Reservoir Characterization of the Wileyville Oil Field

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ABSTRACT

The Wileyville oil field, currently owned and operated by East Resources of Wexford, PA, was discovered in 1900. From 1900 to 1905, the productive and geographic limits of the Upper Devonian Gordon sandstone reservoir in the field were established. Secondary recovery by waterflooding began in 1997; the injection of more than 5 million barrels of water has only recently produced an increase in oil production.

Our study set out to determine the cause of this lag between injection and production by characterizing and evaluating the heterogeneity of the Gordon reservoir. The process of reservoir characterization consisted of a number of phases including: an analysis of the drilling and production history of the field and an investigation of the lithology, petrography, and petrophysics of the reservoir. Additionally, an assessment of uphole hydrocarbon potential was undertaken.

The short time period (six years) during which Wileyville became established as an oil field was the first indicator of relatively low reservoir heterogeneity. Work with core and geophysical logs from the field allowed the identification of the pay sandstone within the reservoir. Termed the *Featureless* Sandstone Lithofacies, this poorly cemented, highly bioturbated, porous (mean porosity greater than 16%) and permeable (mean permeability greater than 90 mD) siliciclastic material is situated in the middle of the Gordon interval. Continuous and well-connected in the southern half of the field, strata of the Featureless Sandstone Lithofacies thin to the north and become interbedded with impermeable shales and tightly cemented sandstones. This disparity in reservoir heterogeneity between the two halves of the field is mirrored in the difference in initial potential (IP) values between south (low heterogeneity - high IP's) and north (higher heterogeneity – lower IP's).

There appears to be potential for the production of additional hydrocarbons in the form of natural gas uphole from the Gordon interval in Wileyville. Sandstones in the Pennsylvanian Allegheny Formation and Pottsville Group are gas-prone in the area. Investigation of the coal-bed methane potential of coals in the Allegheny Formation and Monongahela Group estimates more than 35 Bcf of gas-in-place for these units. In addition, the de-watering of these coals to establish coal-bed methane production could provide an important source of injectable water for ongoing water flood operations.

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INTRODUCTION

Fields in the Appalachian basin have produced oil for over 140 years from sandstones within Upper Devonian rocks. These mature fields are characterized by thin pay zones with high initial open flows that declined over time, leaving 70-80 percent of the original oil in place. The Gordon and Gordon Stray sandstones, deposited in nearshore and onshore environments, have produced oil from about two dozen fields in southwestern Pennsylvania and northern West Virginia. Secondary recovery projects have been implemented in several of these fields, often with mixed success even after a significant outlay of time and expense.

The Wileyville field in northern West Virginia is the location of a line-drive, water-injection project that has only started producing oil; approximately 5 million gallons of water have been injected since February 1997. Frequent causes of injectivity problems include a poor understanding of the lithologic relationships within a field, the presence of discrete compartments or baffles to flow within the reservoir, or the existence of *thief* zones in communication with water injection wells.

The goal of the this study was to establish the nature and degree of heterogeneity within the Gordon interval in Wileyville field through reservoir characterization. The product is a three-dimensional model of depositional and lithologic units within the field. Analysis of historical drilling trends, measurement of permeability, stratigraphic correlation, definition of lithofacies and electrofacies, and identification of depositional units allowed the research team to infer compartments within the field, and to identify stratigraphic and geographic trends in these compartments.

Knowledge of reservoir architecture allows one to more efficiently and effectively design a waterflood of appropriate geometry, to locate injection wells, and to site new production wells.

EXECUTIVE SUMMARY

The Wileyville oil field in northern West Virginia is the location of a line-drive water-injection project that has only recently started producing oil; 5 million gallons of water have been injected since February 1997. Frequent causes of injectivity problems include a poor understanding of the lithologic relationships within a field, the presence of discrete compartments or baffles to flow within the reservoir, or the existence of *thief* zones in communication with water injection wells.

The goal of the this study was to establish the nature and degree of heterogeneity within the Gordon interval in Wileyville field through reservoir characterization. The product is a three-dimensional model of depositional and lithologic units within the field. Analysis of historical drilling trends, measurement of permeability, stratigraphic correlation, definition of lithofacies and electrofacies, and identification of depositional units allowed the research team to investigate compartmentalization within the field, and to identify stratigraphic and geographic trends in these compartments.

From 1900 to 1905, the entire producing reservoir in Wileyville was delineated by the drilling process. Based on our previous experiences with reservoir characterization of siliciclastic reservoirs in West Virginia, we believe that this pattern of completions is indicative of a relatively low degree of reservoir heterogeneity.

Cores from two wells in the Wileyville oil field were examined and described. Lithofacies were defined based on apparent grain size, variability in grain size within beds (sorting), presence or absence of laminations, evidence of bioturbation, lithologic textures, and presence or absence of crossbedding. Lithologic units were then compared with geophysical logs to determine log characteristics corresponding with each lithofacies. Information obtained from East Resources included data used to contour initial potential for comparison with maps of electrofacies and lithofacies.

Five lithofacies occur in the Gordon interval and can be recognized in geophysical logs. The Featureless Sandstone lithofacies with a density around 2.3 g/cm^3 comprises the primary reservoir for the field. In the southern part of the Wileyville field, the reservoir sandstone is continuous and probably well-connected. In the northern part of the field, featureless sandstones thin to almost zero thickness, suggesting that the northern part of the study area is not well-suited to waterflooding. Maps of initial potential shows spatial trends consistent with observed distribution of the featureless sandstone.

Two cores received from East Resources were examined systematically for lithologic and sedimentologic features, and sampled for permeability with a TEMCO MP-401 minipermeameter. Prepared thin sections were examined for grain size, mineralogy, and cementation.

The Featureless Sandstone lithofacies is predominantly quartz, fine-grained, well-sorted, and subangular. These sandstones are poorly cemented and highly permeable, making them good reservoir rock. Elongated quartz grains that have been rotated 90º to bedding indicate bioturbation. Early calcite cementation localized in bioturbated sediment formed barriers to interstratal migration of fluids. Seals between adjacent sedimentary layers probably reduced or prevented late-stage cementation and helped preserve initial permeability. Where bioturbation was more intense, the interstratal seal was more effective in preserving permeability. The Featureless Sandstone has the highest permeability of the five lithofacies, with a mean value greater than 90 mD.

Minipermeameter permeability values from Wileyville cores generally exceed whole core values but are less than core plug values for k_{hmax}.

Cements in the Gordon, in order of appearance, include calcite, clays, quartz overgrowths, and siderite. Combined primary and secondary porosity values in the Gordon range from 3% to 17% with a mean value of 9%. Secondary porosity is primarily intragranular and is often associated with the alteration or dissolution of feldspars.

Electrofacies in two reference wells were established by cluster analysis of depth, gamma ray, density, permeability, and grain size data. It was found that four electrofacies based on a linear combination of density and scaled gamma ray best matched previous stratigraphic correlations. Discriminant function coefficients were used to assign each interval of the available geophysical logs to one of these four electrofacies.

