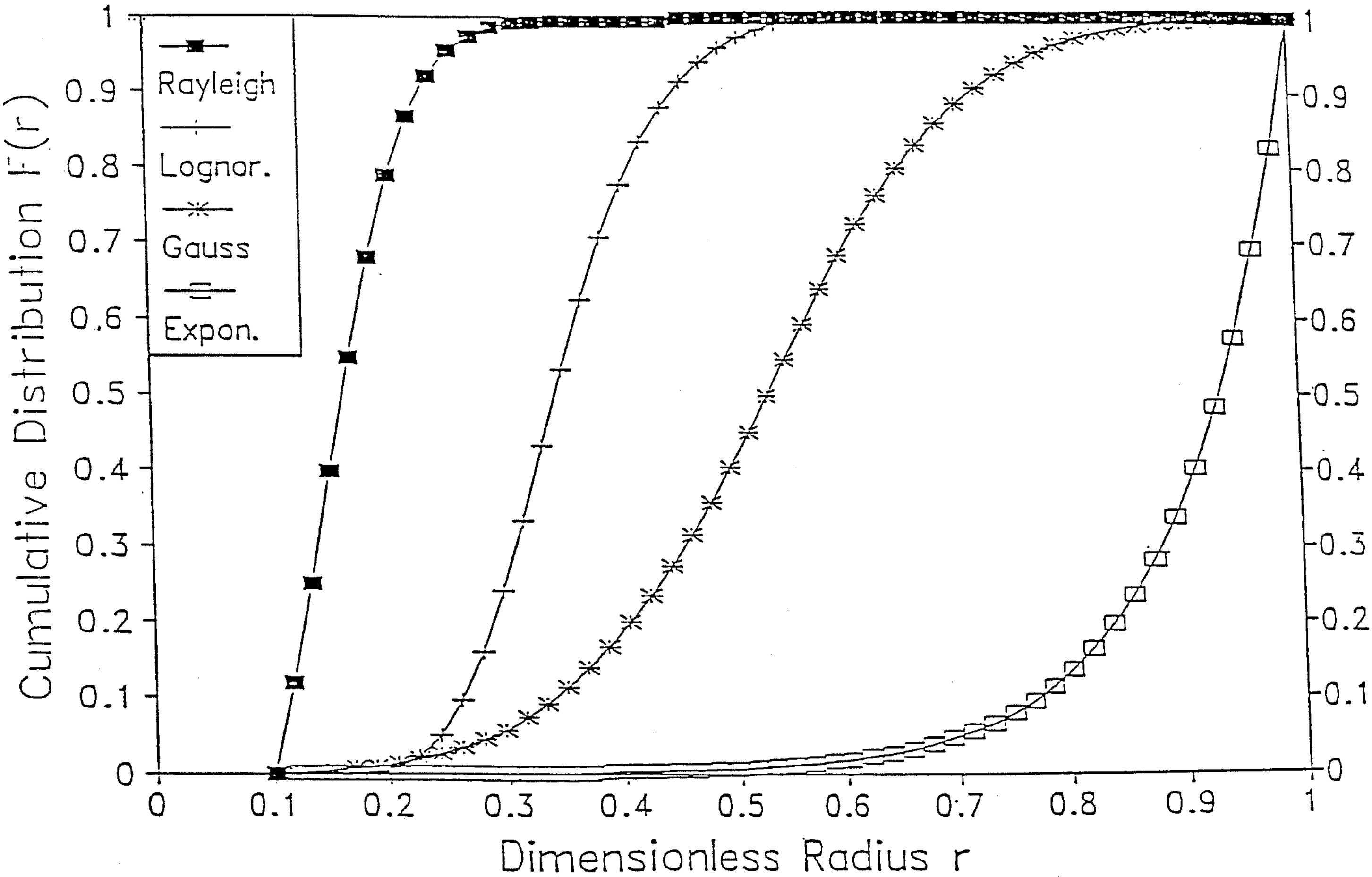


Figure 41. Cumulative distribution for four different ostiole size distributions used in the pore network model.

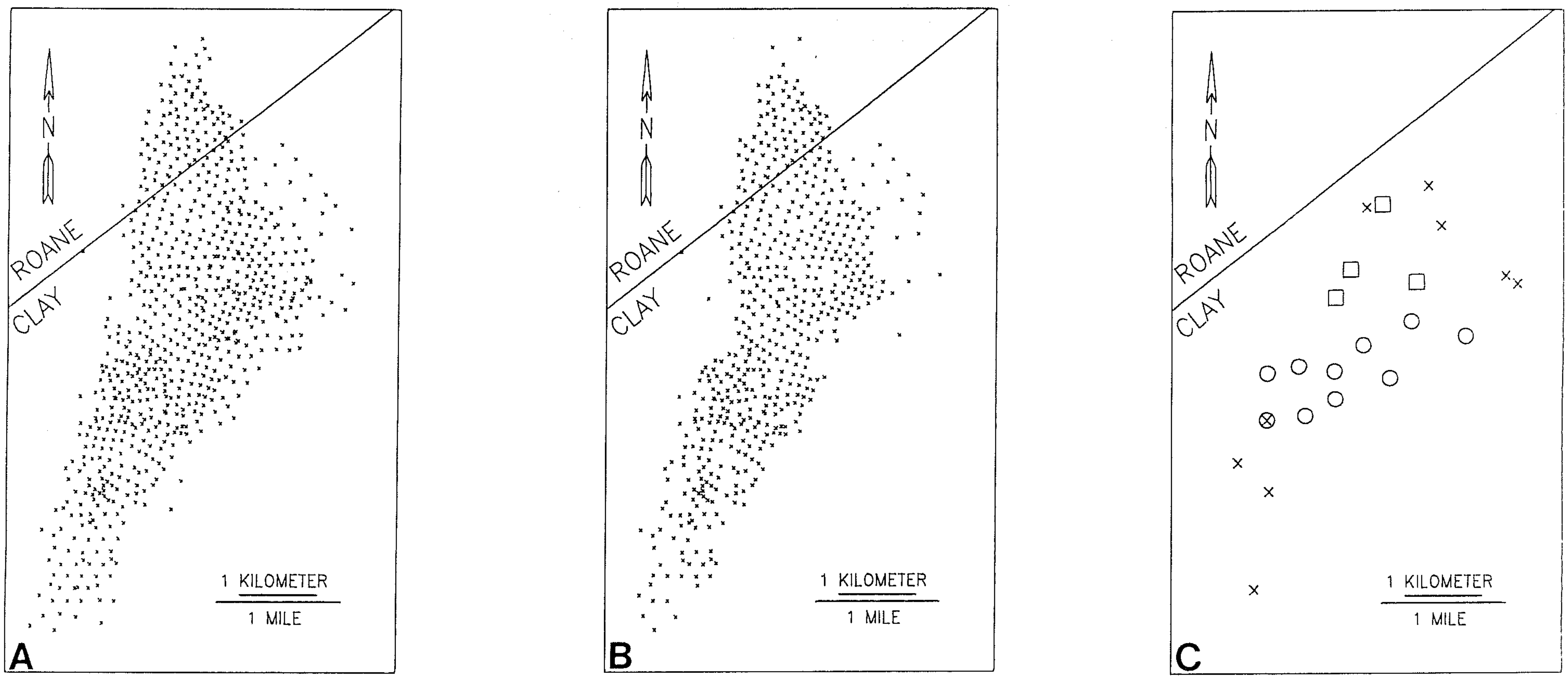


Figure 42. Granny Creek field, Clay and Roane counties, West Virginia. (42a) Big Injun well locations in the Granny Creek field (698 wells). (42b) Location of all Big Injun wells in Granny Creek for which the Survey has gamma-ray logs (517 wells). (42c) Location of all Big Injun wells in Granny Creek for which the Survey has cuttings("X") or cores ("Circle" - Survey cores; "Square" - cores on loan from Pennzoil).

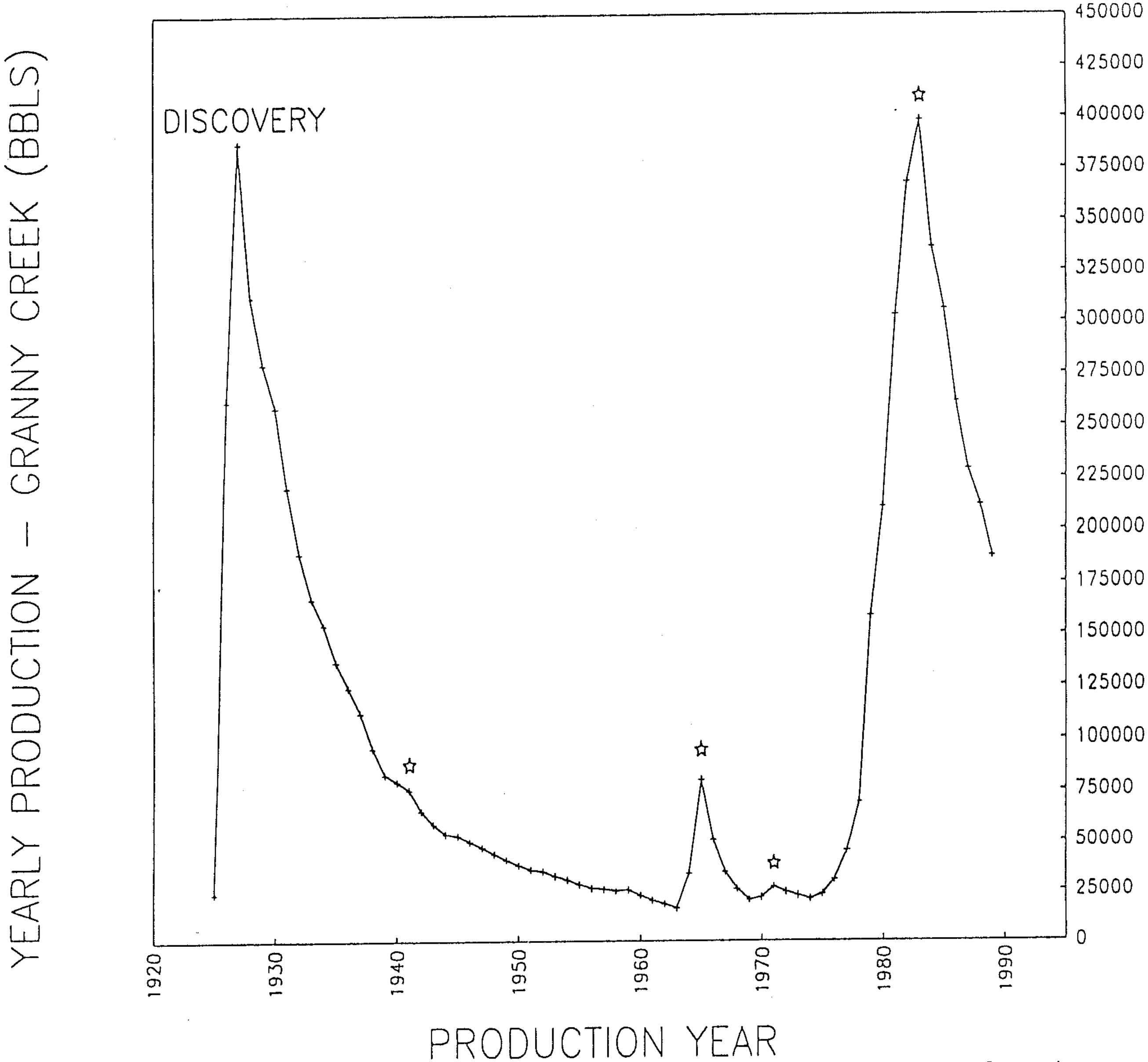


Figure 43. Total yearly production for six Pennzoil leases in the central and northern portion of Granny Creek field. The six leases represent approximately 249 wells. Marked local increases in production are indicated by a star.

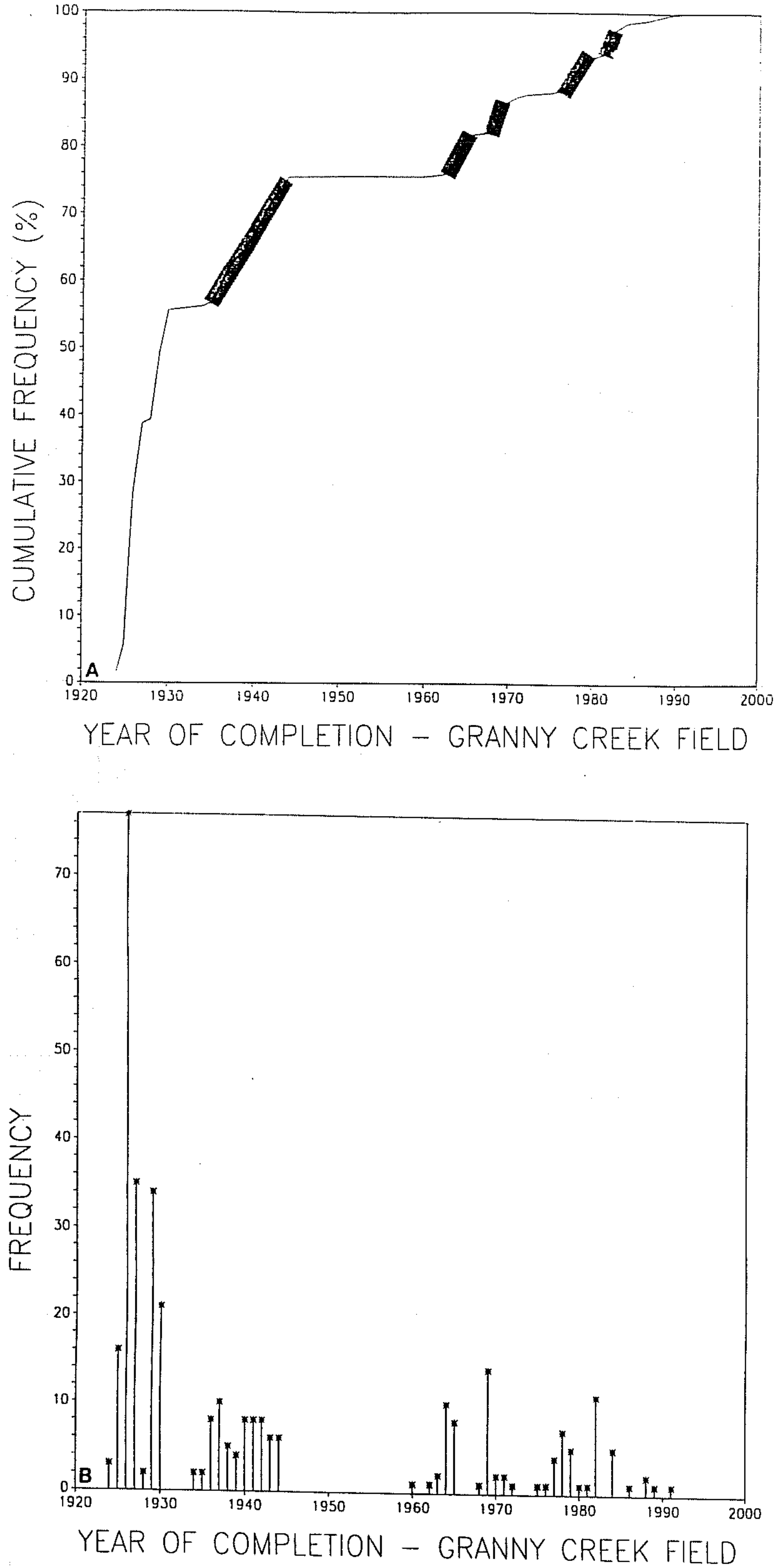


Figure 44. Frequency analysis of Granny Creek well completions. (44a) Cumulative frequency curve for dates of completions of 338 Big Injun oil wells. Shaded slope regions represent an increase in the number of completions; plateaus represent inactivity. (44b) Frequency spectrum for the same data set emphasizing the clustering of well completions through time.

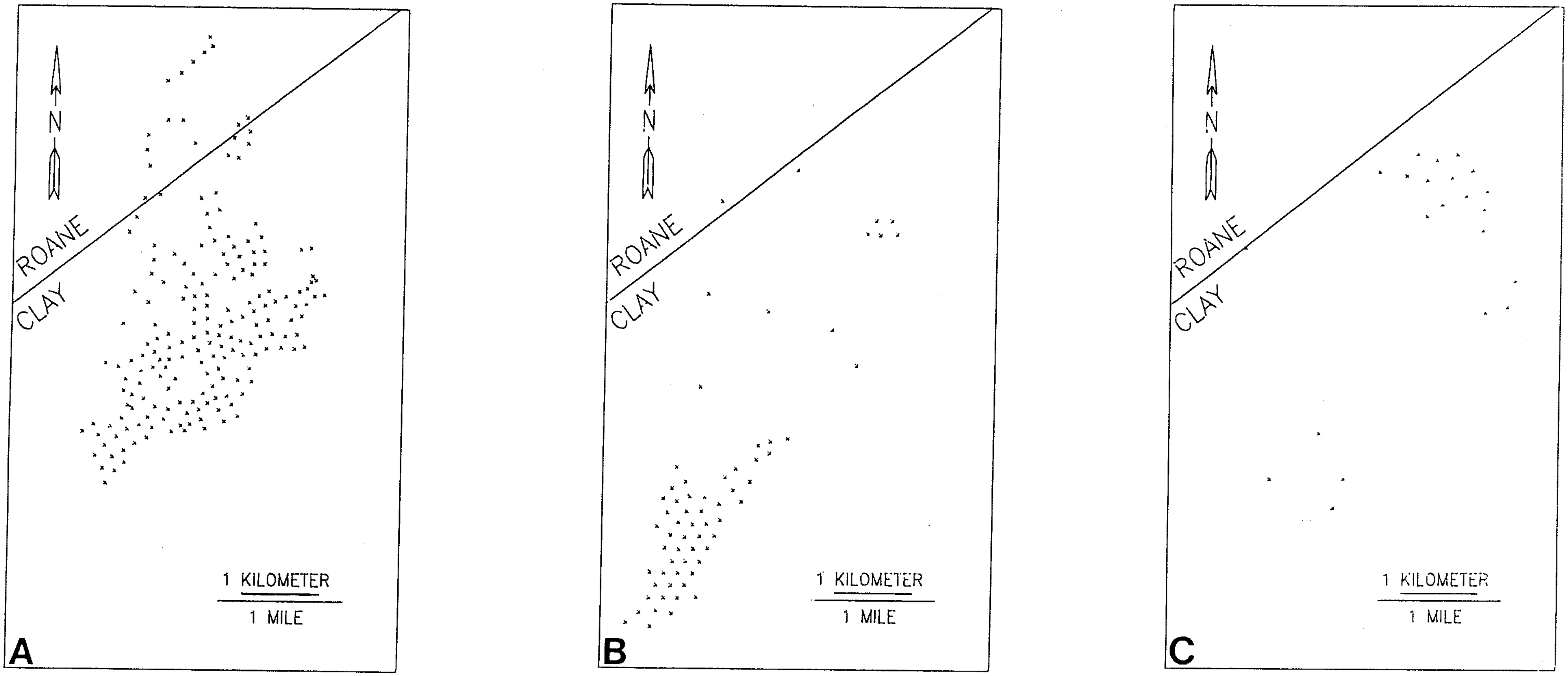


Figure 45. Analysis of the locations of oil-producting, Big Injun wells in the Granny Creek field through time. Each map corresponds to one of the time clusters identified in figure 44b. (45a) 1920 to 1936 (period of field discovery). (45b) 1937 to 1946. (45c) 1947 to 1967.

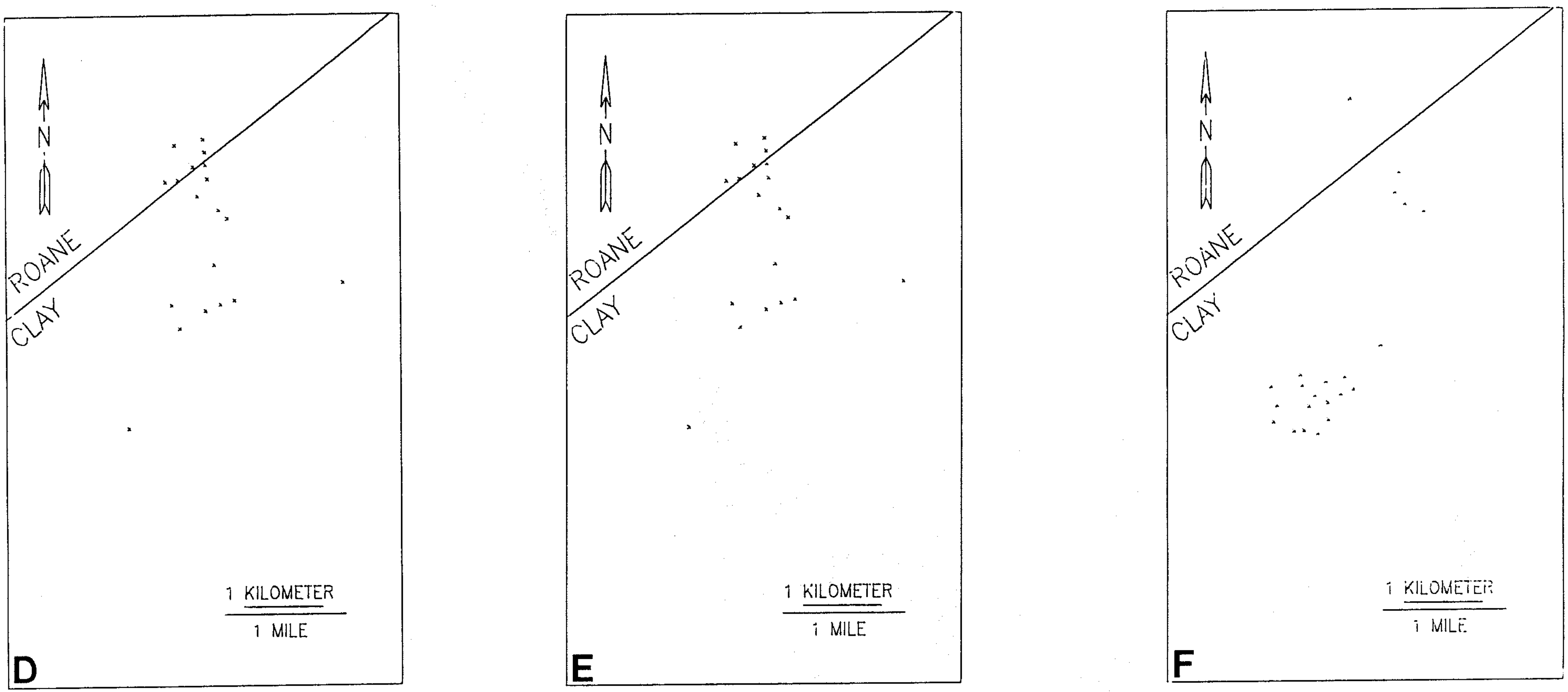


Figure 45 (continued). (45d) 1968 to 1974. (45e) 1975 to 1981. (45f) 1982 to date.