Four electrofacies were identified in the Gordon interval. Electrofacies 4 corresponds with the pay sandstone in the Gordon, a combination of Featureless Sandstone and minor Conglomeratic Sandstone lithofacies. A vertical electrofacies cross-section along the long axis of the field suggests that Electrofacies 4 is generally restricted to the middle of the Gordon interval. The Gordon in the Wileyville field is observed to deepen to the northeast along the plunge of structure. No serious lateral impediments to flow are visible in the cross section. However, a gap in well control is present in the southern portion of the field and this gap corresponds to a distinct break in IP values in the area.

Previous studies of coal bed methane occurrences and major gas plays in the region of the Wileyville field were examined to assess uphole potential in this field. The best uphole potential appears to be in the shallowest plays, the Allegheny and Pottsville sandstones and associated coals, and in developing the coal-bed methane potential of the Allegheny Formation and lower Monongahela Group. Total gas in place for two coals in the lower Monongahela and six coals in the Allegheny, is approximately 35.74 Bcf for the area encompassed by the Wileyville oil field. Coal beds present above the Gordon oil reservoir are expected to be water-filled in this field. In de-watering the coals to establish coal-bed methane production, an important source of water for the continuation of the Wileyville waterflood in the Gordon oil reservoir could be developed.

HISTORY AND GEOLOGIC SETTING OF THE WILEYVILLE FIELD

History

The Wileyville oil field was discovered Wetzel County, WV in 1900 (Figure 1). To investigate the development history of the field and to get a preliminary assessment of heterogeneity within the field, completion-location analysis (McDowell and others, 1992) was undertaken. The completion dates for all producing wells in the field were subjected to spectral analysis (Figure 1) to see how well completions were distributed in time. Next, the geographic locations of all producing wells were plotted within the field in order of each well's date of completion.

We have noted (McDowell and others, 1992; McDowell and others, 1993; Hohn and McDowell, 1993; Hohn and others, 1993a and 1993b; Ameri and others, 2001; Matchen and others, 2001) that, in general, the number of completions of producing wells clustered in the same geographic area within the same short interval of time (five to ten years) corresponds in a qualitative manner to the heterogeneity within the reservoir. Examination of Figure 1 suggest the presence of only three clusters of completions and only one of them (1899-1905) includes more than two wells. Figure 2 shows the locations of producing wells completed in each of the years from 1900 to 1905. During this six year time span, the entire producing reservoir in Wileyville was delineated by the drilling process. Discovery started in the southern portion of the field and proceeded rapidly to the northeast so that, by 1902, the linear nature of the field and its longest dimension had been established. Based on our previous experiences with reservoir characterization of siliciclastic reservoirs in West Virginia, we believe that this pattern of completions is indicative of a relatively low degree of reservoir heterogeneity. Certainly, heterogeneity is lower than that observed in either the Mississippian Big Injun reservoir in the Granny Creek or Rock Creek fields and lower than that observed in the Devonian Gordon reservoir in the Jacksonburg-Stringtown field.

Geological Setting

Structure

The waterflood project within the Wileyville oil field is situated along a small anticline between the larger Nineveh Syncline and the Littleton Anticline (Figure 3). The remaining portion of the field wraps around the anticline to the north and west (Cardwell and Avary, 1982); this portion of the field was not developed for waterflood. Within the project area, the Gordon dips northward following the plunge of the anticline. This dip may be as steep as 25º and appears to be consistent, suggesting that there is no structural compartmentalization within the project area.

Stratigraphy

Gordon sandstones are part of the thick, Upper Devonian sedimentary section. In West Virginia, the outcrop equivalent is the Hampshire Formation (Figure 4). Sediment composition varies considerably between non-marine red shales and fluvial sandstones of the Hampshire Formation in the eastern outcrop belt of West Virginia, Maryland, and Pennsylvania, to distal marine shales of the Ohio Shale in the western outcrop belt of Kentucky and Ohio. Intervening sedimentary rocks grade between these two extremes, containing at different locations, fluvial, shoreline, or shelf sandstones and shales; the Gordon lies within the shoreline portion of this spectrum. In general, marine content decreases to the east.

In the Jacksonburg-Stringtown oil field, the Gordon is composed of four parasequences, three of which contain lithofacies associated with the producing reservoir. The fourth parasequence, located above the primary reservoir is comprised of bioturbated sandstones and shales. Similar strata are encountered in Wileyville and serve as a marker for stratigraphic correlation. North of the Jacksonburg-Stringtown field, the lower two parasequences, both of which contain pay sandstones, grade into shale. Correlation of the Gordon to the north shows the sandier portion of the lowermost parasequence pinching out, reducing the number of definable parasequences in Wileyville to three, one of which contains oil producing reservoir. This correlation suggests that there is a single primary reservoir in the Wileyville field which can, perhaps, be treated as a single compartment for development purposes (Figure 5).

LITHOFACIES, STRATIGRAPHIC FRAMEWORK, AND PRODUCTION

Methodology

Cores from two wells in the Wileyville oil field (Figure 6) were examined and described. Lithofacies were defined from apparent grain size, variability in grain size within beds (sorting), presence or absence of laminations, evidence of bioturbation, lithologic texture, and presence or absence of crossbedding. Lithologic units were then compared with geophysical logs to determine log characteristics corresponding with each lithofacies. A spreadsheet of information obtained from East Resources included initial potential production data from several sources. Wells differed in the number of sources of data. Graphs of reported values showed data from the two main sources to be significantly positively correlated; both sources were used to contour initial potential for comparison with maps of electrofacies and lithofacies.

Results and Discussion

Lithofacies

Five lithofacies can be recognized: Featureless sandstone (*Fss*), Laminated sandstone (*Lss*), Conglomeratic sandstone (*Css*), Shale (*Sh*) and Heterolithic bioturbated (*Hb*).

Each lithofacies is relatively distinctive in core and has a recognizable pattern on geophysical logs. The three sandstone lithofacies (*Fss*, *Lss*, and *Css*) comprise most of the Gordon interval. Where present, the *Sh* Lithofacies is useful for field-scale correlation. The *Hb* Lithofacies lies above the reservoir and is useful for paleoenvironmental interpretations and correlation.

Shale (*Sh*) is dark gray and laminated. Thin bands of siderite are present in some samples. The thickest shale beds are found in the lower part of the Gordon and are known only from log, as core was not available for the lowest interval.

Shale in core may also be interbedded with fine-grained sandstone and shale, which is also often bioturbated. This is the Heterolithic bioturbated (*Hb*) Lithofacies commonly found in the uppermost parasequence of the Gordon interval and correlative from the Jacksonburg-Stringtown oil field to Wileyville. Bioturbation is not as obvious in the Wileyville cores; some horizontal and vertical burrows are present (Figure 7).

Featureless sandstones (*Fss*) are fine- to very fine-grained, very well-sorted, and contain few recognizable sedimentary structures (Figure 8). Faint horizontal laminae and isolated quartz pebbles are observed infrequently. Occasionally, single-pebble layers are present.

Laminated sandstones (*Lss*) are fine- to very fine-grained, very well-sorted, and contain a wide variety of sedimentary structures. Horizontal laminations and low-angle crossbedding (Figure 9) are common. In some cases, crossbedding is bidirectional, perhaps herringbone. Sedimentary structures are clearest when clay laminae are present. Single-grain, quartz pebble layers are limited to a few per core. Bioturbation is rare; when present, it is often in the form of large single burrows.

Conglomeratic sandstone (*Css*) displays a bimodal grain size (Figure 10) ranging from fine- to very fine-grained sand to pebbles. There is little material of intermediate grain size. Texture varies from matrix-supported to clast-supported. Scour surfaces are common and many conglomerate beds appear to be lags deposited upon such surfaces. Other sedimentary structures include: low-angle, bi- and unidirectional crossbedding, high-angle (up to 30^o) crossbedding, reverse grading, rare ripple beds, and shale rip-up clasts.

Because there are many more wireline logs (27) for the field than cores, differentiation of lithofacies in log is critical to characterization of the reservoir. In core, lithofacies *Lss* and *Css* are denser than lithofacies *Fss*. This variation is obvious on wireline logs as well (Figures 11 and 12). On logs, lithofacies *Lss* and *Css* have a density of around 2.5 g/cm^3, whereas *Fss* sandstones have a density of around 2.3 g/cm^3. Gamma ray values are about the same for all three lithofacies, although the *Css* lithofacies often has the lowest gamma ray values. The sharp change in density values for *Fss* make the lithofacies very easy to distinguish as the primary reservoir for the field. Permeability profiles constructed using minipermeameter data (see Figures 11 and 12) show a similar relationship – the highest permeabilities are for *Fss* sandstones. Within the Gordon as a whole, permeabilities range from less than 25 mD to well over 100 mD.

Lithofacies *Hb* has the most variable log signature. In Wileyville, log signatures for this lithofacies display both very low and very high gamma ray and density values. This reflects the heterogeneous lithology and bioturbated nature of the Lithofacies. It comprises no productive reservoir material but has proven useful as a stratigraphic marker.

Stratigraphic Framework

Within the waterflood project area in Wileyville, the Gordon sandstone consists of three parasequences, only one of which contains reservoir-quality sandstone. An isopach of the total Gordon thickness within the waterflood project shows that the Gordon maintains a consistent thickness throughout the project area (Figure 13). The distribution of lithofacies *Fss* within the Gordon (Figure 14) is not as consistent. In the southern part of the waterflood project, the distribution of lithofacies *Fss* is consistent and probably well-connected. However, in the northern part of the project, the *Fss* compartment thins to almost zero thickness, suggesting that the northern part of the study area is less suitable for waterflooding. The same conclusions can be drawn from stratigraphic cross sections through the field (Figures 15, 16, and 17). The southern portion has a consistently thick, well-connected reservoir, whereas the northern part of the project shows a thin, discontinuous reservoir.

Initial Potential

The contour map of oil initial potentials shows that the southern half of the field has higher values than the northern half (Figure 18). The spatial pattern of initial potentials in the northern half is irregular, consistent with the presence of several reservoir compartments in this part of the field. Overall, there is a suggestion of poor communication between the two halves of the field, consistent with the stratigraphic model.

PETROGRAPHY AND PETROPHYSICS

Methodology

Two cores (L. E. Dulaney 10 and L. S. Hoyt 100) were available from the Gordon interval in the Wileyville field. Cores were received from East Resources already split and were examined and described by WVGES personnel. Lithologic and sedimentologic features were recorded in graphical log format (see Figures 11 and 12). Following lithologic description, permeability was sampled at an 0.25’ spacing using a TEMCO MP-401 minipermeameter. Additional permeability samples were taken adjacent to core locations from which 1” diameter plugs had been removed. Permeability data have been added to lithologic logs (see Figures 11 and 12). Based on sedimentological features observed in core and on core permeability values, representative intervals of interest were selected in each core and a total of thirty petrographic thin sections were prepared. Blue epoxy was used to impregnate thin section materials to help in the identification of porosity.

Grain size was assessed in each thin section by the examination and measurement of fifty grains per slide; this was increased to fifty grains in each size fraction when a bimodal grain distribution was present. Grain mineralogy was determined by the examination, identification, and classification of 300 grains in each slide. Mineralogic categories included: Monocrystalline Quartz, Polycrystalline Quartz, Secondary Quartz (as cement), Feldspar, Primary Porosity (intergranular), Secondary Porosity (primarily intragranular), Phyllosilicates, Opaque minerals, Clay (primarily as cement), and *Other* (a catch-all category for rock fragments, fossil fragments, heavy minerals, and other materials). The results of grain size analyses were reported in millimeters and in *phi* units (Krumbein, 1934); the results of mineralogic analyses were reported in percent (see Table 1a).

Thin sections were given a final examination to gain information on cementation history and to select individual slides that were particularly illustrative of typical or unusual features of the Gordon sandstone. Sections were imaged using a Pixera 150es™ digital camera attached to a polarizing petrographic microscope. TIF colour images were converted to JPG format which were then imported into Microsoft PowerPoint™ to produce illustrations for this report.

Results and Discussion

Siderite in clasts (Figure 19a), in mineralized zones (sideritic *fronts* – Figure 19b), and as cement (Figure 20a); rounded quartz pebbles (Figure 20b) and single pebble layers (Figure 21a); and plant debris (Figure 21b) have all been noted in the both the Mississippian Big Injun (Hohn and others, 1993a and 1993b) and the Devonian Gordon (Ameri and others, 2001) sandstones in previous reservoir characterization studies undertaken by the WVGES. The Gordon within the Wileyville field contains similar sedimentologic components.

Based on thin section analyses (Table 1a), the Gordon sandstone in the Wileyville field can be characterized as a fine-grained quartz sandstone, whose grains are generally well-sorted, although distinctive bimodal grain distributions comprising fine to very fine quartz sand and quartz pebbles are also typical (Figure 22a). Feldspar (a mixture of potassium and plagioclase feldspar - Figure 22b) is the most common secondary grain mineral but generally makes up less than 5% grain mineralogy compared to 66% for all types of quartz grains. Shale, siltstone, and sandstone (Figure 23a), and chert (Figure 23b) rock fragments represent an additional 6% of the grains.

Cements in the Gordon, in order of appearance, include calcite (Figure 24a), clays, quartz overgrowths, and siderite. Combined primary and secondary porosity values in the Gordon range from 3% to 17% with a mean value of 9%. Secondary porosity is primarily intragranular (Figure 24b) and is often associated with the alteration or dissolution of feldspars (Figure 25a). Examination and comparison to thin section analyses for the Gordon sandstone in the Jacksonburg-Stringtown field (Table 1b) show similar trends with the following exceptions. The Gordon in Jacksonburg-Stringtown is slightly coarser (medium-grained), is slightly more quartzose (74% all types of quartz grains), is less feldspathic (2.5% feldspars), and is slightly less porous (6% mean combined primary and secondary porosity).

Thin sections from both the Wileyville and Jacksonburg-Stringtown fields were assigned to individual lithofacies based on their core depth, lithology, and permeability. The results of grain size and grain mineralogy point-count analyses have been summarized for both fields (Wileyville – Table 1a; Jacksonburg-Stringtown – Table 1b). The *Fss* Lithofacies is of the most interest to this project because it comprises the actual reservoir rock within the Gordon interval. In general, the *Fss* Lithofacies is characterized by fine-grained quartz sandstone, whose grains are generally well-sorted and subangular. Grain size and grain mineralogy are similar for this lithofacies in both fields. Combined primary and secondary porosity values for the *Fss* Lithofacies range from 16.5% to 17%. Secondary porosity is primarily intragranular.