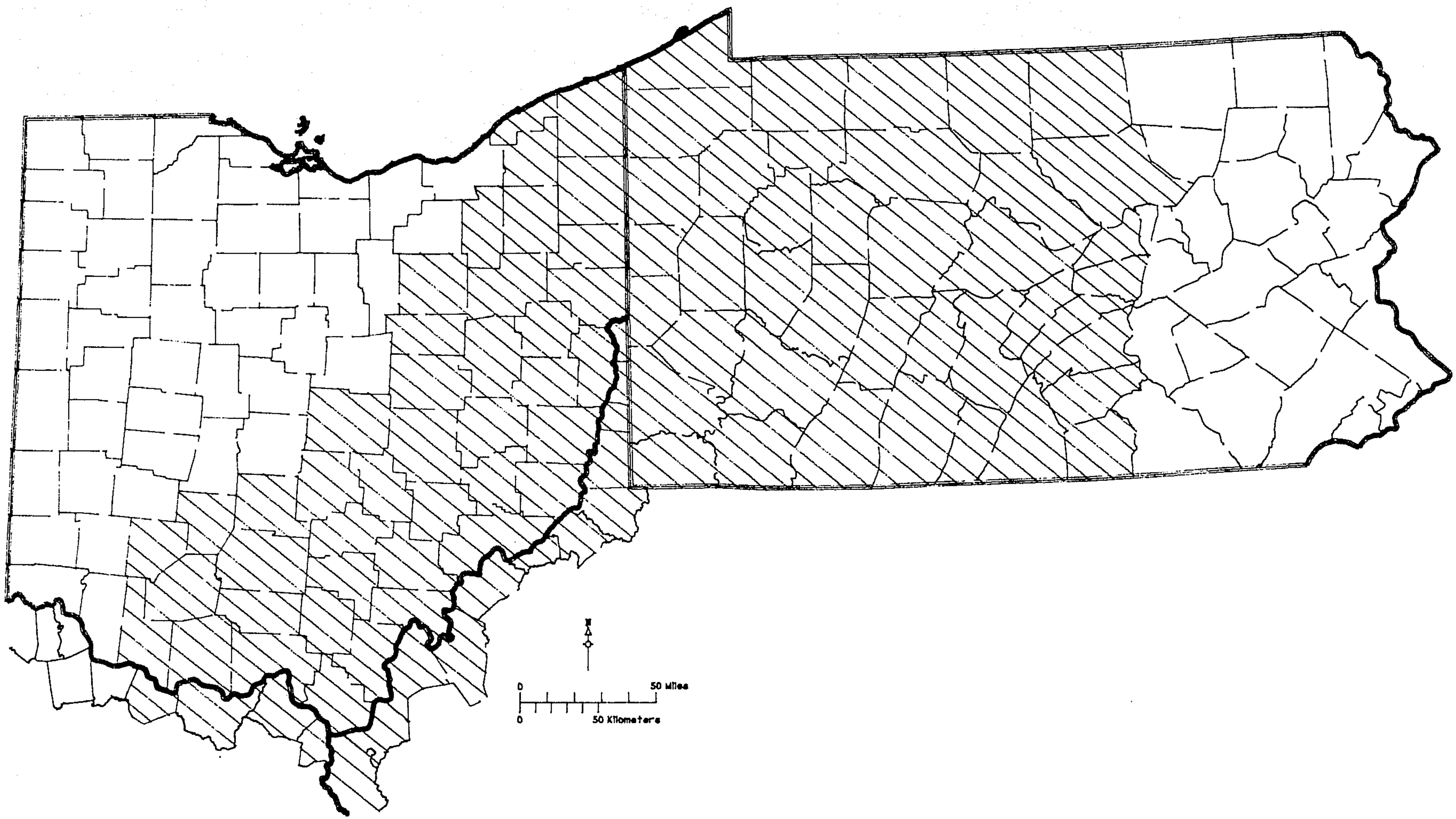


Figure 46. Location of the Rose Run study area.

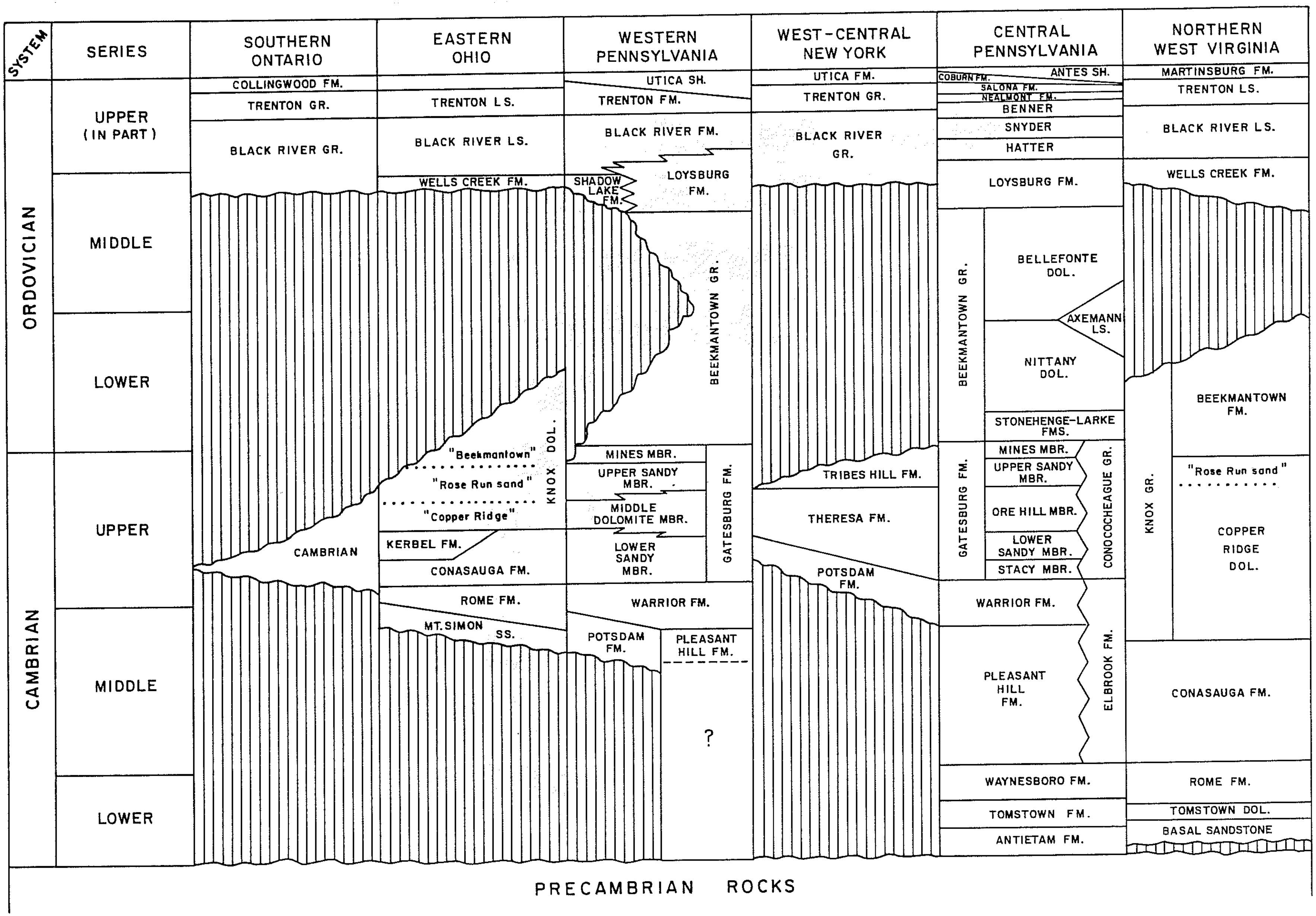


Figure 47. Generalized correlation diagram for Cambrian and Ordovician rocks in Ohio, Pennsylvania, and adjacent states.

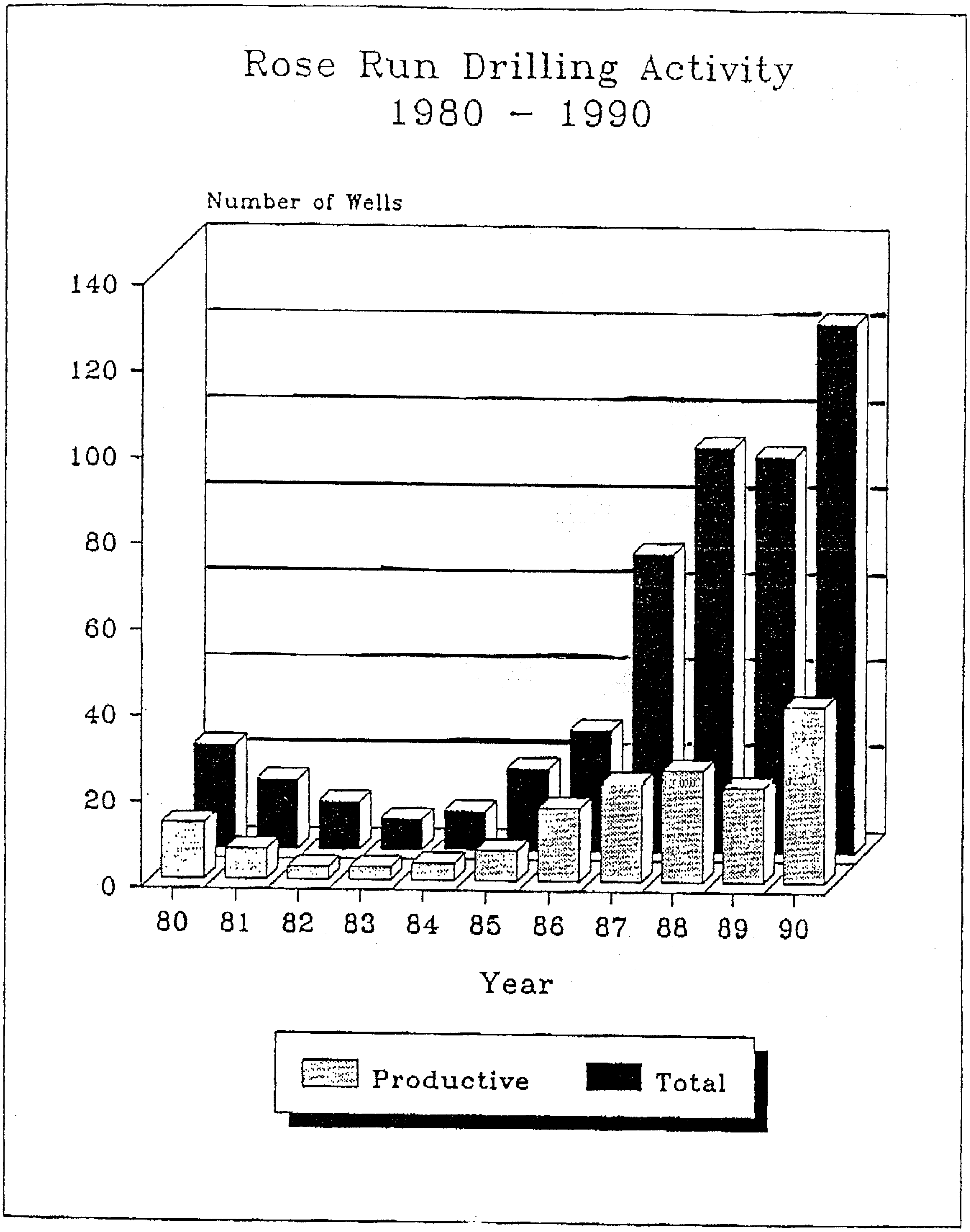


Figure 48. Summary of Rose Run drilling activity in Ohio, 1980 to 1990.

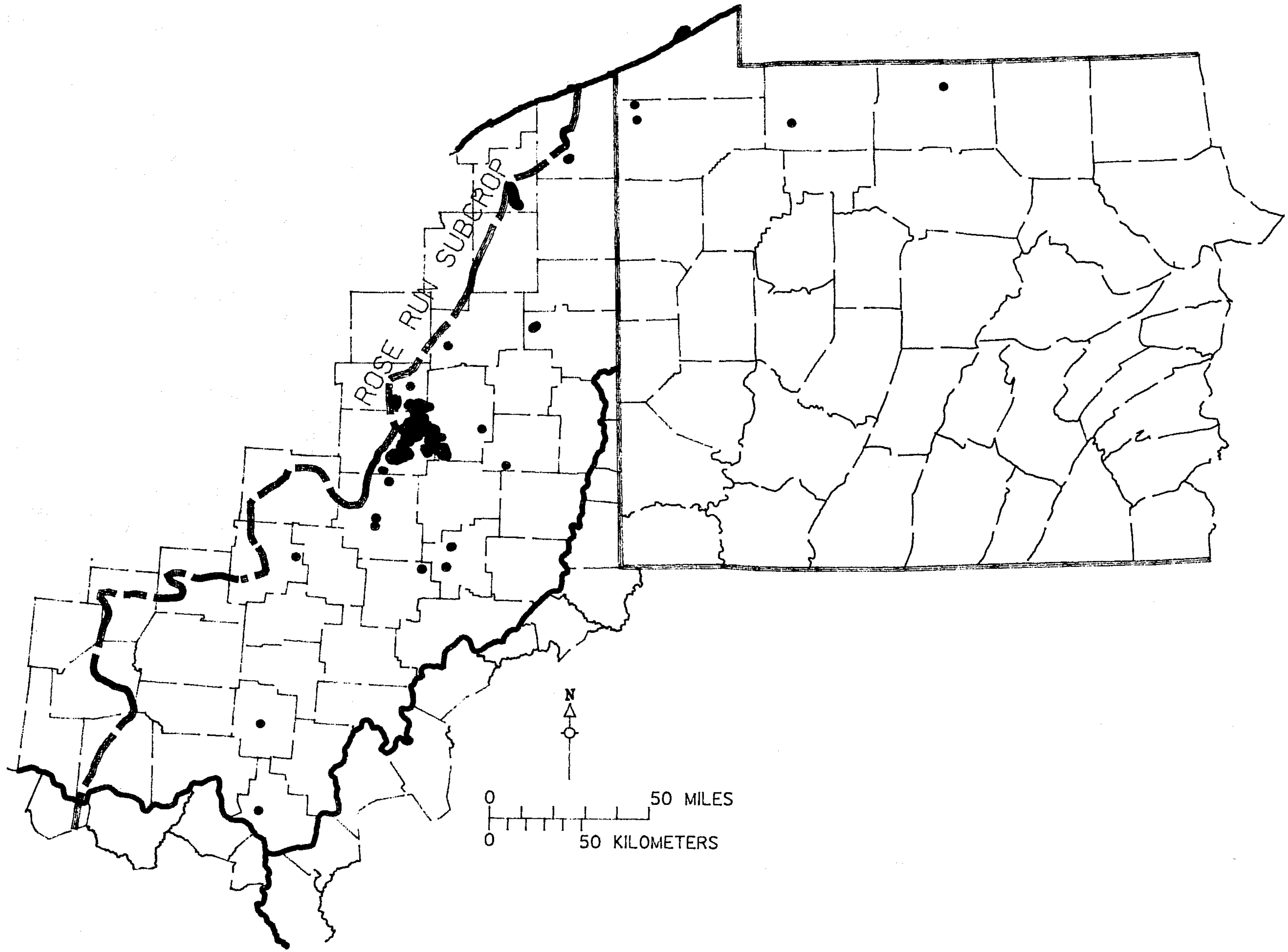


Figure 49. Producing fields and pools in the Rose Run sandstone and Beekmantown Group.

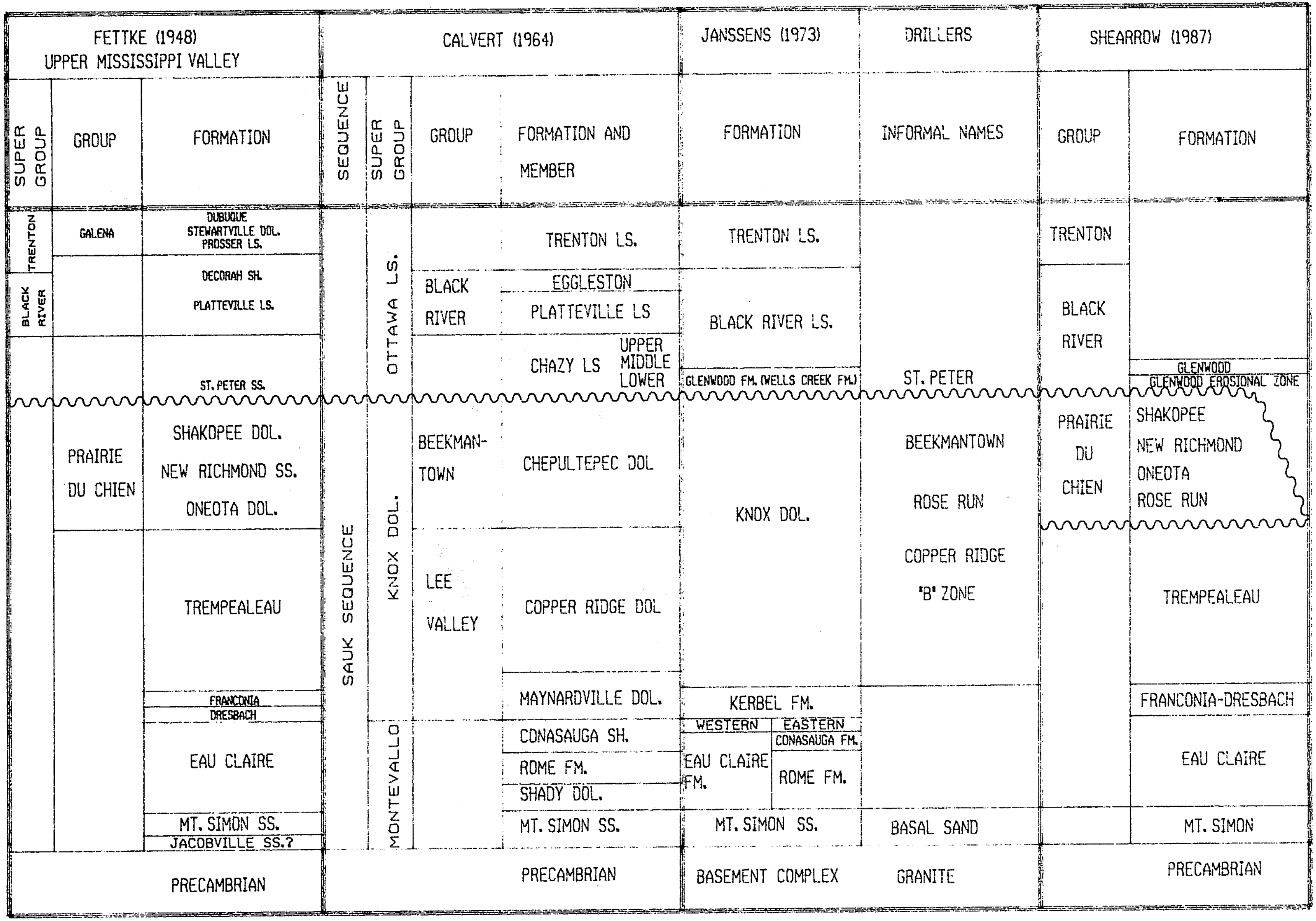


Figure 50. Changes in Cambrian and Ordovician stratigraphic nomenclature used in Ohio.

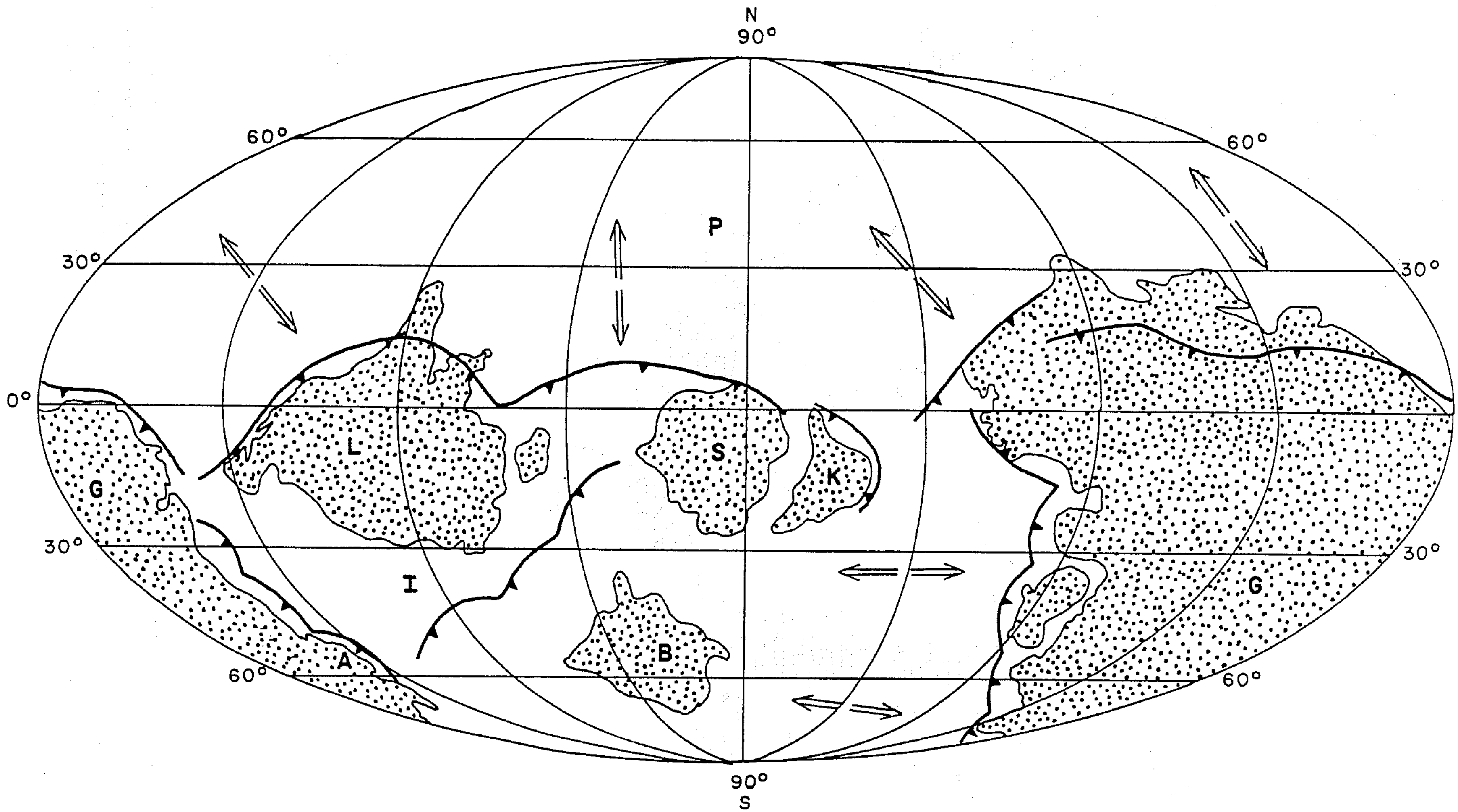


Figure 51. Global Late Cambrian plate tectonic reconstruction (modified from Scotese and McKerrow, 1991). Continents include Baltica (B), Gondwana (G), Kazakhstan (K), Laurentia (L), and Siberia (S). Seas include the Iapetus (I) and Paleotethys (P).

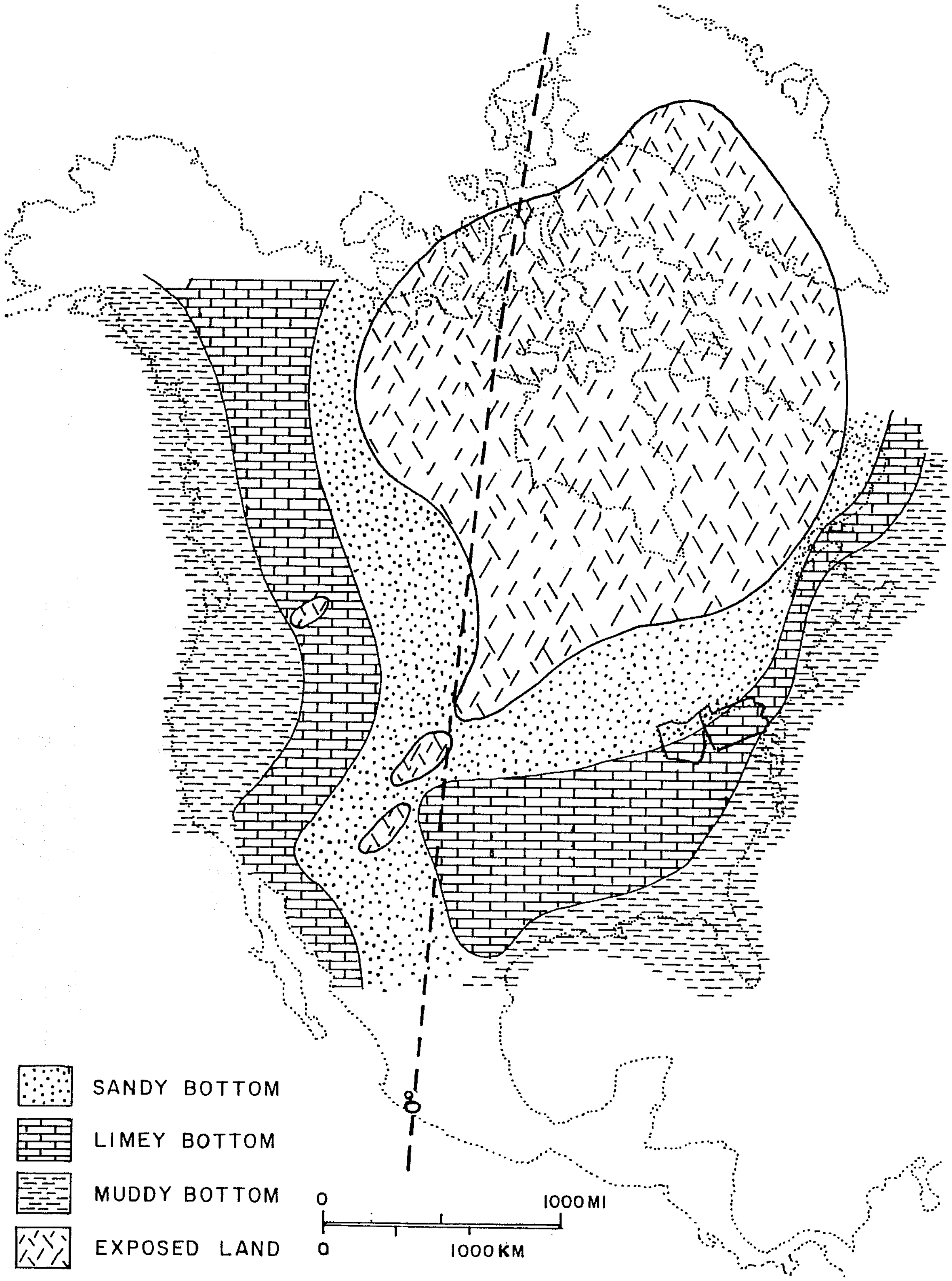


Figure 52. Generalized paleogeography and depositional setting of the Laurentian plate during the Late Cambrian (modified from Dott and Batten, 1976). The present landmass configuration, shown by dotted lines, and the outlines of Ohio and Pennsylvania are shown for orientation.

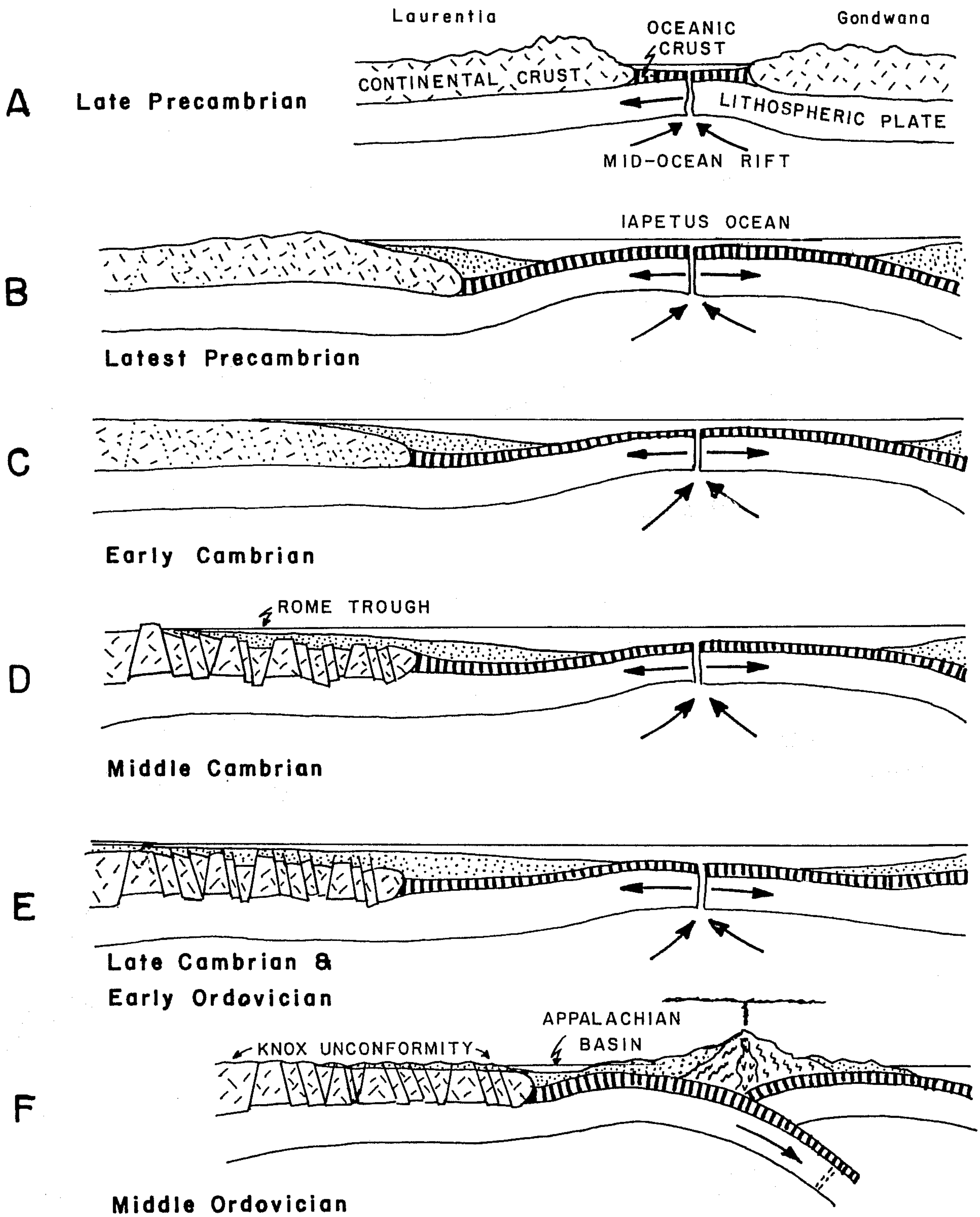


Figure 53. Diagrammatic model of the plate tectonic history of the study area from Late Precambrian to Middle Ordovician. The model is based in part on Dietz, 1972.

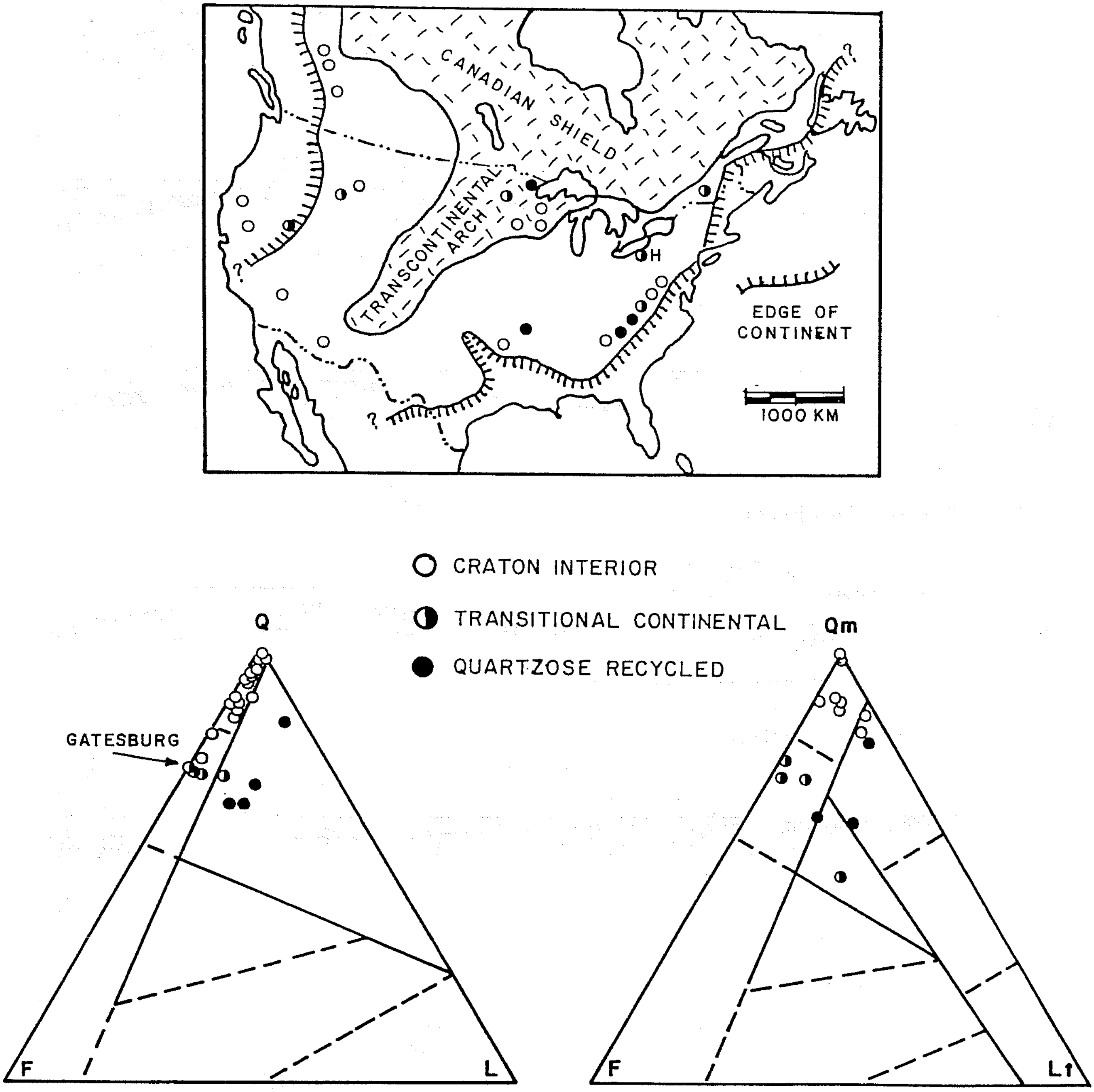


Figure 54. Paleotectonics and sandstone provenance in North America (modified from Dickinson and others, 1988). A. Paleotectonic map showing locations of sandstone suites for Late Precambrian to Middle Ordovician time. H (on Lake Erie) - Hammermill Paper Co. #2 Fee well, Erie County, PA. B. Ternary sandstone composition diagrams. QFL (left) and QmFlt (right) indicate most North American sandstone suites contain quartzose frameworks indicating their derivation from the stable craton. Some suites in different areas have more feldspathic frameworks indicating a continental block provenance transitional between basement uplift and cratonic sediment sources. Rose Run and Conasauga/Gatesburg Lower Sandy sandstones fall into this latter category.

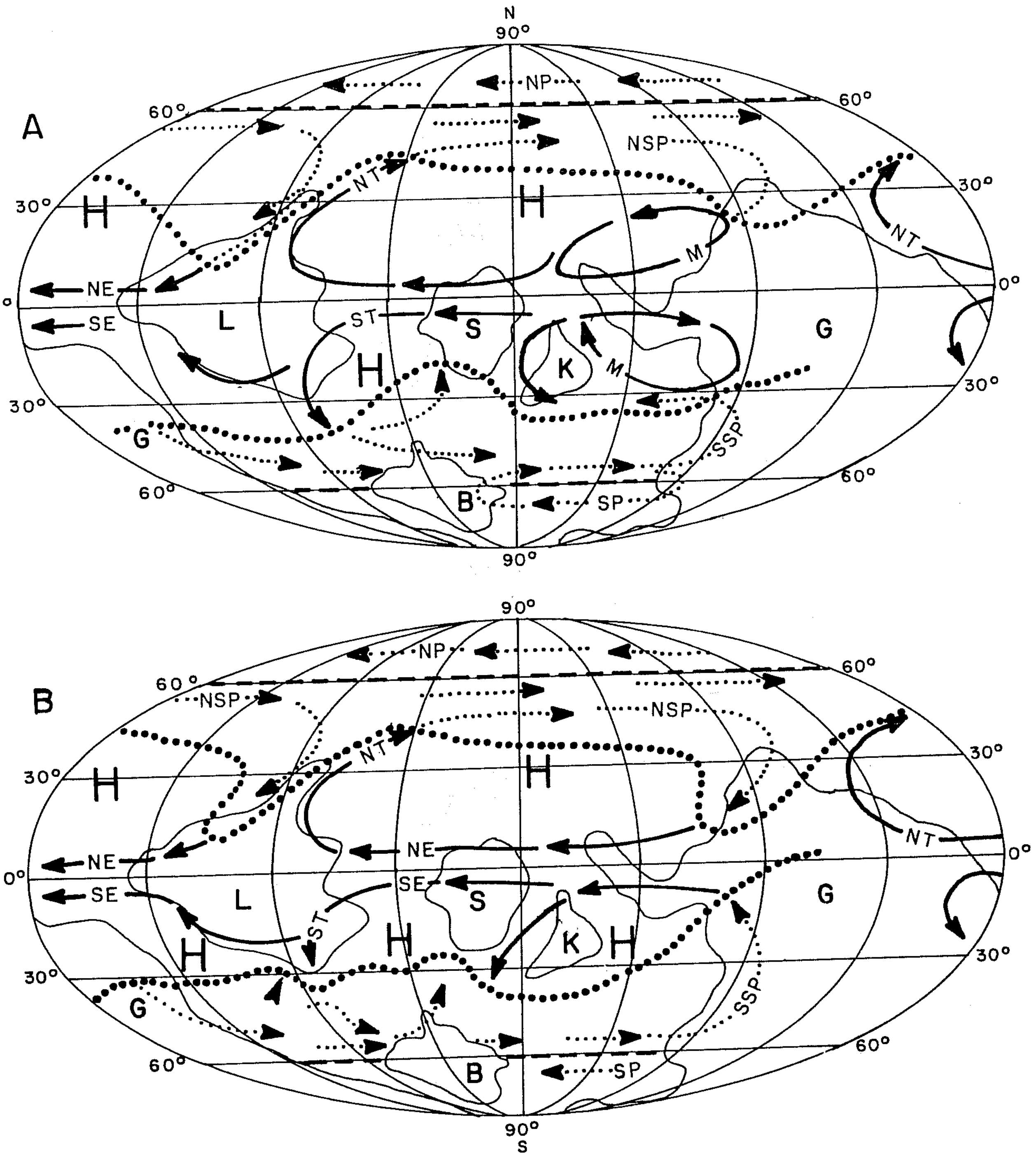


Figure 55. Paleoceanography of earth during the Late Cambrian (modified from Wilde, 1991). A - Southern hemisphere summer and northern hemisphere winter. B - Northern hemisphere summer and southern hemisphere winter. Continents and seas are the same as those in figure 51. Surface currents include north and south polar (NP and SP), north and south subpolar (NSP and SSP), north and south tropical (NT and ST), north and south equatorial (NE and SE), and monsoonal counter (M) currents. Oceanic and atmospheric high pressure cells are designated H.