The *Fss* Lithofacies has been problematical in past studies (Matchen and others, 2001; McDowell and others, 2001) because of an inability to explain the featureless nature of the material. The lack of identifiable sedimentary structures, either physical or biogenic, can be attributed to extremely rapid deposition of fine-grained material of uniform grain size leaving a *massive* deposit; to complete homogenization of a fine-grained deposit by bioturbation removing all prior sedimentary structures; or to a combination of these effects. All of this would be academic except for the fact that materials of the *Fss* Lithofacies are also poorly cemented and highly permeable, making them good reservoir rock. Speculation on the cause for the lack of sedimentary structures (even in thin section) and the exclusion of cementation – maintenance of high permeability, has leaned towards bioturbation (McDowell and others, 2001). A thin section from the *Fss* Lithofacies in the L. S. Hoyt 100 well appears to have finally settled the argument. Figure 25b shows elongated quartz grains that have been rotated 90º to bedding, an indication of disruption of sedimentary fabric by bioturbation (Howard, 1975; 1978).

Figure 26 compares the cementation history of the Gordon sandstone in the Wileyville and Jacksonburg-Stringtown oil fields. Based on thin section examination, it appears that secondary quartz and siderite appear later as cements in the Gordon in Wileyville than in Jacksonburg-Stringtown. McDowell and others (2001) suggested that in Gordon sandstones, the presence of bioturbation, especially in the form of vertical and oblique ichnofossils, and early calcite cementation localized in bioturbated sediment formed barriers to interstratal migration of fluids. Seals between adjacent sedimentary layers probably reduced or prevented late-stage cementation and helped preserve initial permeability. Where bioturbation was more intense, the interstratal seal was more effective in preserving permeability (Figure 27).

Whole core and core plug permeability analyses were available for L. E. Dulaney 10; core plug permeability analyses were available for L. S. Hoyt 100. Analyses were performed by Core Laboratories of Dallas, TX. Results were compared to minipermeameter sampling values taken by WVGES personnel. Figure 28 presents these results in graphical fashion. As observed in previous reservoir studies (Ameri and others, 2001; Matchen and others, 2001); minipermeameter permeability values generally exceed whole core values but are less than core plug values of k_{hmax}. The advantage of using the minipermeameter is that the user can set the sample spacing and frequency and that no chemical or thermal manipulation of the core takes place prior to the measurement of permeability. The disadvantages of the minipermeameter is that only horizontal and vertical permeability measurements are possible on slabbed core and the k_h value will generally not be k_{hmax}.

ELECTROFACIES

Methodology

The two cored wells in the Wileyville field were chosen as *reference* wells for the purpose of determining electrofacies. The criteria required for reference wells have been established in reservoir characterization studies cited previously. These include: wells must be cored and have all of the following data: gamma ray, density, permeability, and grain size logs, all at a 0.25' sampling spacing. LAS (Log ASCII Standard) files were created for each reference well by first adjusting core depths to match log depths and then merging permeability (minipermeameter) and grain size data into existing digitized geophysical logs for the wells. Data within the LAS files were further restricted to the depth interval specified by the Project's stratigraphers - the Gordon interval. Next, depths for all wells were corrected to sea level by subtracting drilling depth from kelly bushing or drilling platform elevation. L. E. Dulaney 10 (103-1171) was chosen as the *superwell* (the top of the Gordon interval in this well serves as datum) for correlation purposes. Finally, all well depths were converted to metric units (subsea) so that they were compatible with the metric UTM coordinates used for geographical well locations.

A single data file was created containing: depths, gamma ray, density, permeability, and grain size (millimeters) values from reference wells. The entire range of gamma ray responses for the Wileyville field was scaled into the range [0,1] so that these values were of a similar order of magnitude as the density values. Two additional data elements (county code and permit number) were added to the file for bookkeeping purposes. Data were analyzed using the *k-Means Clustering* technique in the SPSS™ statistical software package. This technique requires the user to specify the number (*k*) of groups or *clusters* expected to be present within the data and to choose which data variable or combination of variables is to be used to establish the clusters. The technique proceeds to calculate *central* (mean) values for each cluster and to iteratively modify the Euclidean distance between cluster centers until centers are equidistant. If this process cannot be completed in 10 iterations for every cluster, the process is considered to have failed to produce a stable or convergent solution. Additionally, the cluster membership for every data point is saved.

The clustering process was repeated specifying 2, 3, 4, 5, and 6 clusters using a variety of variables and combinations of variables. Once all data points had been assigned to a cluster, electrofacies logs were constructed for the reference wells and displayed in the form of an electrofacies cross section. The Project's stratigrapher examined each of these cross sections and by comparison to correlations done independently using only gamma ray and density logs, decided that four electrofacies most closely resembled his work. In addition, he concluded that four electrofacies based on a linear combination of density and scaled gamma ray best matched his correlations.

The cluster membership, density, and scaled gamma ray values for every point in the reference data set were subjected to SPSS's *Discriminant Analysis* technique. This technique was used to confirm the statistical significance of the clustering solution and to generate a set of Fisher's linear coefficients that could be used to classify other geophysical log values from the Wileyville field into the same four electrofacies. Each cluster (electrofacies) was described by a different set of Fisher's coefficients ($\hat{a}_0$, $\hat{a}_1$, $\hat{a}_2$,

… $\hat{a}_n$); where n = number of variables used to create the clusters). Cluster or electrofacies group membership is then determined for any set of data values by computing a test statistic (T) using the Fisher's coefficients for each one of the electrofacies. The data values are *plugged* into a linear equation of the form:

$$T = \hat{a}_0 + \hat{a}_1(\text{variable}_1 \text{ value}) + \hat{a}_2(\text{variable}_2 \text{ value}) + \ldots\ldots\ldots \hat{a}_n(\text{variable}_n \text{ value})$$

The given data values are assigned to the cluster or electrofacies whose computed test statistic is the largest.

Once it was determined that the four cluster – density and scaled gamma ray model was a statistically and stratigraphically significant solution, the scaled gamma ray and density values from the Gordon interval for all 16 geophysical logs in the Wileyville field were extracted, and their depths converted to subsea elevations in meters. Scaled gamma ray and density values for each well were run through a computer program that determined the maximum test statistic based on Fisher's coefficients for four electrofacies. An electrofacies membership (integer values 1, 2, 3, or 4) was assigned to each pair of data values. Next, a three-dimensional electrofacies dataset was created by taking the depth, gamma ray, density, and electrofacies value for every data point in the Gordon interval from every logged well in the field and adding the UTM coordinates appropriate to each well. This information was placed into a single file that could be *sliced* to produce electrofacies maps and cross sections. Finally, permeability and grain size data were added and summary statistical analyses were performed for each electrofacies help to characterize them. Table 2 shows the resulting petrophysical characteristics of each electrofacies.

Results and Discussion

Examination of Table 2 suggests that the four electrofacies identified in the Gordon reservoir in the Wileyville field are petrophysically similar to those in the Jacksonburg-Stringtown field. The notable exception is regarding mean permeability. Electrofacies 2, 3, and 4 in Wileyville have significantly higher mean permeability than comparable units in Jacksonburg-Stringtown. However, because of the small number of reference wells available in Wileyville (2) versus Jacksonburg-Stringtown (7), it is not possible to assess the *statistical* significance of these differences.