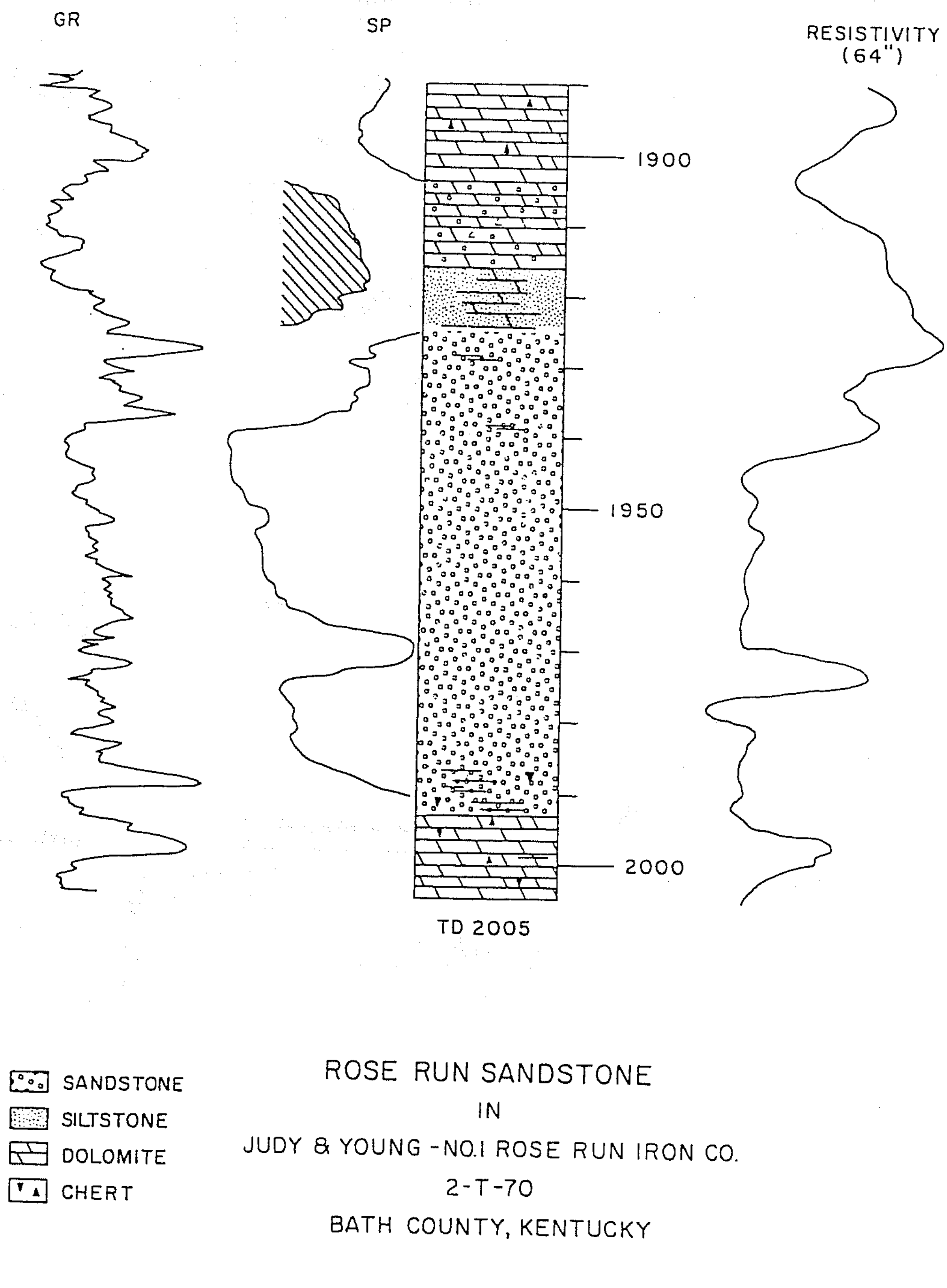


Figure 56. Type section of the Rose Run sandstone in the Judy and Young #1 Rose Run Iron Co. well in Bath County, Kentucky (modified from McGuire and Howell, 1963, see figures 2-15).

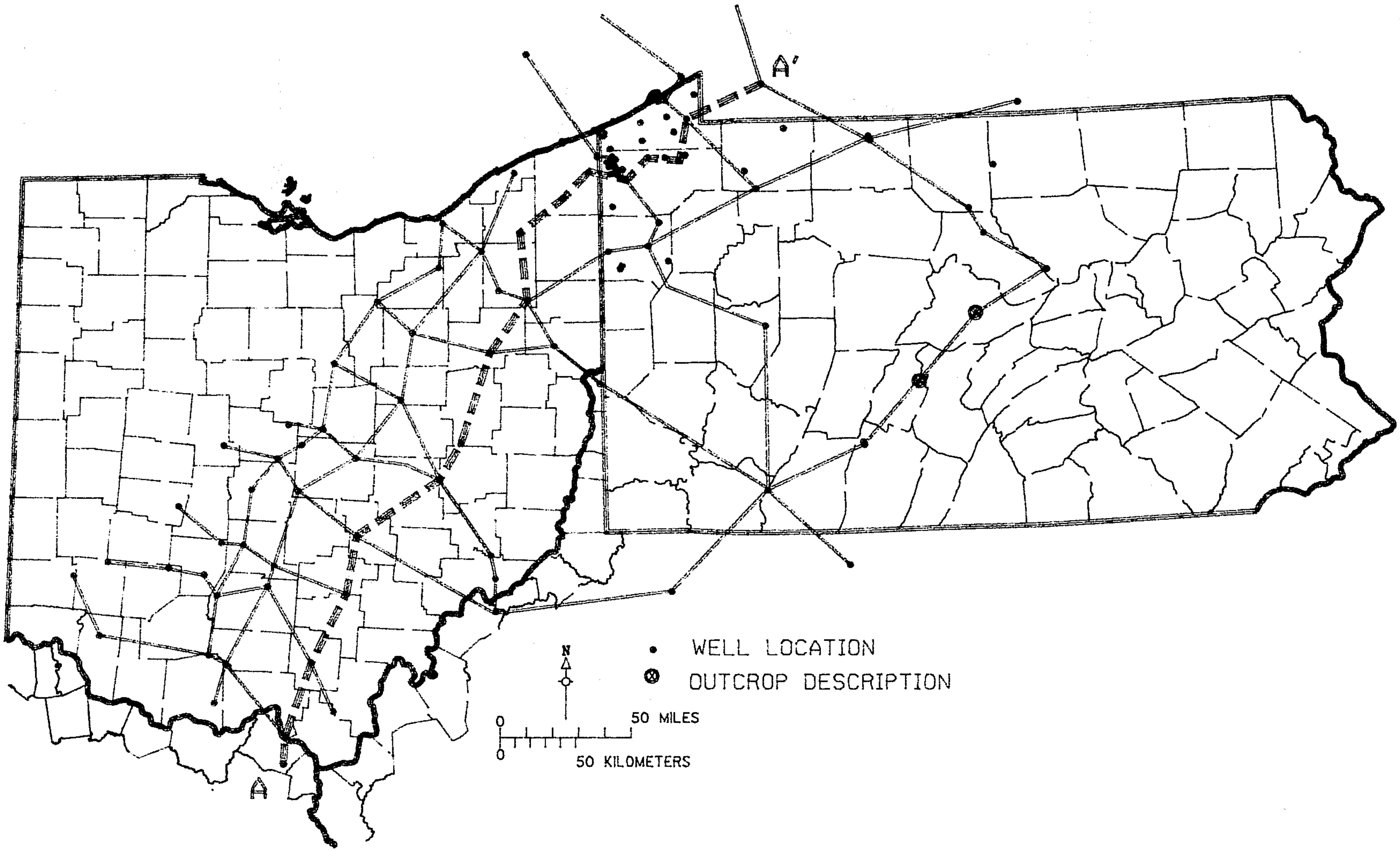


Figure 57. Location of cross sections constructed during early phase of study. Cross section A-A' is shown in figure 59.

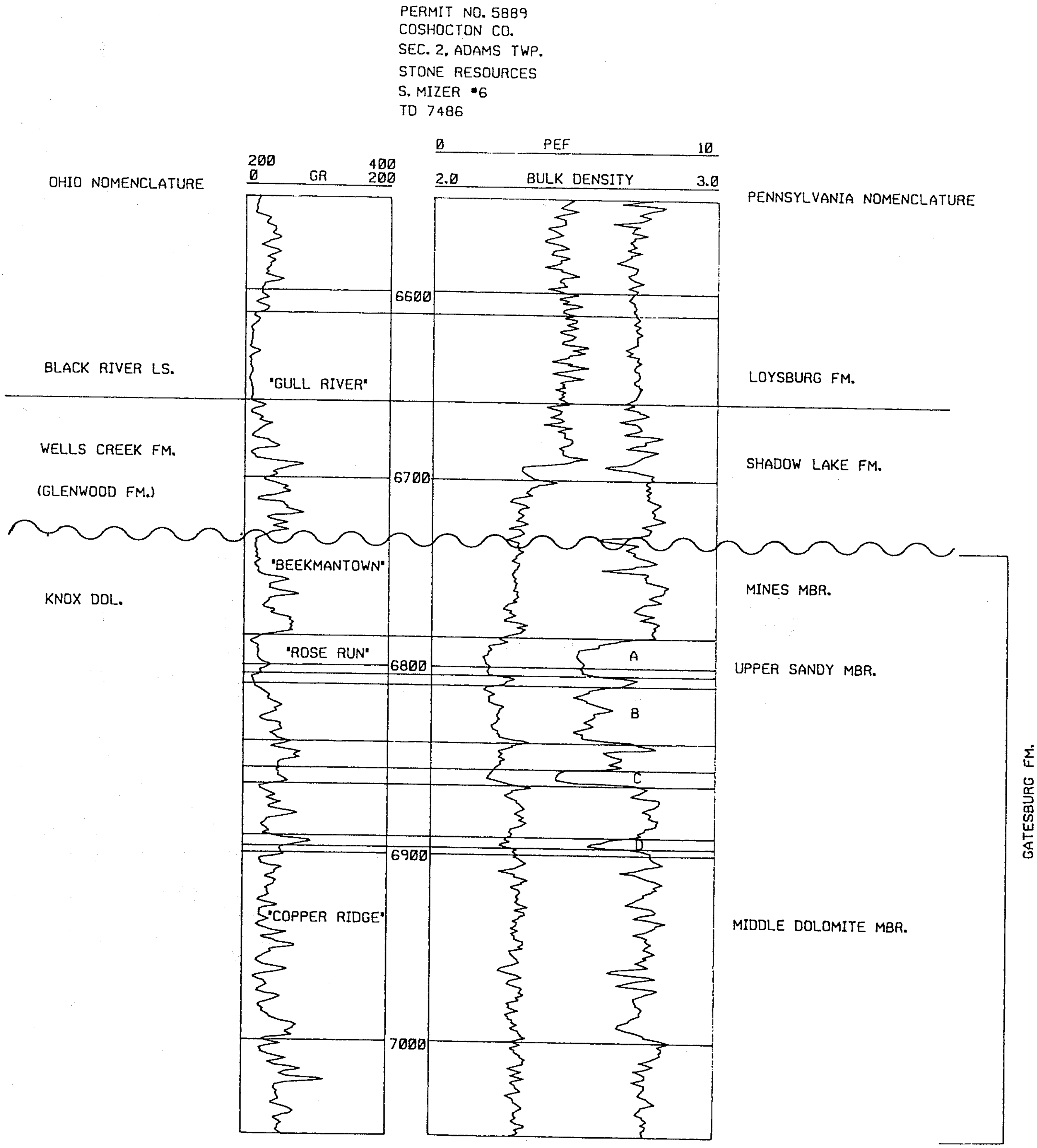


Figure 58. Log suite for the Rose Run sandstone and adjacent units for a typical well in the study area.

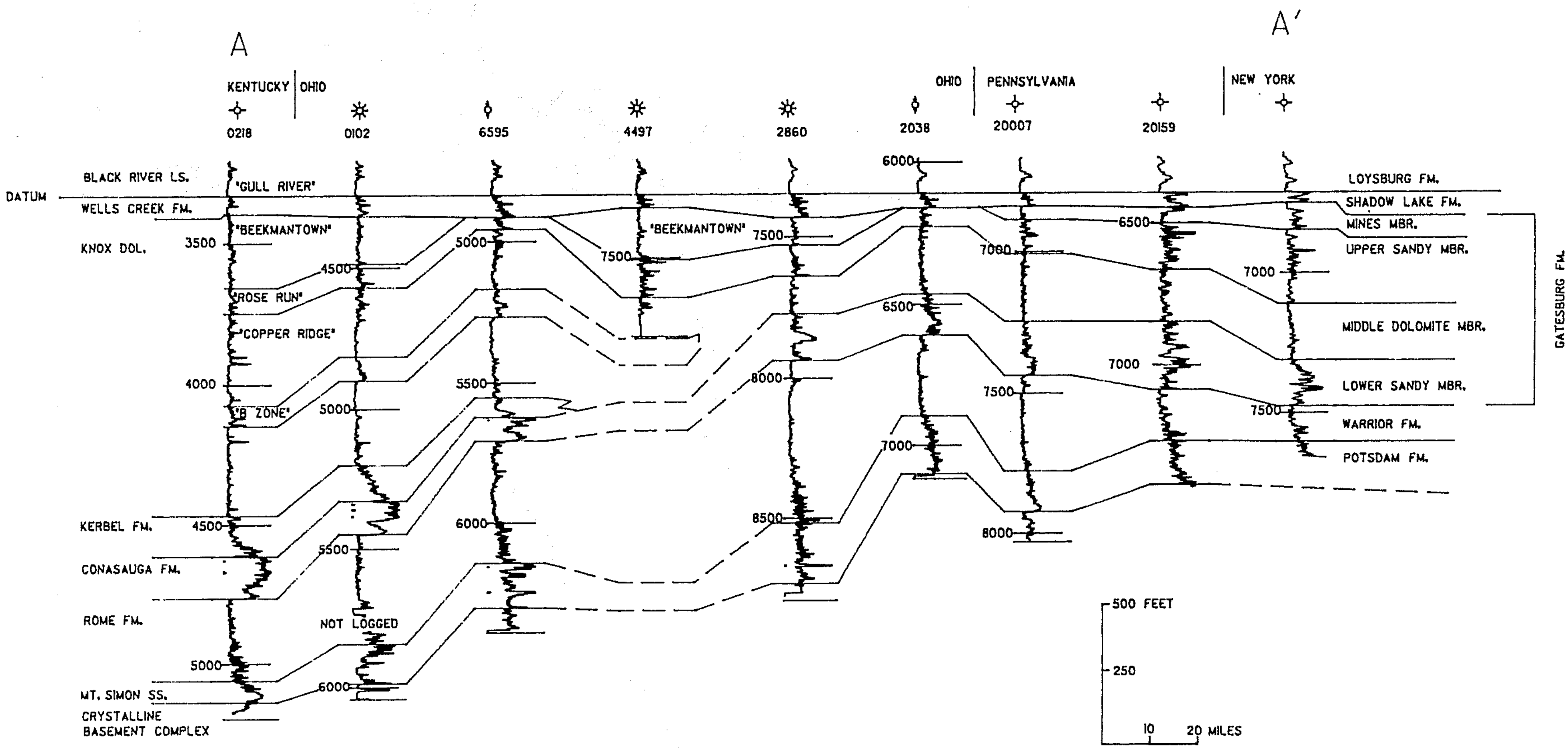


Figure 59. Regional stratigraphic cross section A-A'.

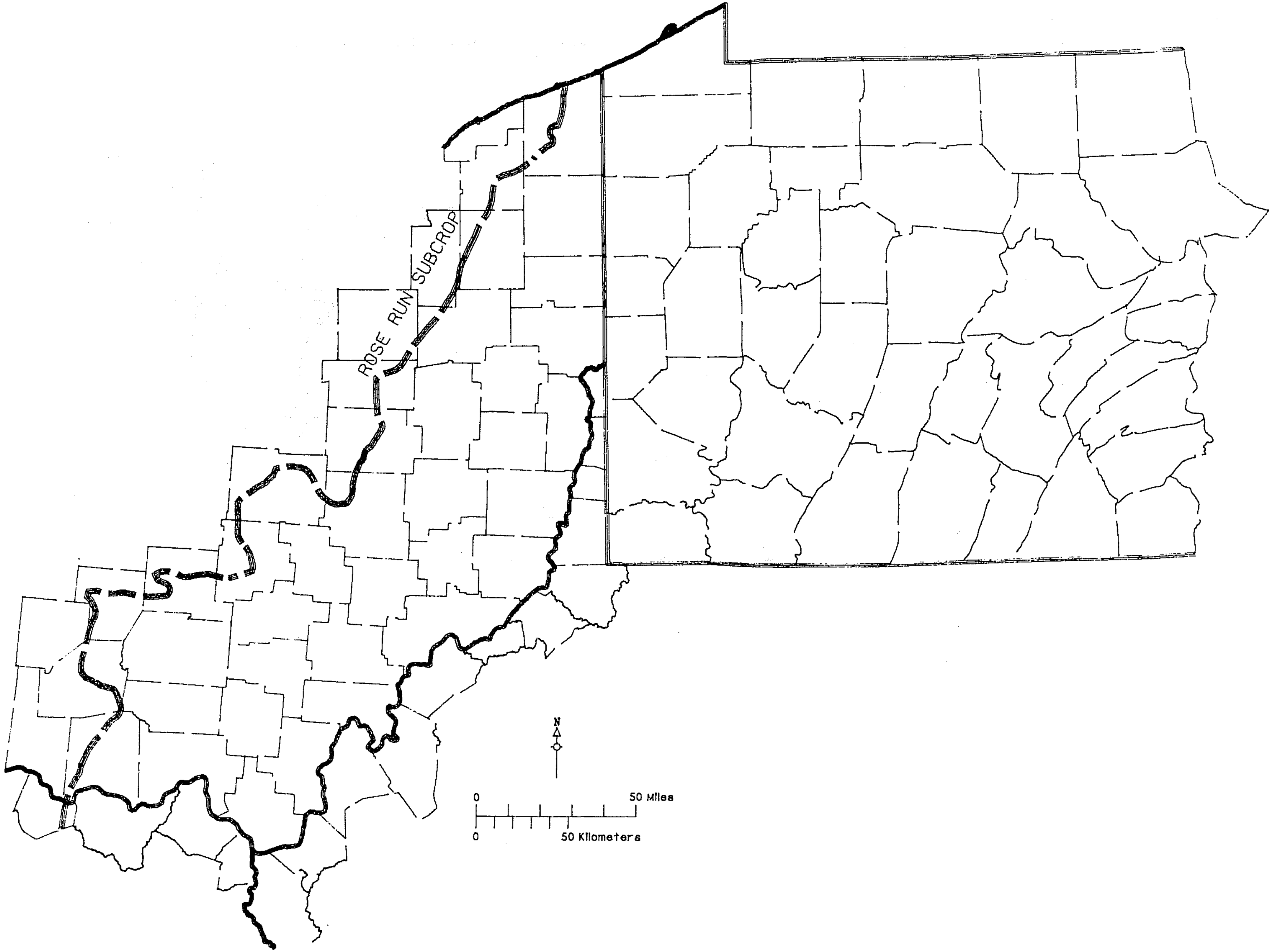


Figure 60. Regional subcrop map of the Rose Run sandstone.

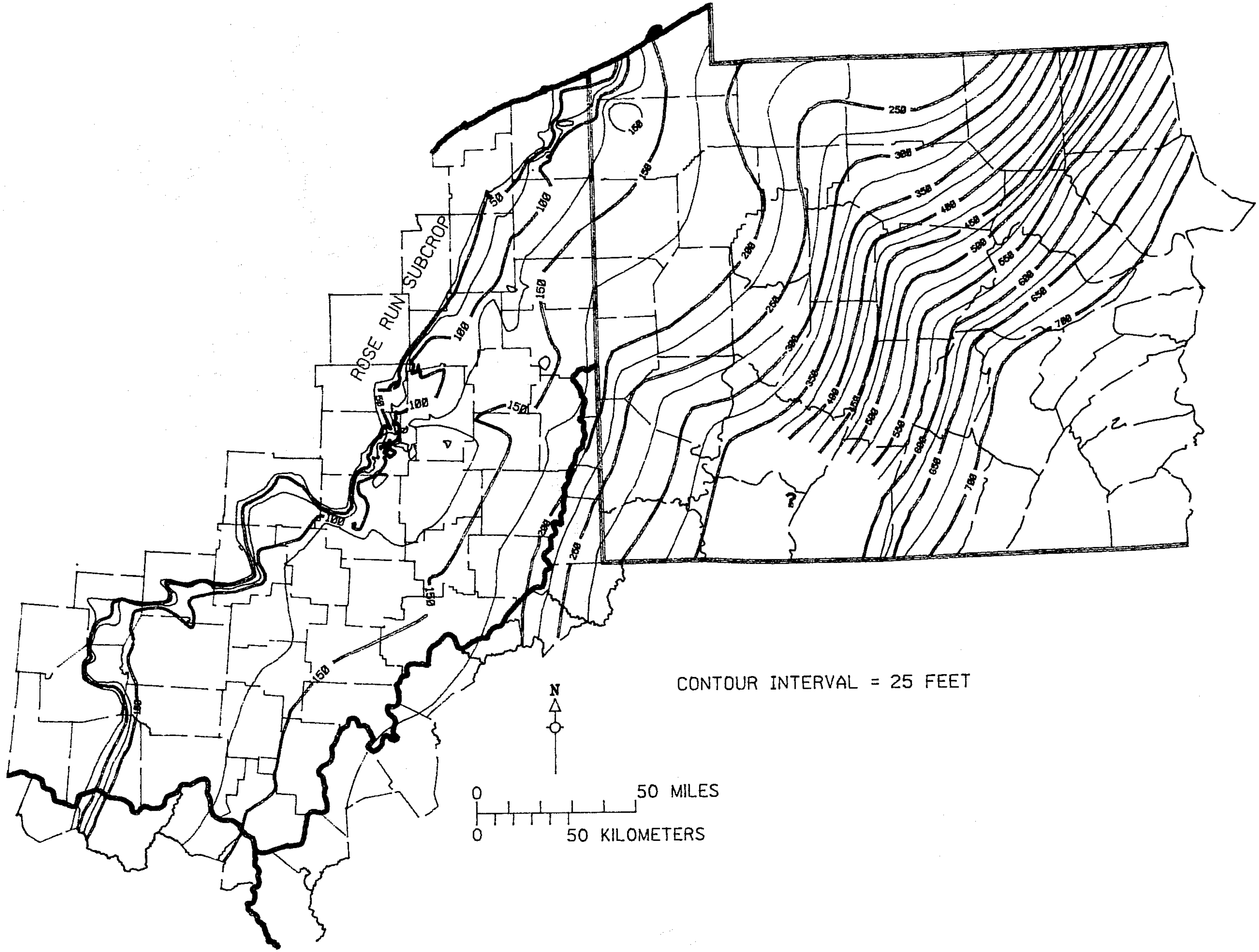


Figure 61. Regional isopach map of the Rose Run sandstone in Ohio and western Pennsylvania.