Electrofacies identified in the Gordon from Wileyville are probably similar enough to those from Jacksonburg-Stringtown to add additional comparisons to lithofacies. The Shale Lithofacies (*Sh*) is believed to correspond to Electrofacies 1. Electrofacies 2 and 3 correspond to combinations of material from the Conglomeratic Sandstone, Laminated Sandstone, and Heterolithic Bioturbated lithofacies (*Css*, *Lss*, and *Hb*, respectively); the pay sandstone in the Gordon, a combination of Featureless Sandstone (*Fss*) and minor Conglomeratic Sandstone (*Css*) lithofacies, corresponds to Electrofacies 4.

In reservoir characterization studies cited previously, wells with geophysical logs were numerous and fairly well-distributed throughout the entire oil field. In Wileyville, this was not the case; logged wells are concentrated along the long axis of the field. Consequently, many cross sections produced by slicing the electrofacies data for these wells are not illustrative of the distribution of electrofacies for the entire field. Figure 29 shows a vertical cross section along the long axis of the field and looking to the northwest. Electrofacies 4, corresponding to the pay sandstone within the Gordon, is generally restricted to the middle of the Gordon interval. The Gordon in the Wileyville field is observed (Figure 29) to deepen to the northeast along the plunge of structure (see Figure 3). No serious lateral impediments to flow are visible in the cross section. However, a gap in well control is present in the southern portion of the field and this gap corresponds to a distinct break in IP values in the area (see Figure 18).

UPHOLE POTENTIAL – SHALLOW GAS PLAYS

Methodology

Seven shallow gas plays described in the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996) have been developed in reservoirs stratigraphically younger than the Gordon sandstone. Each play could have some potential to produce uphole gas in the Wileyville field. Therefore, the productive extent and potential of each play was examined in detail. Potential uphole gas plays are discussed below:

Middle Pennsylvanian Allegheny Formation/Group Sandstone Play (Hohn, 1996) **-** The Wileyville field lies near the axis of this northeast-southwest trending play. Gas production has been established to the east, north and west, relative to Wileyville field. Allegheny reservoirs have been developed in fluvial-deltaic sandstones associated with siltstones, shales, limestones, and coals that are known to occur over the Wileyville field. These reservoirs include the upper and lower Freeport, Kittanning and Clarion sandstones; coals in the formation include the various Freeports, Kittannings and the Clarion at the base.

Lower & Middle Pennsylvanian Pottsville*, *New River and Lee Sandstones Play (Hohn, 1996) **-** Wileyville lies near the axis of the play trend. Reservoirs in the play are fluvial-deltaic and nearshore sandstones. Structure enhances, but does not seem to control, production, although gas fields have been developed on the Washington anticline west of Wileyville field, and on the Littleton and Hundred anticlines to the east. The main reservoirs in these Wetzel County gas fields are the Salt sands.

Upper Mississippian Mauch Chunk and Equivalent Strata (Barlow, 1996) **–** The Wileyville field occurs beneath the extreme western edge of this play. Given that the Mauch Chunk sandstones are not well-developed this far west, this play has no potential above Wileyville field.

Upper Mississippian Greenbrier/Newman Limestones (Smosna, 1996) - Wileyville is just west of the axis of the play trend, but near the northern limit of play. Although scattered gas production has been established in this part of Wetzel County, most of the production from this play is in a well-established trend to the south. This play appears to have very low potential above the Wileyville oil field, although some porosity may exist in the basal part of the formation.

Lower Mississippian Big Injun Sandstone (Vargo and Matchen, 1996) – The Wileyville field lies in the center of the northern lobe of this bilobate play area. Good gas production has been established to the east, south, and west, and some to the north in Majorsville field. One could expect to encounter 175-200' of Big Injun sandstone in wells in Wileyville field. A Big Lime porosity zone overlies an unconformity in this area, with an additional porous zone in the Big Injun sandstone beneath the unconformity. However, the thickness of the Big Injun decreases to the south as the unconformity cuts deeper into the sandstone. Thus, much of the Big Injun porosity zone has been eliminated in the field area.

Lower Mississippian Weir Sandstone (Matchen and Vargo, 1996) - Wileyville lies near the northern edge of this play, and only a few gas wells have been completed to the northwest and south in Wetzel county. Furthermore, one could only expect only 50-60 feet of sandstone above Wileyville field, versus 100-125 feet in productive areas to the south. Therefore, we concluded that this play has very low to no potential in this area.

Lower Mississippian-Upper Devonian Berea and Equivalent Sandstones (Tomastik, 1996) - Wileyville lies within the play area, but there is no production from the play in Wetzel County. The true Berea trend occurs to the west in Ohio, and the Wileyville field is near the eastern edge of the shallow marine sandstone trend that produces to the west. The only sandstone above Wileyville field is probably the eastern type of Berea Sandstone that is less productive. Thus, this play has very low potential above Wileyville.

Results and Discussion

It appears that there is little or no uphole potential in the Mauch Chunk, Big Lime, Weir and Berea plays, but there may be some in the Big Injun. The best uphole potential appears to be in the shallowest plays, the Allegheny and Pottsville sandstones and their associated coals, discussed below. We have concluded that the best strategy is to develop the coal-bed methane potential of the Allegheny Formation and lower Monongahela Group.

UPHOLE POTENTIAL – COAL-BED METHANE

Methodology

There is a long history of gas production from coal beds in the Appalachian basin. During two WVGES studies (Patchen and others, 1991; Bruner and others, 1995) conducted for the Gas Research Institute (now Gas Technology Institute) in the 1990’s, a map was prepared showing the locations of all wells from which gas shows from coal beds had been reported and all wells producing gas from coal beds. These coal-bed methane wells were all drilled on or near the axes of subsurface anticlines, where the coals are structurally high and water-free (Figure 30).

Additionally, maps of initial potential and cumulative production and a decline curve were produced, along with maps of net coal thickness, thickness of the single thickest coal, and the number of coals reported per well greater than 2 feet in thickness

A stratigraphic framework for Pennsylvanian coals and sandstones for this area was established by Patchen and others (1991) and further enhanced by Bruner and others (1995) from cores taken for coal tests and from logs of adjacent gas wells (Figure 31). The Sewickley, Redstone, and Pittsburgh coal beds occur in the lower 100-110 feet of the Monongahela Group, with the Pittsburgh defining the base of the group. Only two named coals, the Bakerstown and Mahoning, are present in the 550-600 foot Conemaugh Group below. Several marine zones and red beds occur in the lower half of the Conemaugh, which typically is described as barren of coal. The underlying Allegheny Formation is defined by the upper Freeport coal at the top and the Clarion coal at the base, above the Homewood sandstone at the top of the Pottsville Group. Other coals in the Allegheny include, from top to bottom, the lower Freeport, and the upper, middle, and lower Kittanning coal beds.

Major structural features in Wetzel County trend northeast-southwest, and include the Washington, Littleton and Hundred anticlines, and the Ninevah syncline (see Figure 3). Oil is produced from the Gordon sandstone in the Ninevah syncline; gas is produced from coal beds on each of the major anticlines and on several smaller, associated anticlines. In all cases, gas is produced from coals that are structurally high and water-free. No production has been established in structurally low, water-filled coals, even though the gas content in coals in these structural areas should at least equal, if not exceed, the gas content on water-free structural highs that may have been partially depleted over time.

The best coal-bed methane production in Wetzel County has been from the Pittsburgh coal in Big Run field, which was developed on a small bifurcating structure mapped on the eastern flank of the Littleton anticline. The smaller Pine Grove field was developed on a small anticline west of the larger Littleton structure. Additional wells with production from the Pittsburgh coals were drilled on the Hundred anticline, due east of Big Run field, and to the northeast on the Littleton anticline, near the Pennsylvania border. Gas shows were reported from the Pittsburgh coal in wells drilled on the Washington anticline to the northwest. However, to the southwest along this structure, where it plunges in that direction, water was reported in the Pittsburgh.

Three types of coal-occurrence maps were produced for the previously cited studies, primarily using information in the WVGES oil and gas database: isopach, isolith, and isopleth maps of the lower Monongahela and entire Allegheny intervals. Although the Pittsburgh coal usually is reported by oil and gas well drillers, other coals, especially coals below the Pittsburgh, commonly are not, even when present. Other than the Pittsburgh, the shallower Washington, Waynesburg, and Sewickley are reported more often than the deeper Allegheny coals, and thus are cased off by drillers, in accordance with the rules and regulations governing drilling in West Virginia.

Because of this, gamma ray-density log combinations were used to map coal occurrence in the Allegheny Formation. Usually 4-6 coals can be observed on the logs in wells drilled in and around Wileyville field. The cumulative thickness of these coals ranges from 10 to 20 feet over the area, with the single thickest Allegheny coal usually being 4-5 feet thick. Drillers' records which reported the younger Pittsburgh and Sewickley coals, indicate cumulative thickness generally less than 12 feet, with the thicker Pittsburgh less than 8 feet.

Gas potential for Wileyville from the Pittsburgh and Sewickley coals was calculated by digitizing areas of common thickness within the Wileyville field taken from contoured maps of coal thickness for the Sewickley, Pittsburgh, and total Allegheny coals. Gas content of 150 Scf/ton was assumed for the Sewickley and Pittsburgh coals and 200 Scf/ton for the deeper Allegheny coals; a coal density of 1800 tons/acre-foot was assumed. Results are summarized in Tables 3a and 3b.

Results and Discussion

The significance of structural control on coals in the Wileyville area seems to be that it allows operators to produce gas from coal beds that are water-free; the gas is not structurally controlled. Indeed, gas probably occurs in the coals throughout the area, even in structurally low areas like the Ninevah syncline (see Figures 3 and 30).

Previous work (Bruner and others, 1995) defined two, prospective coal-bed methane intervals: the Monongahela interval, essentially from the Sewickley to the Pittsburgh coal; and the deeper Allegheny interval. The Allegheny interval was expanded to include the younger Mahoning coal bed in the lower part of the overlying Conemaugh Group. Channel-fill sandstones of conventional oil and gas reservoir quality are associated with these coals and have produced gas for decades. Much of this gas may have actually come from associated coal beds, so the gas potential in the Allegheny coals has probably been reduced. In spite of this, the potential of the Allegheny interval is thought to exceed that of the younger Monongahela Group because Allegheny coals are of higher rank and contain greater total gas content per ton of coal (Kelafant and others, 1988; Hunt and Steele, 1991).

Average thickness of the coals in these two intervals, based on cores taken at eight locations in Wetzel County, West Virginia and Greene County, Pennsylvania, is approximately 14-15 feet for the Monongahela coals and 11-12 feet for the deeper Allegheny coals. Thus, one could expect approximately 25 feet of coal to be encountered in these two prospect intervals in much of northern West Virginia.

Coal rank is relatively uniform in northern West Virginia, with coals falling within the high-volatile B and A bituminous ranks. Data from five cores taken near Big Run field show a consistent vitrinite reflectance of the Pittsburgh coal in the R_{max} = 0.69 - 0.70% range (Bruner et al, 1995). Although thermally derived coal-bed methane initially appears when vitrinite reflectance ranges from 0.8% to 1.0%, Hunt (1979) showed that a small amount of gas can be produced at lower values, in the 0.6% to 0.7% range.

Vitrinite reflectance values for coals below the Pittsburgh generally are higher than the shallower coals, so it might be assumed that gas content values for the deeper coals also would increase. This has proven to be the case in adjacent parts of Pennsylvania, where gas content values for the Freeport, Kittanning and Clarion coals were in the 192 to 252 Scf/ton range (Markowski, 1993).

The Sewickley-Pittsburgh prospect interval contains a higher percentage of coal than the deeper Mahoning-Clarion interval, and based on coal thickness and coal volume per acre, would be a more attractive coal-bed methane target than the Allegheny prospect interval. However, these deeper coals have a lower ash content, higher rank, and higher gas content per ton, and this may compensate for the lower ton per acre values of these coals.

Estimates of coal-bed methane potential should take into account historical production from coals in the general area of the Wileyville field and specific parameters of the potential coal reservoirs. Although the main reservoir in the Big Run and Pine Grove fields is the Pittsburgh coal, gas shows were reported from the Sewickley coal in at least nine Big Run wells and three Pine Grove wells. Both fields produced for many years in spite of low initial open flows and low rock pressure. Final open flows in Big Run field ranged from 8 to 121 Mcf/d/well, with an average of 38.5 Mcf/d. All but four wells, which were shot with nitroglycerine, were natural producers. No water problems were reported, with the exception of the discovery well which produced for 36 years before water problems developed.

In Pine Grove field, open flows from the Pittsburgh ranged from 8 to 60 Mcf/d, with an average of 28 Mcf/d. Only one well was shot; the others were natural completions. More than 2 billion cubic feet of gas has been produced from Big Run field, plus an undetermined volume from Pine Grove field.

The volume of gas desorbed from the Pittsburgh coal varies according to location, rank and depth of the coal sample. Gas content values for the Pittsburgh coal range from 100 Scf/ton to as much as 200 Scf/ton, generally from west to east, across the Pittsburgh coal basin in northern West Virginia. Core samples taken from the Pittsburgh coal near Big Run field contained less than 50 Scf/ton at a depth of 520 feet, but it is reasonable to assume that the gas content of the Pittsburgh coal in this area has been depleted by more than 50 years of production in the Big Run field (2.1 Bcf cumulative). A more reasonable estimate for gas content in the Pittsburgh in this area is 140-150 Scf/ton of coal.

Examination of Tables 3a and 3b suggests that the total gas contained in the Sewickley coal within the confines of the Wileyville field is 3.09 Bcf. For the Pittsburgh coal, this figure rises to 7.21 Bcf and for the combined Allegheny coals, the estimated gas content is 25.44 Bcf. Thus, the total gas in place for both coal-bed methane intervals, two coals in the lower Monongahela and six coals in the Allegheny, is approximately 35.74 Bcf for the area encompassed by the Wileyville oil field.

The Wileyville field is in close proximity to two established areas of coal-bed methane production: the Pine Grove and Big Run gas fields. Production in both fields is structurally enhanced, if not controlled, and a gas-water contact is present in both fields. In contrast, the Wileyville oil field lies near the axis of the Ninevah syncline to the west. All of the coal beds present above the Gordon oil reservoir are expected to be water-filled in this area. Thus, before any gas could be produced from these coal beds, dewatering of the coals in the syncline would be necessary. However, it is suggested that in de-watering the coals to establish coal-bed methane production, an important source of water for the continuation of the Wileyville waterflood in the Gordon oil reservoir could be developed.