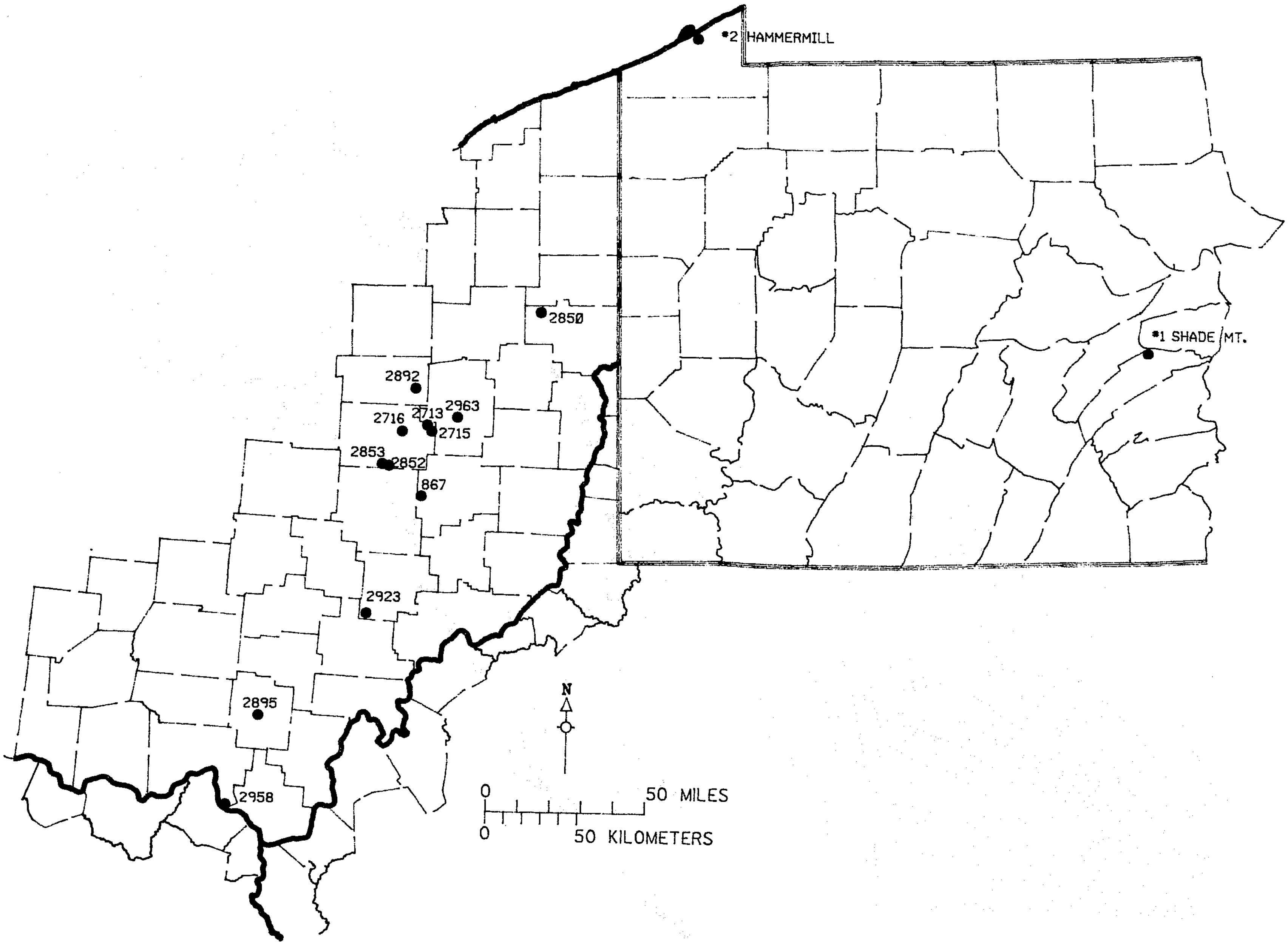


Figure 62. Location of Upper Cambrian and Lower Ordovician cores to be examined during this study.

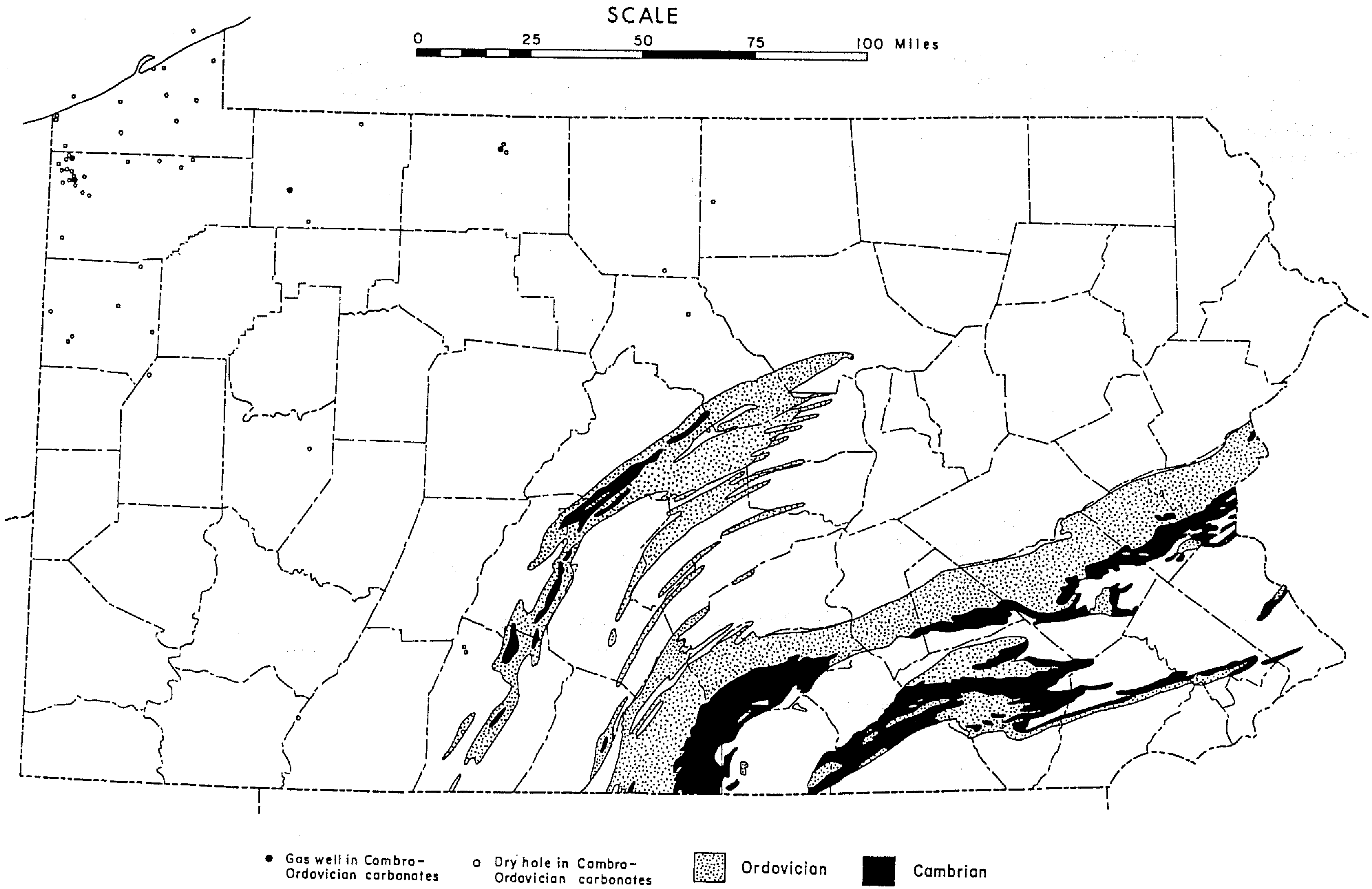


Figure 63. Map of Pennsylvania showing location of outcrop areas of Cambrian and Ordovician rocks and of wells penetrating the section.

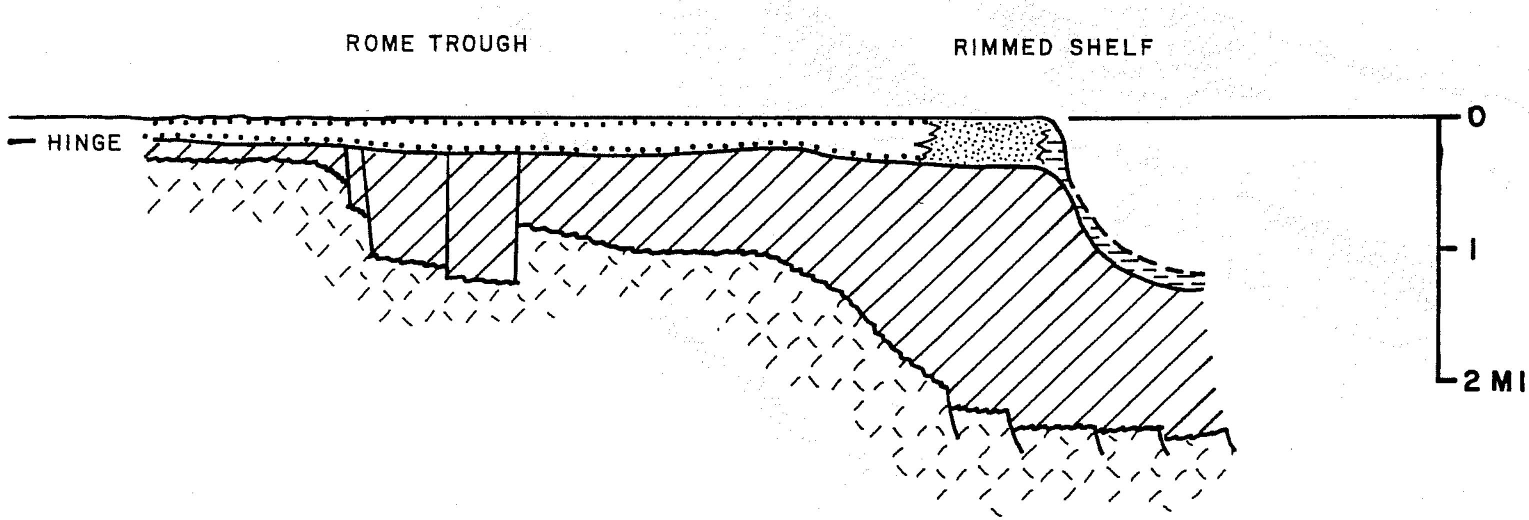


Figure 64. Cross section of Late Cambrian continental shelf of Laurentia illustrating the concept of the rimmed shelf with platform morphology developed by Read (1989). The eastern edge of the platform had over 3,900 ft of relief in what is now eastern Pennsylvania. Intermittent basement faulting in the Rome trough influenced platform morphology and the sedimentary sequences developed on it in western Pennsylvania. The landward hinge line, a limit of major flexuring, was more than 250 miles landward of the rimmed shelf edge.

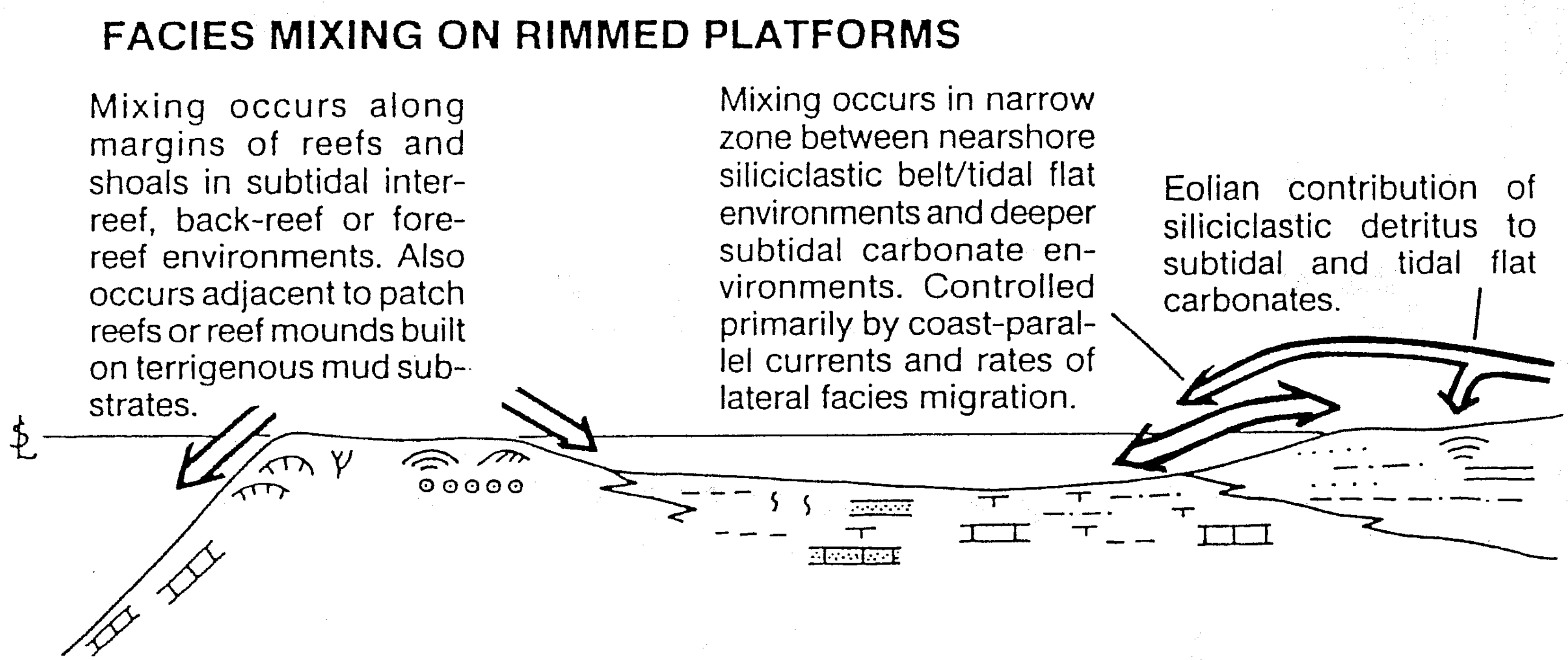


Figure 65. Example of facies mixing on rimmed platforms (from Mount, 1984). Symbols are taken from the AAPG Sample Examination Manual (Swanson, 1981).

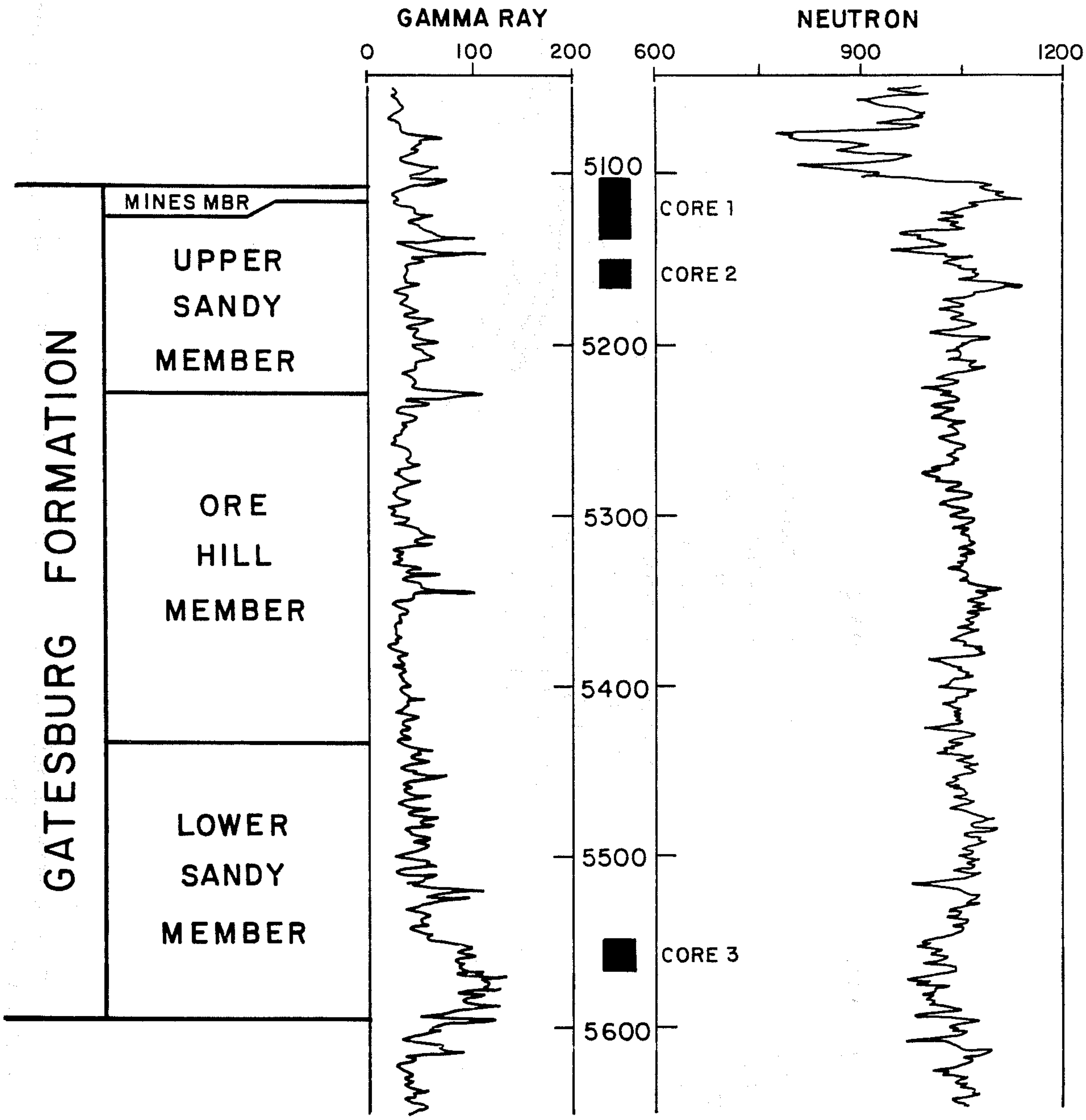


Figure 66. Geophysical log signature through the Gatesburg Formation in the Hammermill Paper Co. #2 Fee well, Erie County, Pennsylvania. Black boxes indicate recovered whole-diameter core intervals. Gamma ray is measured in API units. Neutron is measured in Birdwell neutron log units. Depth in feet.

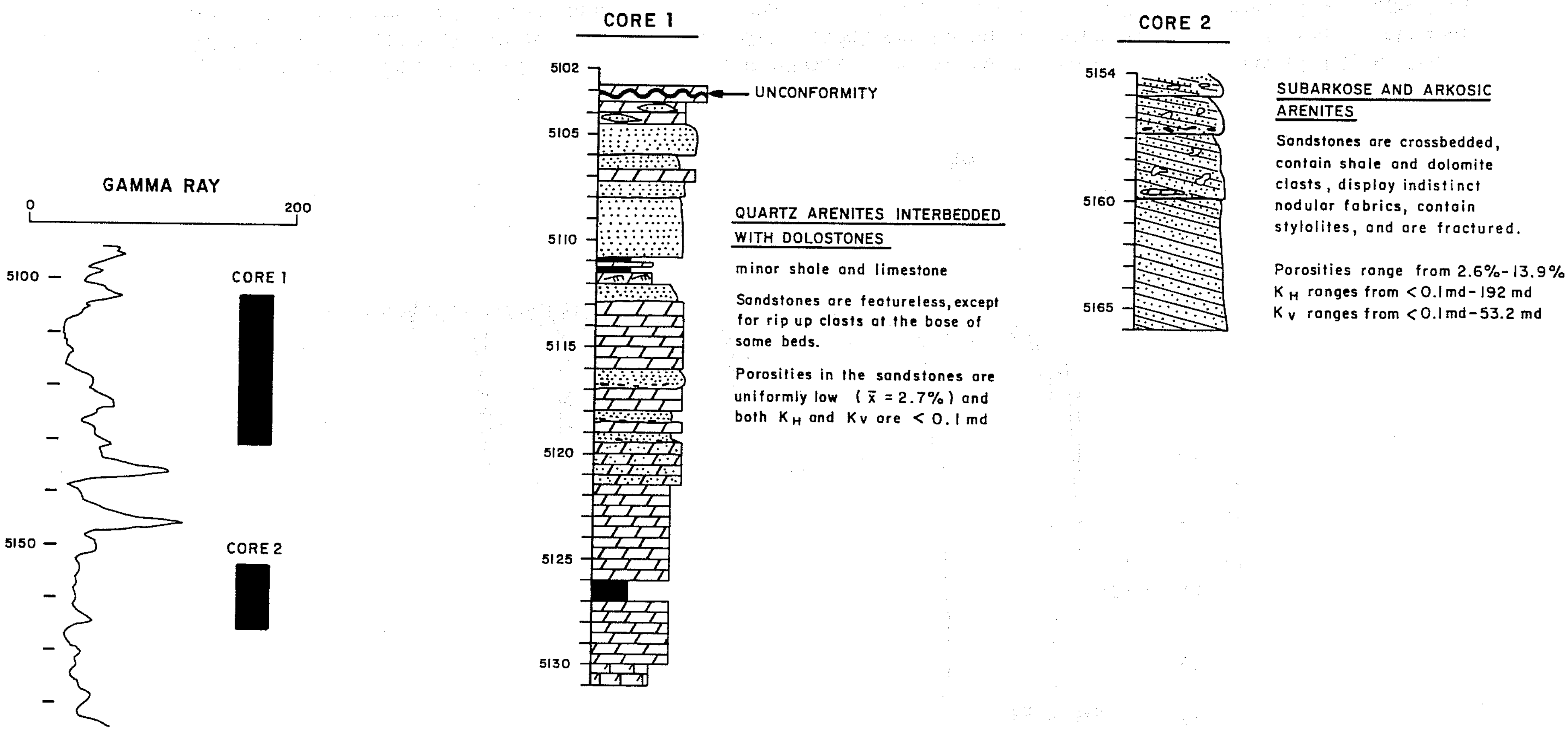


Figure 67. Graphical descriptions of cores 1 and 2 from the Hammermill Paper Co. #2 Fee well (from Laughrey, in press). Gamma-ray log (measured in API units) and cored intervals (dark boxes) on left. Symbols for core lithologies are standard.

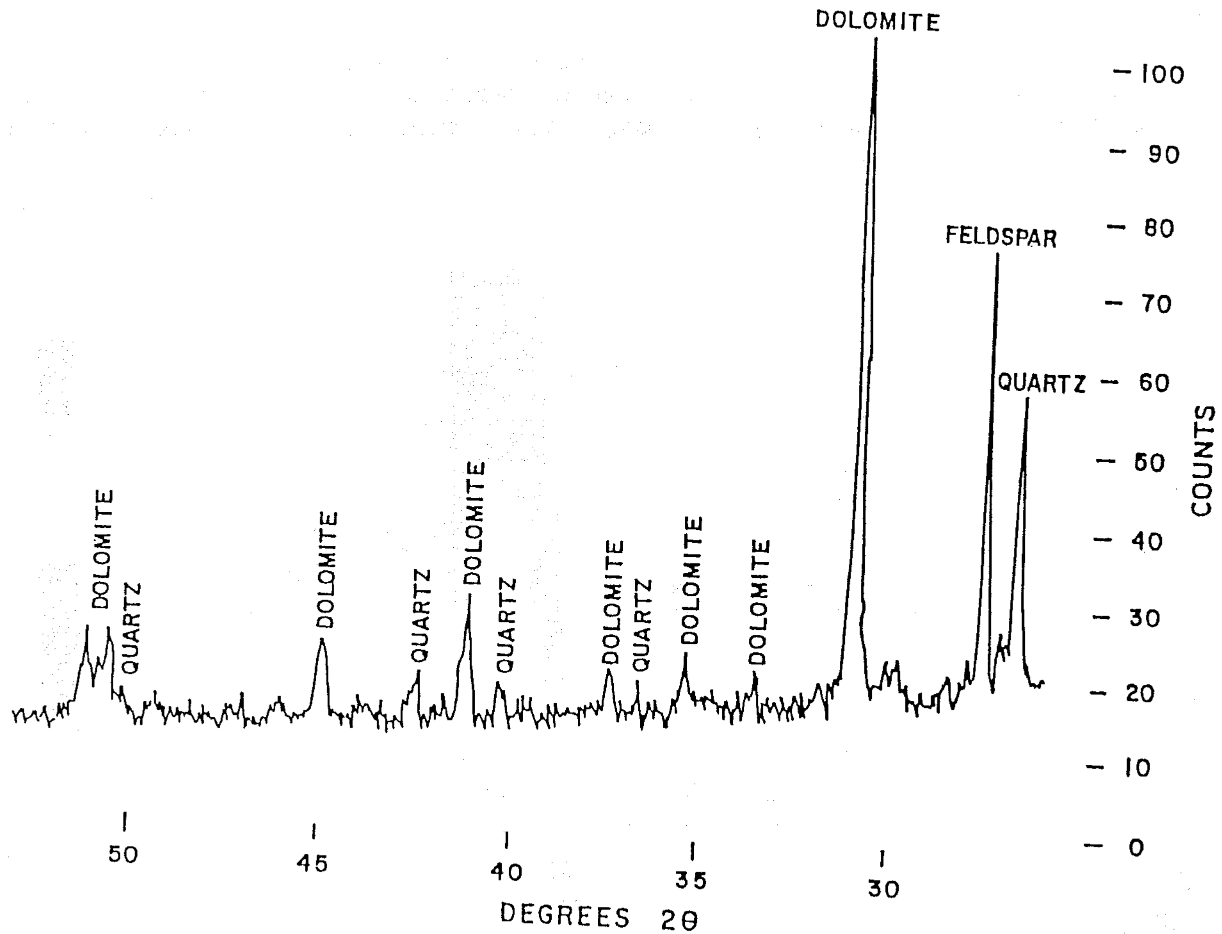


Figure 68. X-ray diffraction scan of the Rose Run sandstone from 5,159 ft, core 2, Hammermill Paper Co. #2 Fee well (from Laughrey, in press). The sandstone is an arkosic arenite. Quartz, feldspar, and dolomite are the major peaks. Lower dolomite intensities may indicate iron, i.e. ankeritic dolomite.

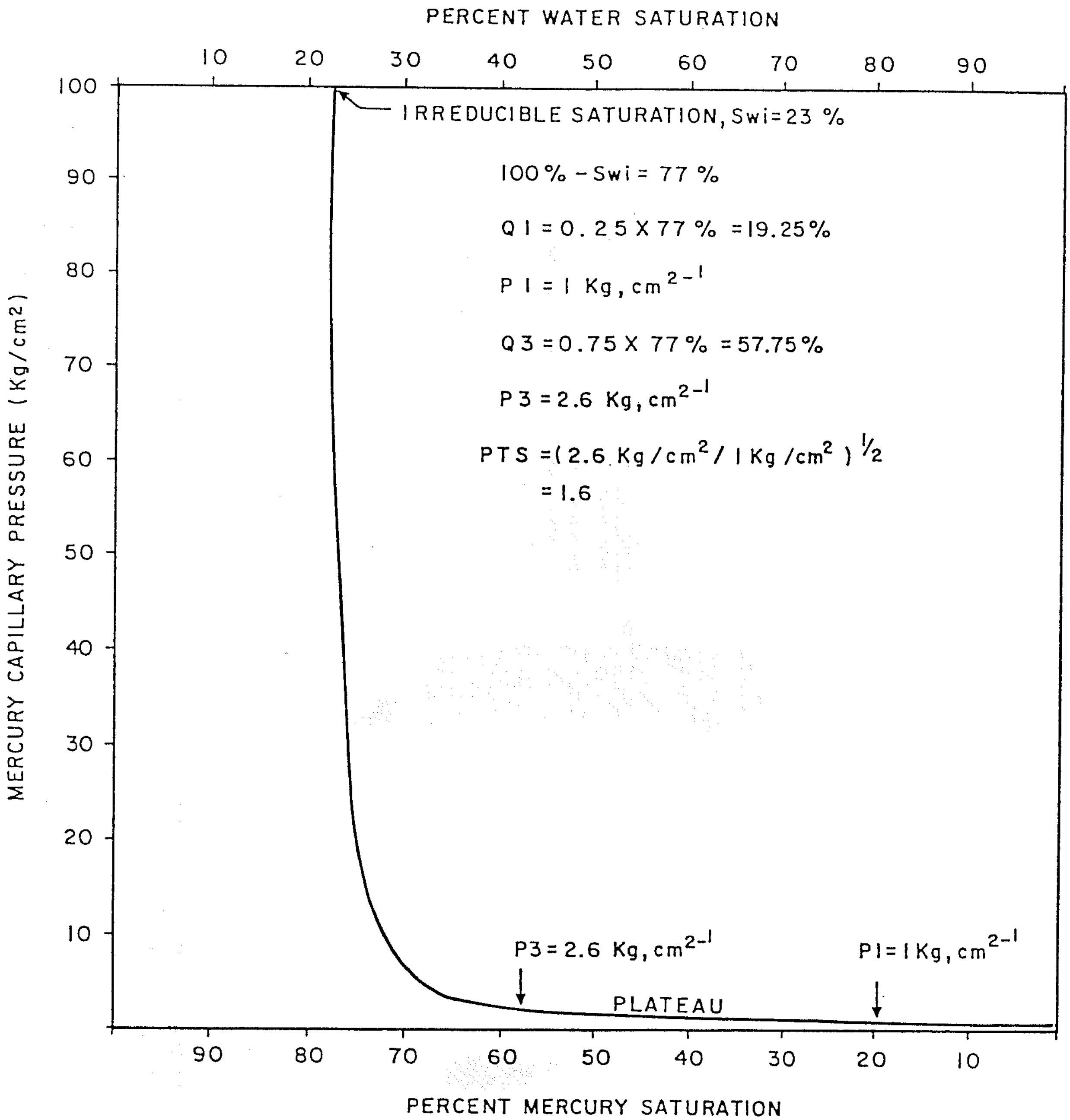


Figure 69. Capillary pressure curve for a Rose Run subarkose in core 2 from the Hammermill Paper Co. #2 well (from Laughry, in press). Note the irreducible water saturation at 23%. PTS - pore throat sorting (a measure of the sorting of the pore throats within the sample - Jennings, 1987). Q1 and Q3 - first and third quartile pressures on the capillary pressure curve, i.e., the 25% and 75% saturation pressures (P1 and P3, adjusted for 5 wi). A PTS value 1.0 represents a perfectly horizontal plateau segment; PTS values above 5.0 represent little or no plateau development. PTS = 1.0 means perfect sorting. PTS = 8.0 means no sorting. The pore throats in this sample are well sorted.

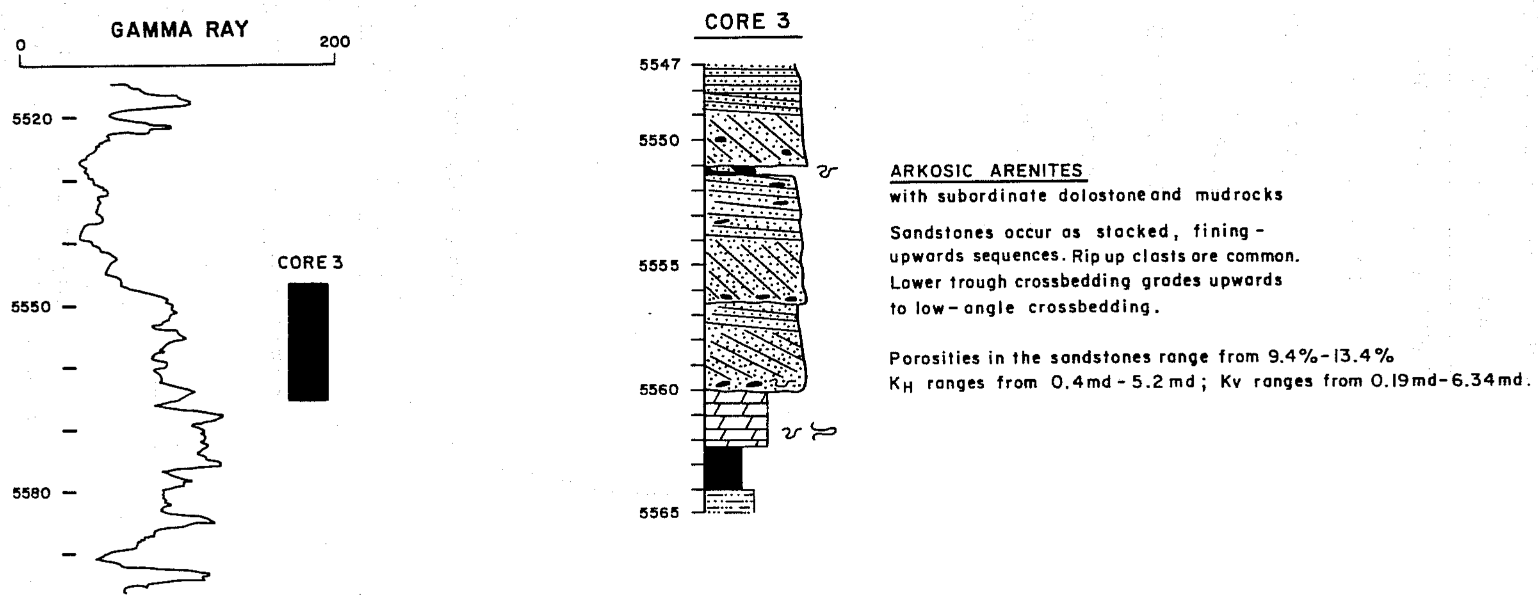


Figure 70. Graphical description of core 3 from the Hammermill Paper Co. #2 Fee well (from Laughrey, in press). See figure 67 for explanation.

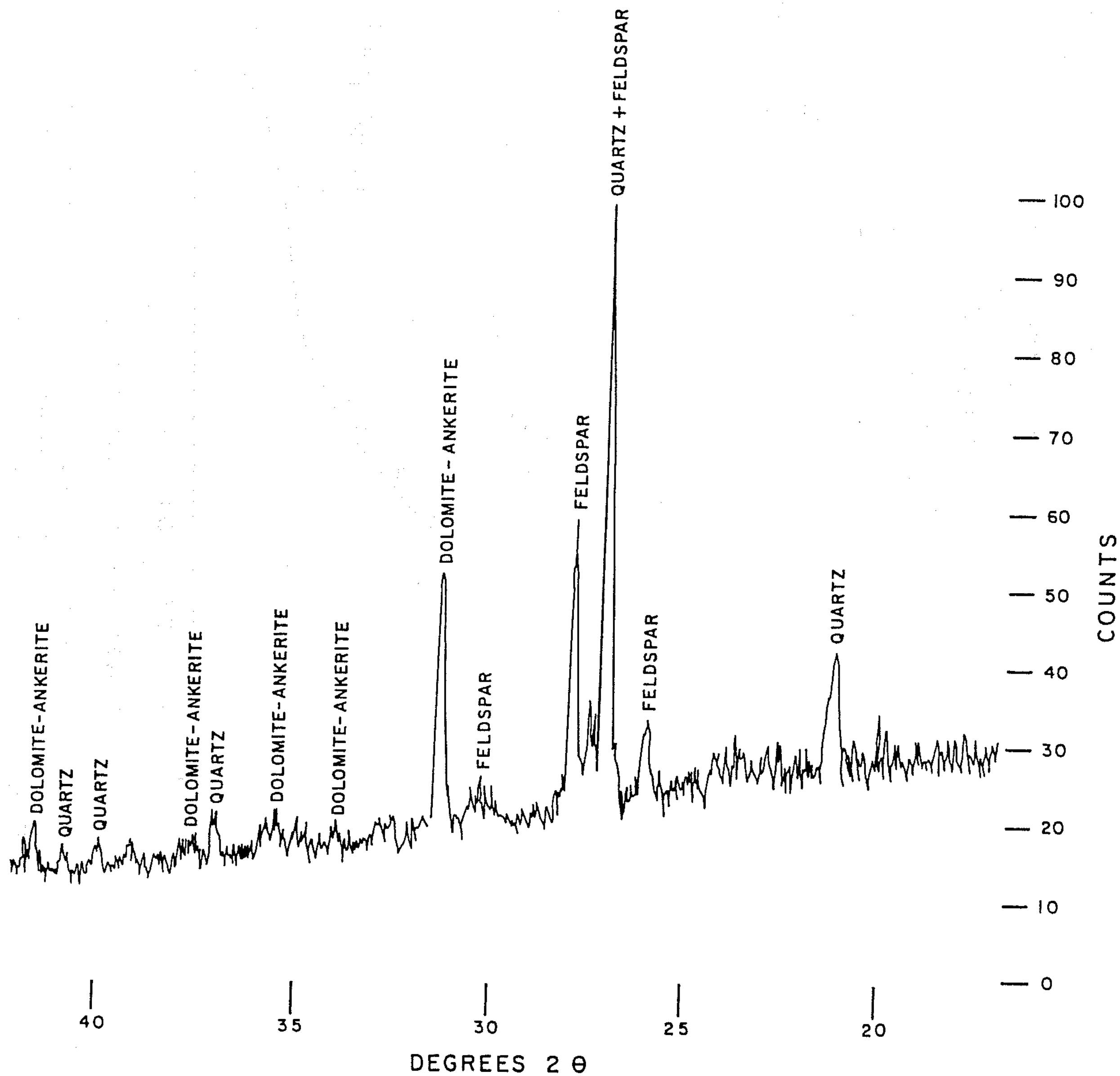


Figure 71. X-ray diffraction scan of a Lower Sandy member arkosic arenite from core 3 in the Hammermill Paper Co. #2 Fee well from a depth of 5,559 ft.

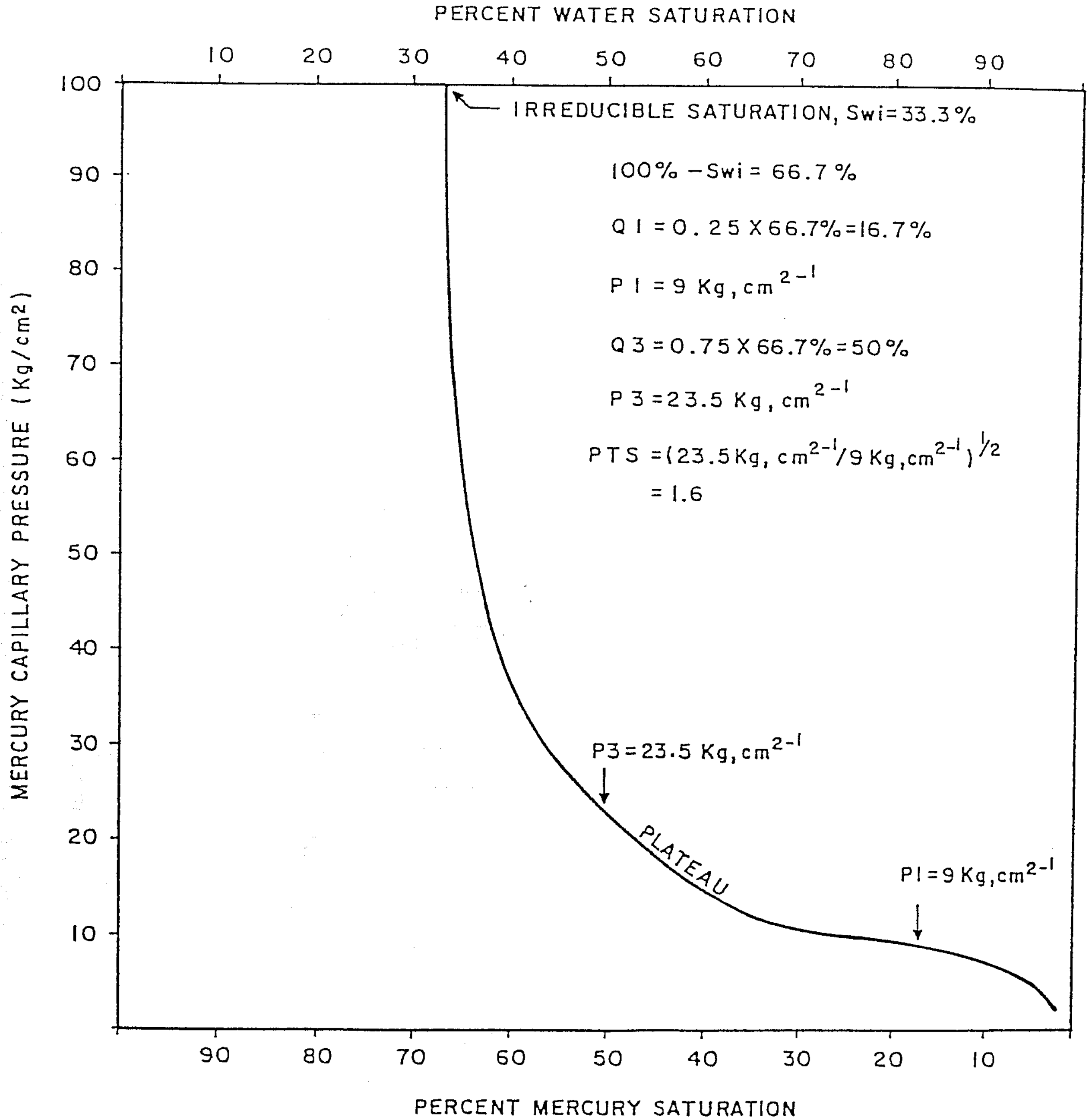


Figure 72. Capillary pressure curve and calculation of pore throat sorting for sample of the Lower Sandy member of the Gatesburg Formation in the Hammermill Paper Co. #2 Fee well at a depth of 5,559 ft (from Laughry, in press).