Our recommendation is to conduct an engineering study to determine the feasibility of producing water through shallow wells drilled through the Clarion coal and completed in multiple coals, and injecting this water into the Gordon oil reservoir through deeper injection wells. Under this scenario, the produced water would have an immediate value, whereas in a typical coal-bed methane de-watering scenario, one has to wait until water production declines and gas production begins to begin to receive a return on investment.

CONCLUSIONS AND RECOMMENDATIONS

Field History

From 1900 to 1905, the entire producing reservoir in Wileyville was delineated by the drilling process. Based on our previous experiences with reservoir characterization of siliciclastic reservoirs in West Virginia, we believe that this pattern of completions is indicative of a relatively low degree of reservoir heterogeneity.

Lithofacies, Stratigraphic Framework, and Production

Five lithofacies can be recognized: Featureless sandstone (*Fss*), Laminated sandstone (*Lss*), Conglomeratic sandstone (*Css*), Shale (*Sh*) and Heterolithic bioturbated (*Hb*). Each lithofacies is relatively distinctive in core and has a recognizable pattern on geophysical logs.

Fss sandstones have a density of around 2.3 g/cm^3 which makes the lithofacies very easy to distinguish as the primary reservoir for the field. Permeability shows a similar relationship – the highest permeabilities are for *Fss* sandstones, with a mean value greater than 90 mD.

The distribution of lithofacies *Fss* within the Gordon is inconsistent. In the southern part of the Wileyville field, *Fss* sandstones are continuous and probably well-connected. However, in the northern part of the project, *Fss* sandstones thin to almost zero thickness, suggesting that the northern part of the study area is not well-suited to waterflooding.

The spatial pattern of initial potentials in the northern half of the field is irregular, consistent with the presence of several reservoir compartments in this part of the field. Overall, there is a suggestion of poor communication between the two halves of the field, consistent with the stratigraphic model.

Petrography and Petrophysics

Cements in the Gordon, in order of appearance, include calcite, clays, quartz overgrowths, and siderite. Combined primary and secondary porosity values in the Gordon range from 3% to 17% with a mean value of 9%. Secondary porosity is primarily intragranular and is often associated with the alteration or dissolution of feldspars.

The *Fss* Lithofacies is characterized by fine-grained quartz sandstone, whose grains are generally well-sorted and subangular.

The *Fss* Lithofacies has been problematical in past because of an inability to explain the featureless nature of the material. *Fss* sandstones are also poorly cemented and highly permeable, making them good reservoir rock. A thin section from the *Fss* Lithofacies shows elongated quartz grains that have been rotated 90º to bedding, an indication of disruption of sedimentary fabric by bioturbation.

Early calcite cementation localized in bioturbated sediment formed barriers to interstratal migration of fluids. Seals between adjacent sedimentary layers probably reduced or prevented late-stage cementation and helped preserve initial permeability. Where bioturbation was more intense, the interstratal seal was more effective in preserving permeability.

Minipermeameter permeability values generally exceed whole core values but are less than core plug values for k_{hmax}.

Electrofacies

Four electrofacies were identified in the Gordon reservoir in the Wileyville. The pay sandstone in the Gordon, a combination of Featureless Sandstone (*Fss*) and minor Conglomeratic Sandstone (*Css*) lithofacies, corresponds to Electrofacies 4.

A vertical electrofacies cross-section along the long axis of the field suggests Electrofacies 4, corresponding to the pay sandstone within the Gordon, is generally restricted to the middle of the Gordon interval. The Gordon in the Wileyville field is observed to deepen to the northeast along the plunge of structure. No serious lateral impediments to flow are visible in the cross section. However, a gap in well control is present in the southern portion of the field and this gap corresponds to a distinct break in IP values in the area.

Uphole Potential

The best uphole potential appears to be in the shallowest plays, the Allegheny and Pottsville sandstones and associated coals, and in developing the coal-bed methane potential of the Allegheny Formation and lower Monongahela Group. Total gas in place for two coals in the lower Monongahela and six coals in the Allegheny, is approximately 35.74 Bcf for the area encompassed by the Wileyville oil field.

Coal beds present above the Gordon oil reservoir are expected to be water-filled in this field. In de-watering the coals to establish coal-bed methane production, an important source of water for the continuation of the Wileyville waterflood in the Gordon oil reservoir could be developed.