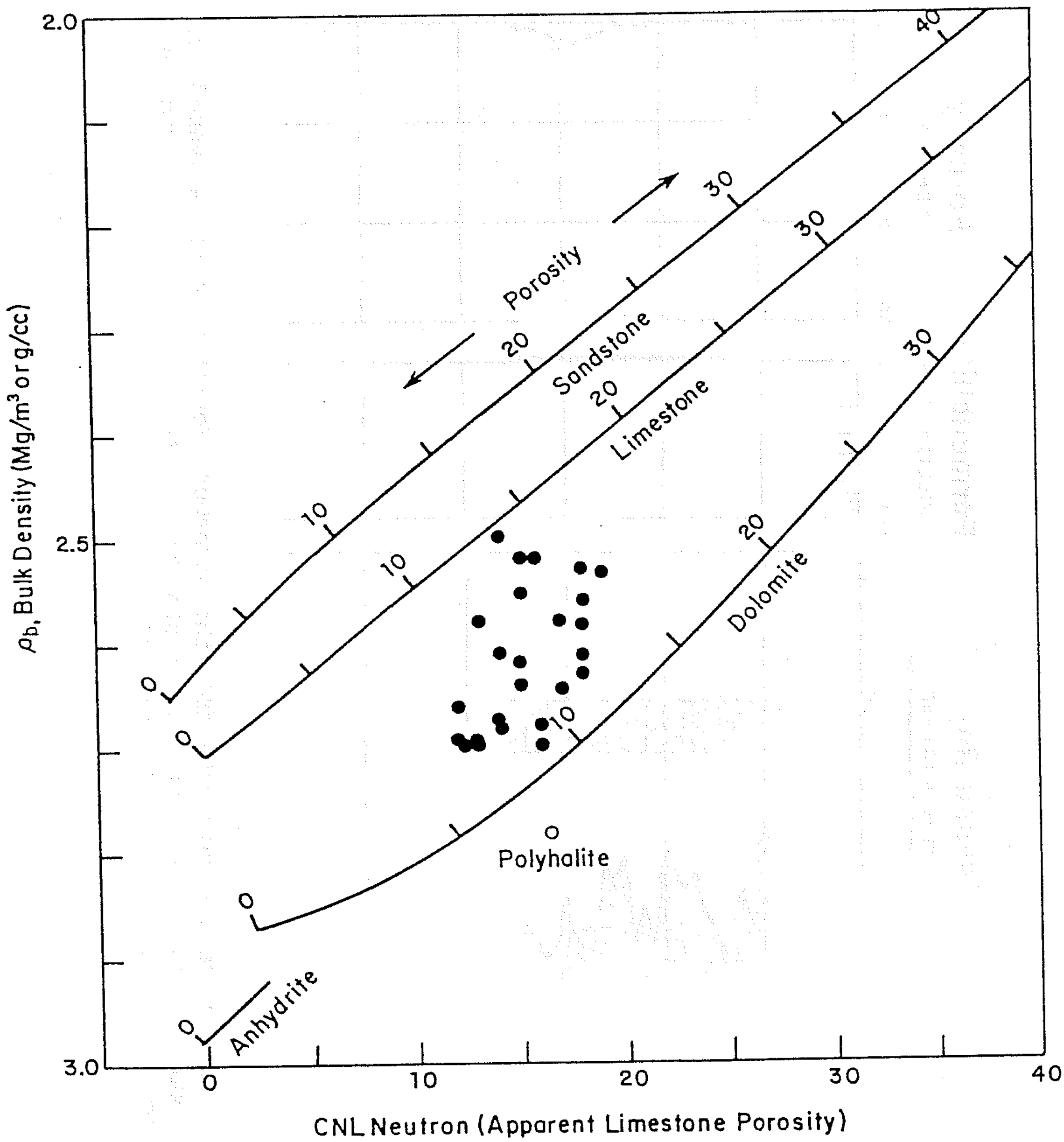


Figure 73. Porosity and lithology determination from crossplot of sonic transit time and neutron porosity of the Rose Run sandstone in the Cardinal Oil Co. #1 Ewig well in Crawford County, Pennsylvania. Core studies document the mixture of dolostone, limestone, and dolomitic sandstones in the section. This crossplot does not clearly resolve the lithologies in the well.

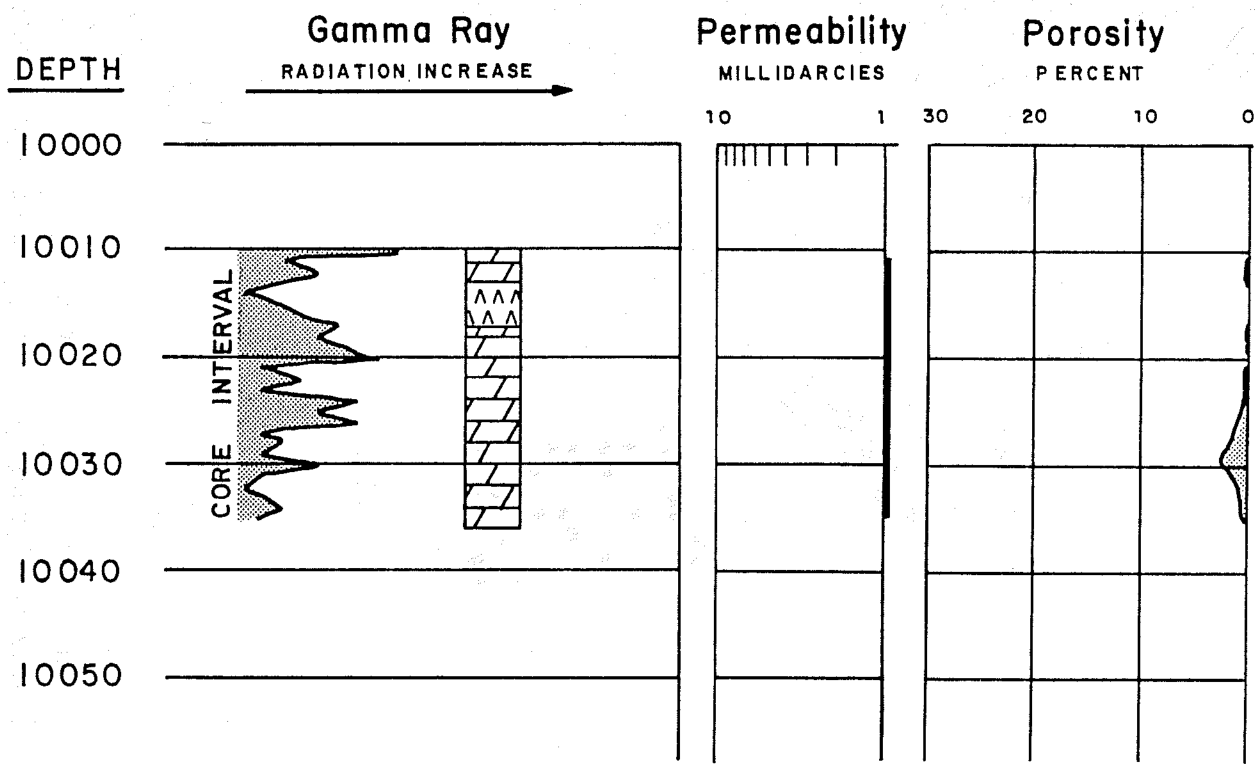


Figure 74. Graphical plot of core analysis data from the Gatesburg Formation core recovered from Shell Oil Co. #1 Shade Mountain Unit well in Juniata County, Pennsylvania. The gamma-ray signature was obtained by scintillometer from the core.

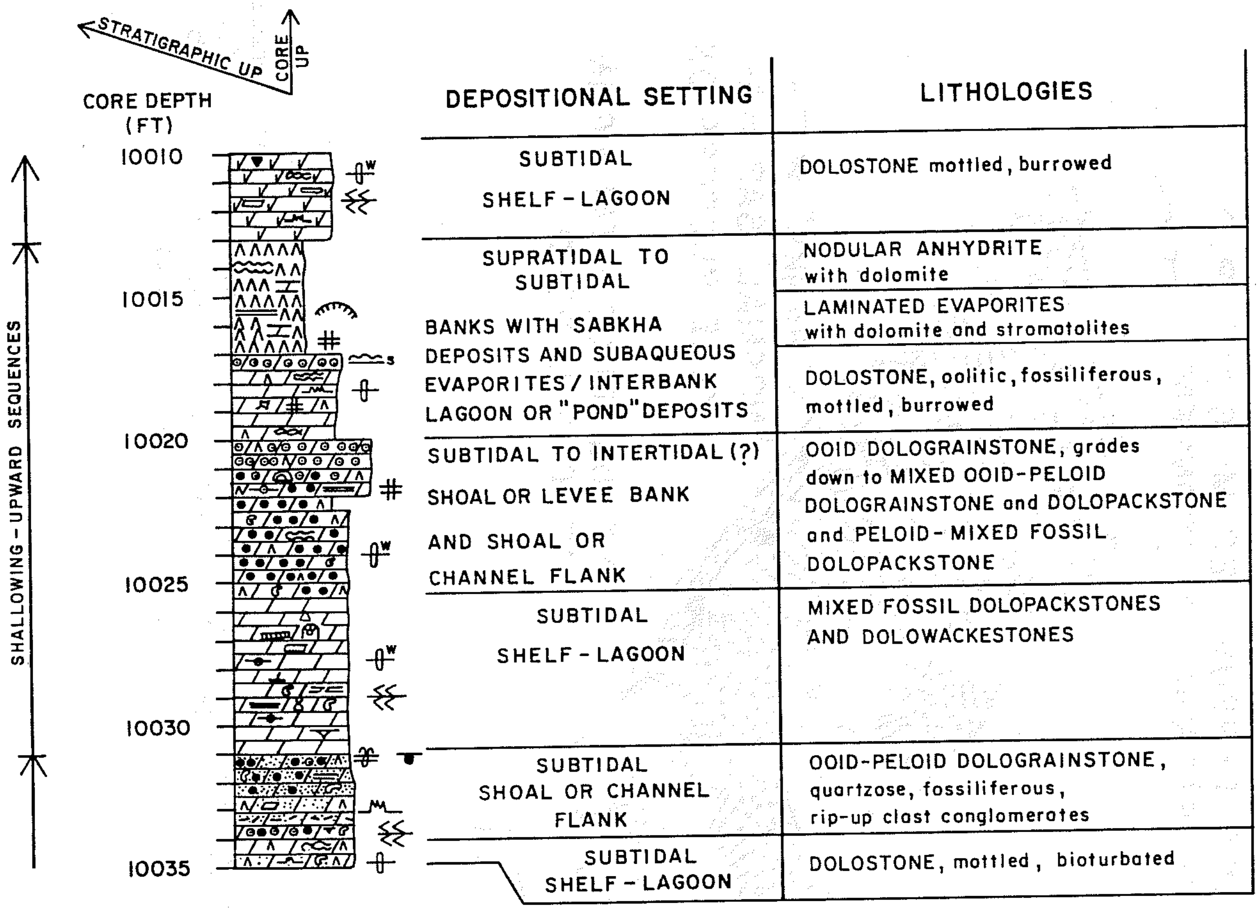


Figure 75. Graphical core description of the Gatesburg Formation in the Shell Oil Co. #1 Shade Mountain Unit well. Symbols are taken from the AAPG Sample Examination Manual (swanson, 1981).

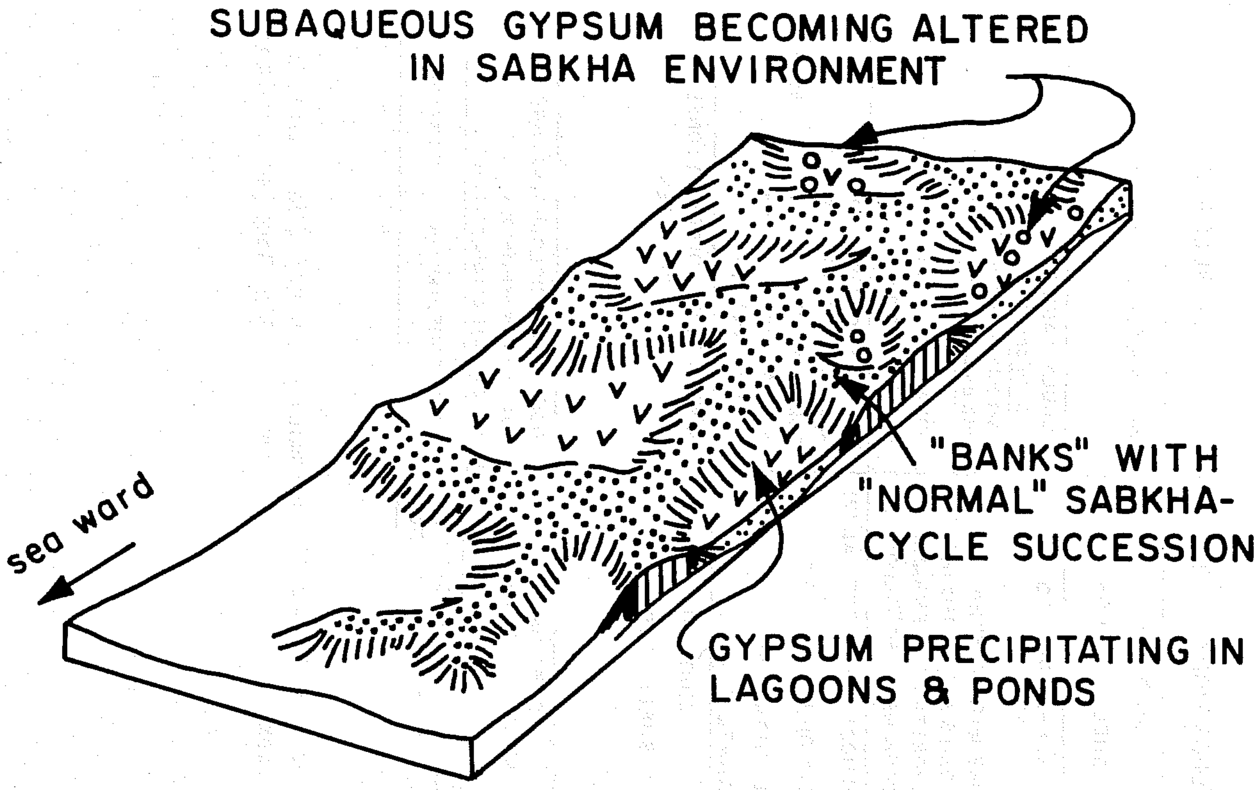


Figure 76. Inferred depositional environment of Mississippian Frobisher Evaporite in southeastern Saskatchewan provides a valid model for Late Cambrian Gatesburg deposition in central Pennsylvania (from Kendall, 1984). Numerous shallow maritime lakes, ponds, or lagoons are isolated by carbonate shoals and banks on top of which strips of supratidal sabkha rest.

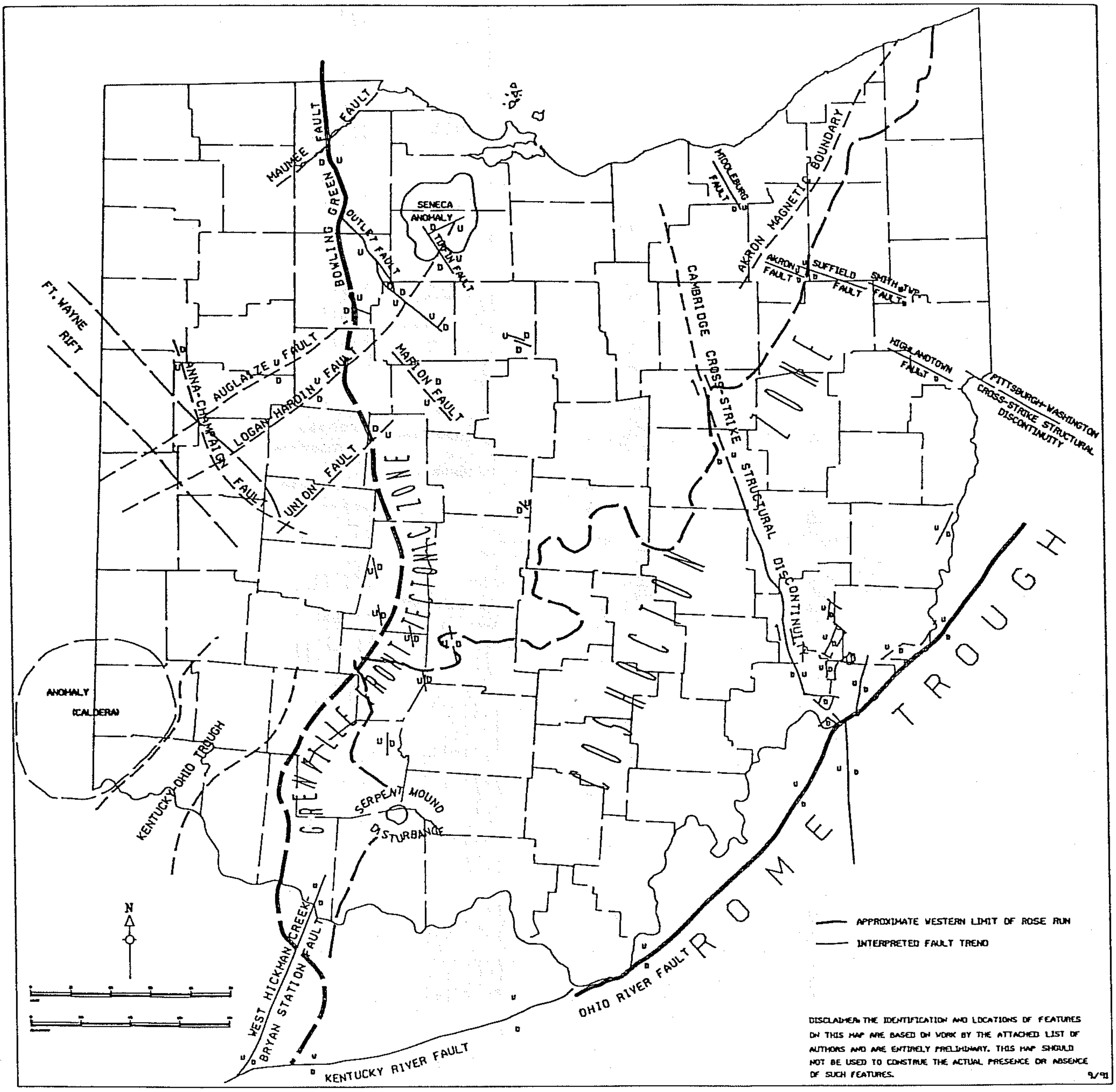


Figure 77. Basement structures in the subsurface of Ohio.

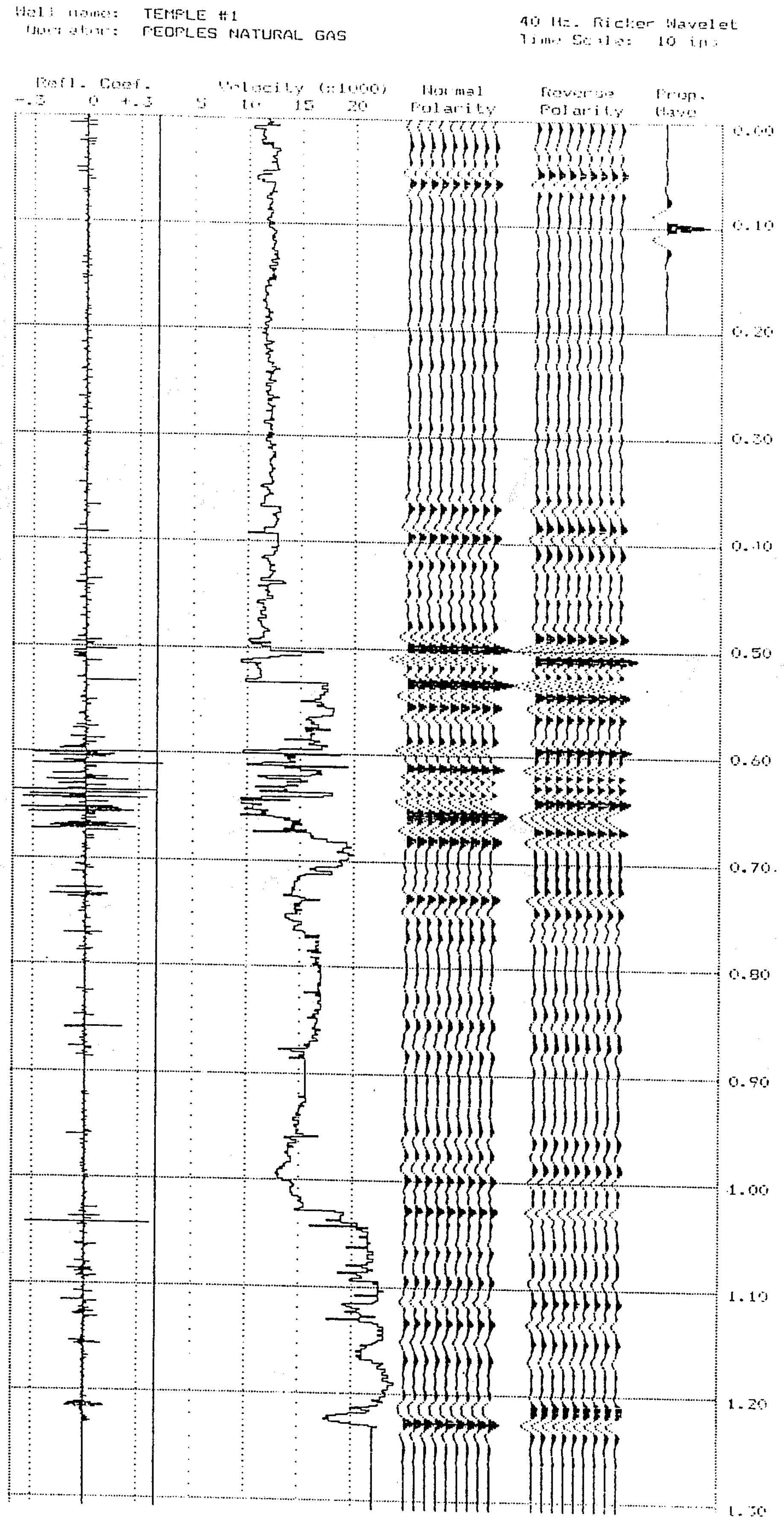
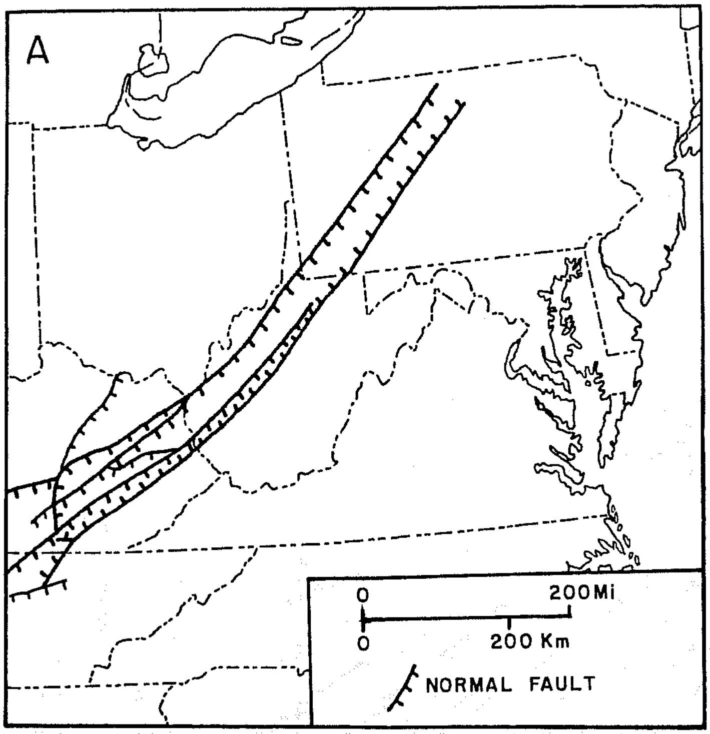


Figure 78. Synthetic seismogram of the Peoples Natural Gas #1 Robert Temple well in Mercer County, Pennsylvania.



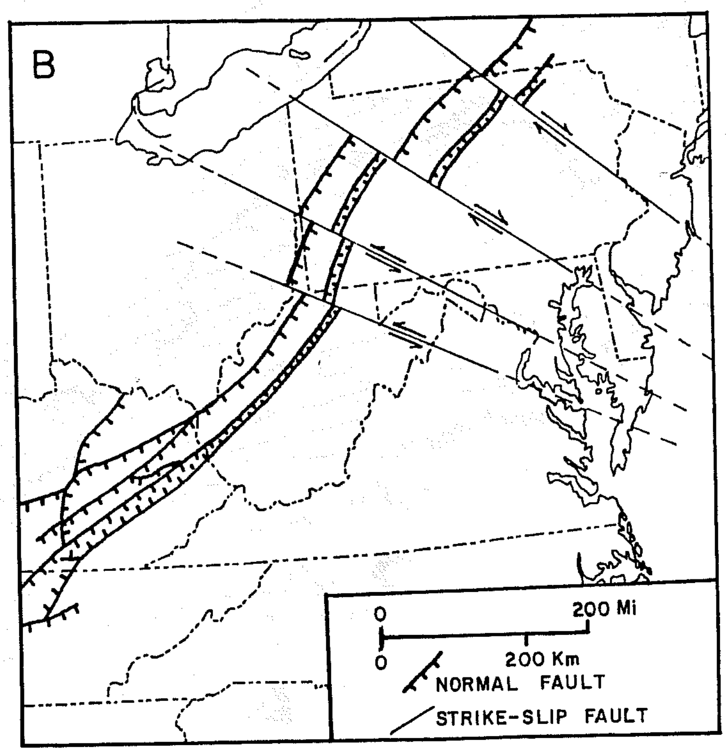


Figure 79. A. Commonly accepted configuration of the Rome trough in the central Appalachian Basin (modified from Rankin, 1976). B. Reinterpretation of figure 79A on probable segmentation and offset along major basement wrench fault assemblages (from Harper and Laughrey, 1984 - see text for explanation).

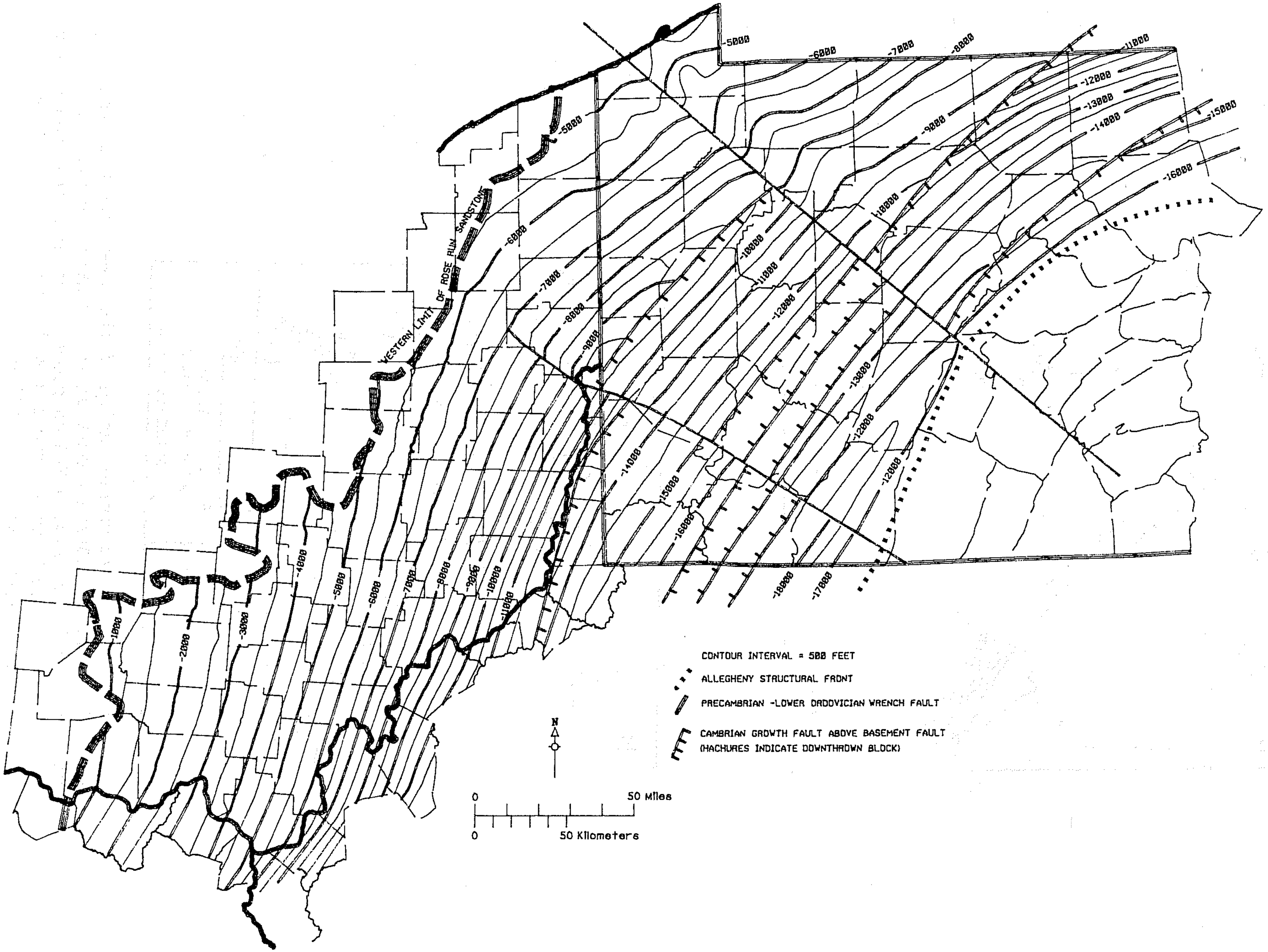


Figure 80. Structure map on top of the Knox unconformity.

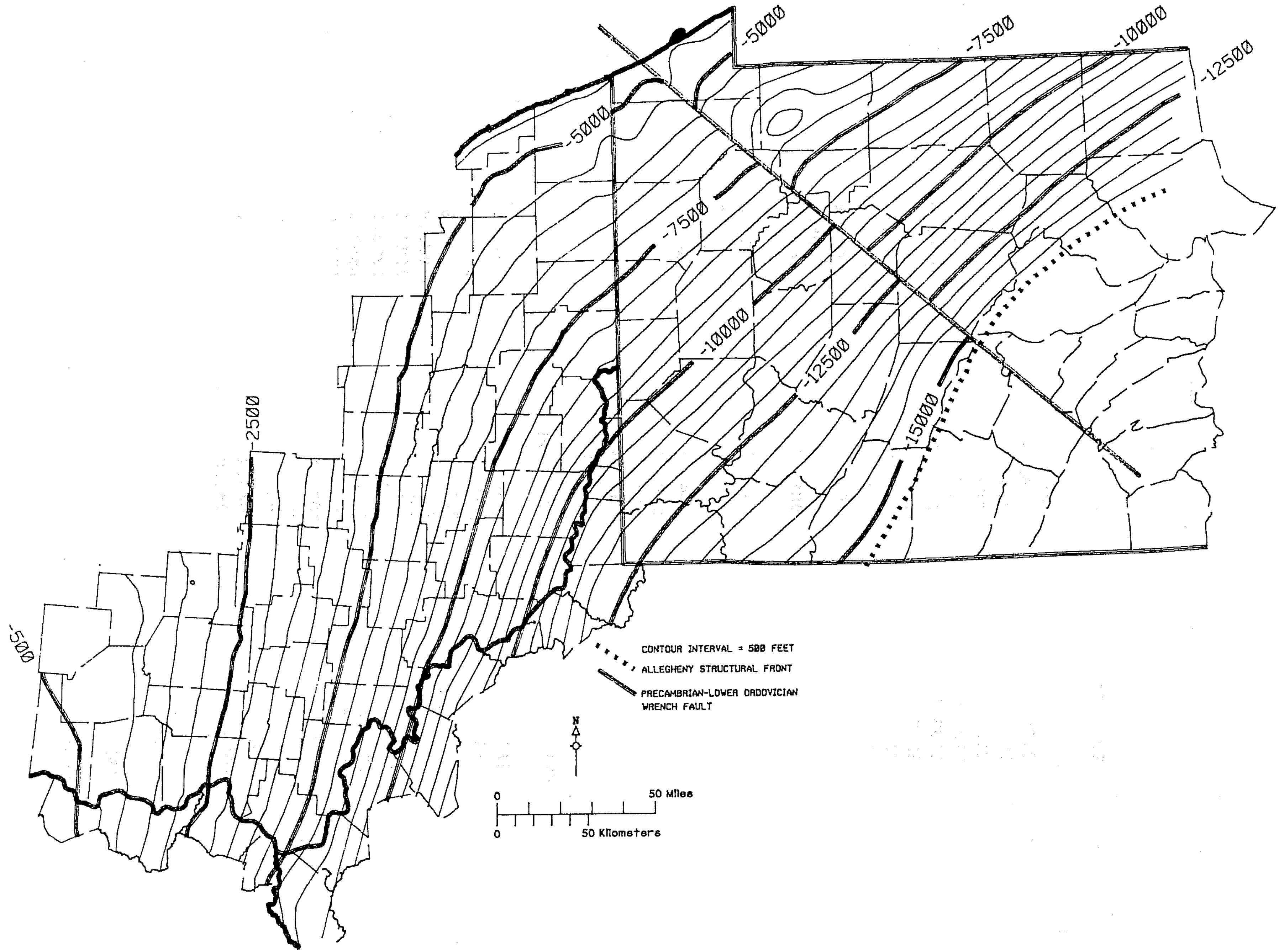


Figure 81. Structure map on top of the Rose Run sandstone.

Table 1. List of thin sections prepared from 10 Big Injun cores.

CLAY 1107	CLAY 1108	CLAY 1109
2119.5'	2063.4'	1881.1'
2125.8	2065.9	1881.9
2127.4	2069.0	1890.3
2132.5	2070.0	1894.5
2134.5	2071.9	1895.8
2138.8	2073.3	1896.8
2140.0	2075.5	1897.3
2148.5	2077.5	1898.5
2151.4	2080.8	1901.8
2153.8	2081.6	1902.9
2157.5	2083.5	1905.0
	2084.7	1906.1
	2085.5	1908.3
	2087.0	1910.8
	2089.9	1915.6
	2091.4	1923.0
	2093.0	1926.9
	2094.8	
	2097.4	
	2099.4	
	2109.6	

CLAY 1110	CLAY 1128	CLAY 1130
1887.0'	1997.3'	1864.5'
1883.3	2002.9	1870.7
1888.6	2003.8	1874.5
1890.3	2004.7	1879.8
1894.5	2007.2	1881.9
1899.2	2011.4	1895.3
1900.8	2014.8	1897.0
1902.2	2015.9	1906.9
1904.0	2024.1	
1905.8	2027.2	
1906.9	2032.3	
1910.3	2034.4	
1913.0	2041.0	
1917.5		
1923.3		
1924.0		
1925.43		
1928.8		
1930.3		
1930.7		

Table 1. continued

CLAY 1132	CLAY 1133	CLAY 1134
1970.1'	2084.0'	2203.1'
1972.3	2086.4	2204.0
1974.3	2089.8	2206.3
1981.9	2096.8	2208.6
1991.2	2098.9	2212.6
1994.9	2103.6	2216.8
2009.3	2107.4	2218.7
2011.0	2109.3	2225.1
	2113.8	

L. W. SHAFFER PI #2

2084.25'
2087.0
2089.0
2093.0
2094.0
2095.33
2095.5
2097.0
2098.0
2098.75
2103.0
2104.0
2107.0
2108.0
2110.0
2112.5
2114.0
2115.0
2118.4
2120.4
2122.0
2123.75
2124.9
2126.67
2127.0
2128.5
2130.0
2131.5
2134.5

Table 2. Depths sampled in five cores for additional thin sections.

ROANE 1020

2029-30'
2037-38
2041.42
2041-42
2044.45
2046.47
2052-53
2055-56
2059-60
2064-65
2067-68
2069-70
2073-74
2080-81
2082-83
2092-93

ROANE 1021

2118-19'
2117-18
2119-20
2121-22
2122-23
2130-31
2131-32
2134-35
2137-38
2143-44
2148-49
2155-56
2157-58
2160-61
2164-65
2167-68
2172-73

ROANE 1051

1984.5-85.5'
1986-89
1989-90
1991-92
1992-93
1993-94
1996-97
2001-01
2003-04

2017-18
2024-25
2026-27

ROANE 1052

1966.5-68'
1968-70
1975-77
1981-82
2019-20

PENNZOIL-LEWIS #29

1930.0'
1931.5
1934.0
1935.0
1935.5
1937.25
1938.0
1939.0
1943.0
1944.0
1948.0
1950.0
1954.0
1959.0
1966.0
1974.0

Table 3. List of Big Injun cored wells in Granny Creek field for which log suites are available.

Well Permit #	Log Suite	Log Analysis Porosity %	Log Analysis Sw%	Core Analysis
108	FDC,DIL	yes	yes	no
120	FDC,DIL	yes	yes	yes
133	GR,LTD	yes	yes	yes
134	GR,SFL,DIL	yes	yes	yes
733	FDL	no	no	yes
735	GR,FDL	no	no	yes
852	DIL,FDC,SLC	no	no	no
864	GR	no	no	yes
868	N,DIL	no	no	yes
874	GR,N	no	no	yes
903	GR,D	no	no	yes
932	GR,N	no	no	yes
1059	DIL,DI,GR,FDL	yes	yes	no
1107	DI,FDL,N	yes	yes	no
1108	N,I	no	no	yes
1109	GR,DIL,I	no	no	yes
1126	GR,CD,IND	no	no	yes
1128	D	no	no	yes
1130	GR	no	no	no
1132	GR	no	no	yes
1933	FDC	no	no	yes
1935	FDC	no	no	yes
1936	FDC	no	no	yes
1941	FDC	no	no	yes
1942	FDC	no	no	yes
1951	FDC	no	no	yes
1952	FDC	no	no	yes
1953	CDL	no	no	no

FDC - Formation Density Compensate
GR - Gamma Ray
FDL - Formation Density Log
N - Neutron
I - Induction
DI - Dual Induction
FD - Formation Density
LDT - Litho-Density Tool
DIL - Dual Induction Log
SFL - Sperical Focused Log
SLC - Sonic Log Compensated
D - Density
CD - Compensated Density
CDL - Compensated Density Log
CN - Compensated Neutron

Table 4. List of cored wells by company for the Granny Creek field for which cores and/or core data are available.

Permit #	Company	Analysis
2253	Pennzoil	Dowell Schlumberger
2255	Pennzoil	Dowell Schlumberger
1184	Pennzoil	Core Lab Incorporated
1598	Pennzoil	Core Lab Incorporated
1108	Columbia	Oilfield Research Inc
1109	Columbia	Oilfield Research Inc.
1126	Columbia	Oilfield Research Inc.
1128	Columbia	Oilfield Research Inc.
1130	Columbia	Oilfield Research Inc.
1132	Columbia	Oilfield Research Inc.
1107	Columbia	Oilfield Research Inc.
735	Columbia	Core Lab Incorporated
852	Columbia	Core Lab Incorporated
864	Columbia	Core Lab Incorporated
868	Columbia	Core Lab Incorporated
874	Columbia	Core Lab Incorporated
903	Columbia	Core Lab Incorporated
932	Columbia	Core Lab Incorporated
733	Columbia	Core Lab Incorporated
1059	Columbia	Core Lab Incorporated
1110	Columbia	West Virginia University
1133	Columbia	West Virginia University
1134	Columbia	West Virginia University

Table 5. Source and numbering system of collected maps.

Map	Description	Map Source	Well Numbering
(1)	Granny Creek (total field)	WVU Geology	Permit Nos.
(2)	Granny Creek (water flood) (Pennzoil section)	Pennzoil	Company Nos.
(3)	Granny Creek (Pennzoil section)	Pennzoil	Company Nos.
(4)	Granny Creek (Iso-Cumulative)	Pennzoil	Company Nos.
(5)	Granny Creek	WVGES	Permit Nos.
(6)	Granny Creek (Columbia)	Columbia	Company Nos.
(7)	Granny Creek (Columbia)	Columbia	CompanyNos. & Permit Nos.
(8)	Walton Field	WVGES	Permit Nos.
(9)	Granny Creek Proposed Pilot project (Columbia)	Columbia	Company Nos.

WVGES - West Virginia Geologic and Economic Survey

Table 6. Types of collected production records for the Granny Creek field.

1. Reports - Daily production reports from CO_2 mini-flood, collected from 1-18-80 to 9-30-80.
2. Graphs - Monthly production graphs, from 7-76 to 9-80 for:
   a. Well No. 4254, original pilot and mini-flood,
   b. Original CO_2 pilot, total production from inside and outside the pattern, from 7-76 to 12-79,
   c. Primary monthly production graphs, Columbia's leases, from 1964 and 1965, and
   d. Waterflood monthly production graphs, from 1965 to 1975.
3. Gross annual production records, for Well Permit No's. 20381 and 20382, from 1927 to 1983.
4. Weekly production records, from 1976 to 1983 for 12 wells in or near the pilot area.
5. Monthly production records from mini-flood, from 1980 through 1981 for:
   a. Well Permit No's. 737, 738 and 2090, and
   b. Total production records.
6. Monthly production records for the original pilot, from 1976 to 1979 for:
   a. Well Permit No's. outside the pattern, 870,871, 879, 2047,880, 881, 21,2088 and 96,
   b. Well Permit No's. inside the pattern, 734, 737, 2090, and 1059, and
   c. Total production records.

Table 7. Big Injun sandstone porosity measurements for cored wells Clay 1110, 1133, and 1134, Granny Creek field.

Well Permit # 1110	Depth	Porosity %
	1886' 8"	9.8
	1894' 11"	0.0
	1894' 11" V	0.0
	1898' 11"	10.3
	1901' 9"	3.3
	1902' 6"	9.2
	1908' 0"	9.0
	1908' 0" V	8.1
	1912' 6"	14.0
	1928' 2"	11.7

Well Permit # 1133	Depth	Porosity %
	2083' 6"	0.0
	2086' 3"	0.0
	2086' 3" V	0.0
	2089' 10"	0.0
	2089' 10" V	1.4
	2096' 6"	13.1
	2105' 9"	10.8
	2111' 7"	7.4
	2115' 0"	5.8
	2115' 0" V	6.7

Well Permit # 1134	Depth	Porosity %
	2191' 0"	0.0
	2195' 0"	0.0
	2198' 6"	11.1
	62198' 6" V	11.6
	2201' 11"	7.2
	2201' 11" V	8.6
	2209' 9"	9.4
	2209' 9" V	8.0
	2214' 6"	11.4
	2221' 6"	10.1

Table 8. Porosity and permeability relationships in the Upper and Lower Sandy members of the Gatesburg Formation in the Hammermill Paper Co. #2 Fee well, Erie Co., Pennsylvania.

DEPTH	VERTICAL PERMEABILITY TO GAS (in md)	HORIZONTAL PERMEABILITY TO GAS (in md)	POROSITY (%)
5,110	<0.10	<0.10	2.7
5,154A	11.1	192	13.9
5,154B	53.2	76.0	11.2
5,159	<0.10	<0.10	2.6
5,552	6.34	5.14	13.4
5,556	2.05	1.33	12.6
5,559A	0.19	0.43	9.4
5,559B	1.84	1.92	12.9