ACKNOWLEDGMENTS

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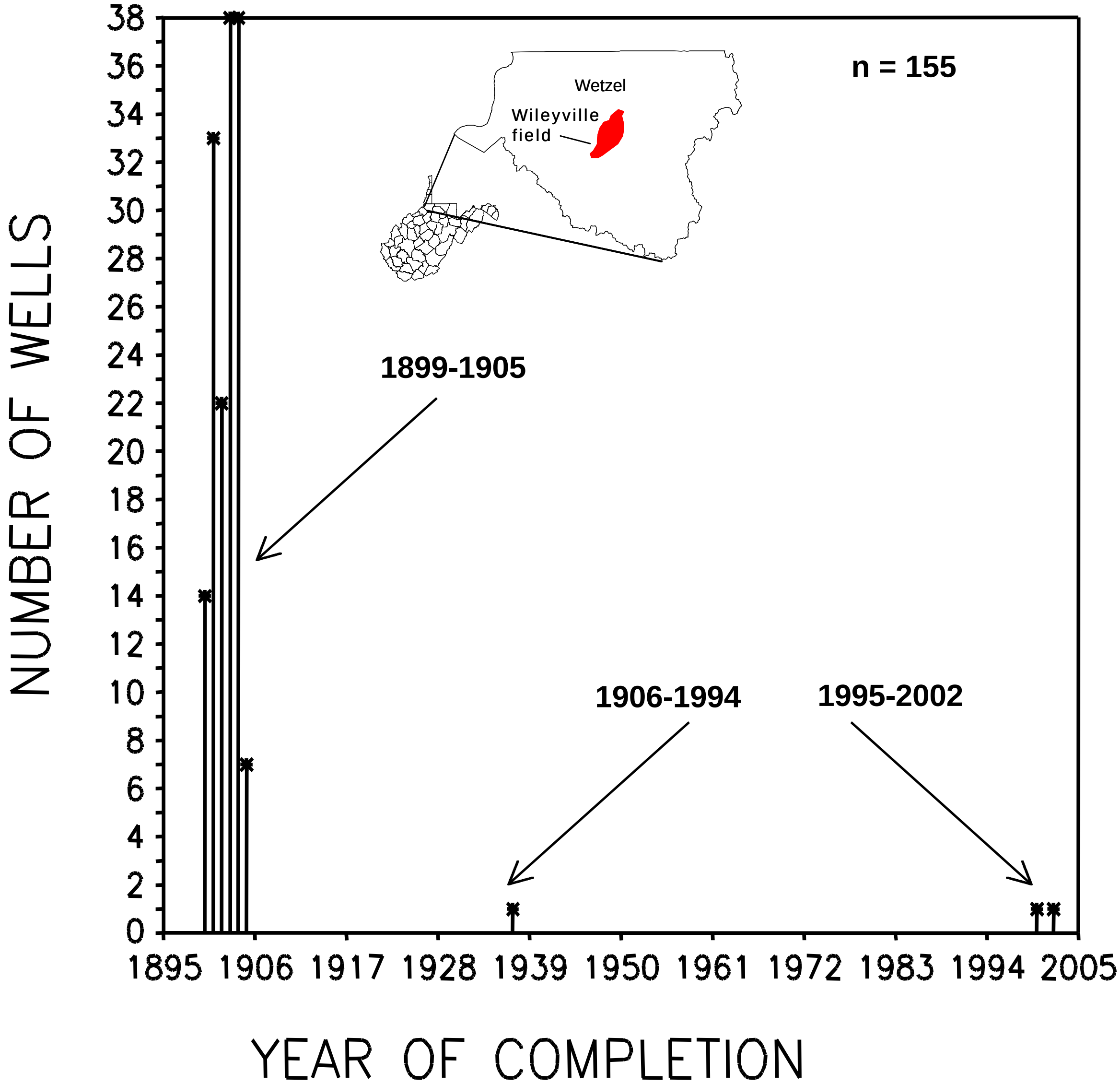
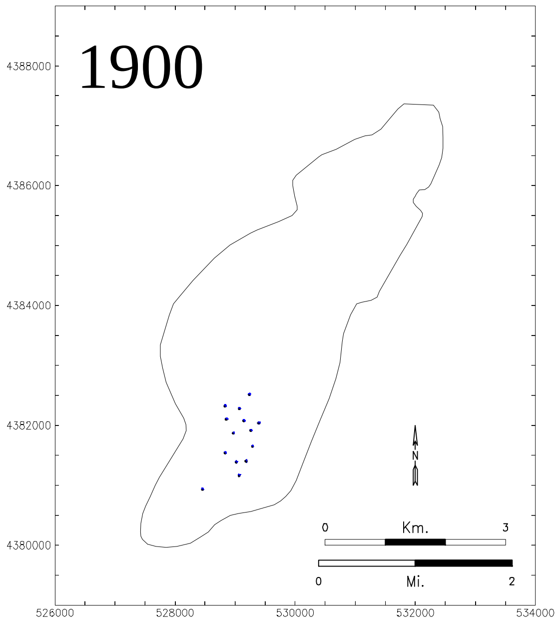
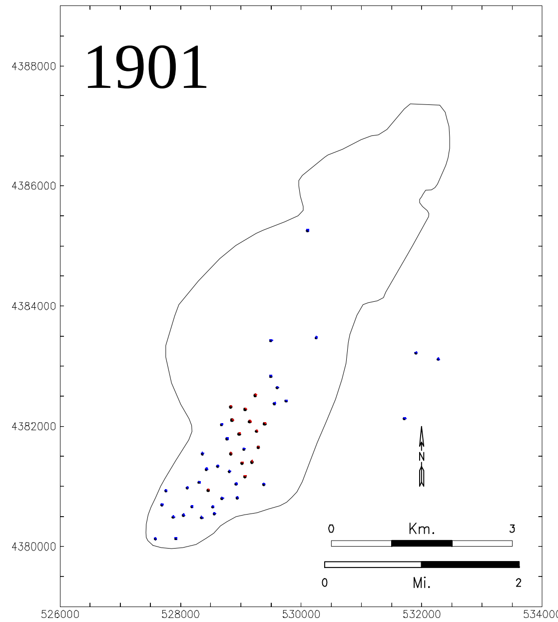


Figure 1. Plot of the time-domain spectral analysis of completions of producing oil wells in the Wileyville oil field. Three clusters are apparent; only the first (1899-1905) contains a significant number of wells. Inset map shows the location of the Wileyville field in northern West Virginia.





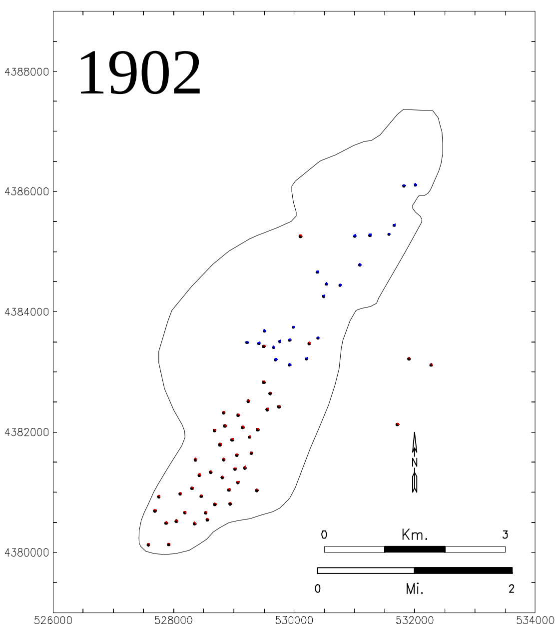
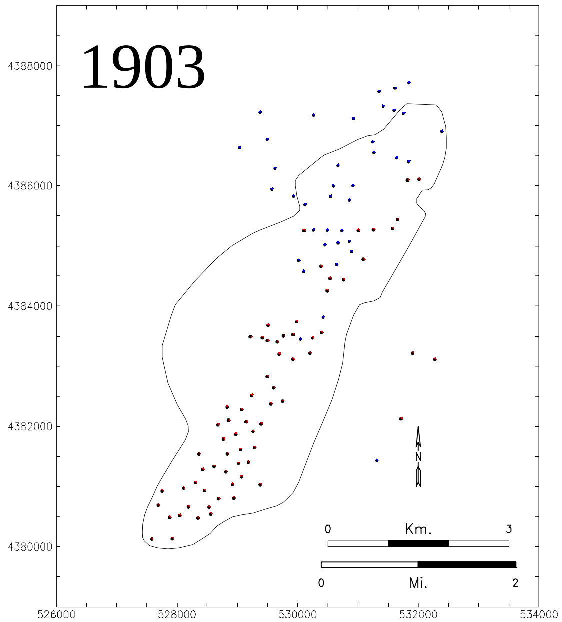
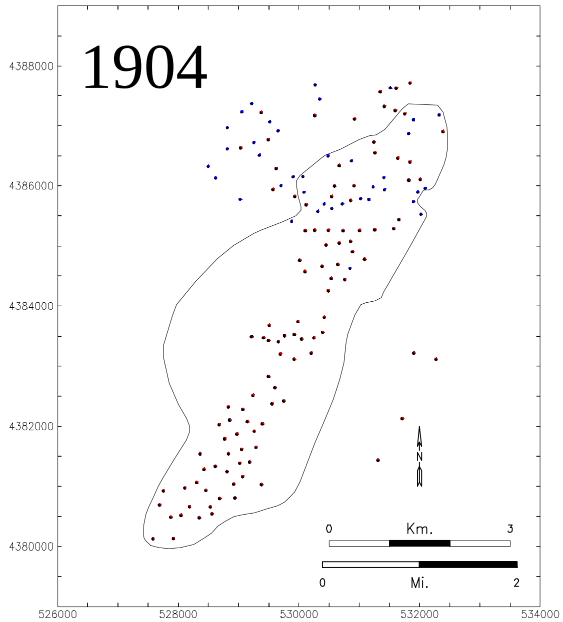


Figure 2. Locations of producing oil wells completed during initial development of the Wileyville oil field. Discovery starts in the southern portion of the field.





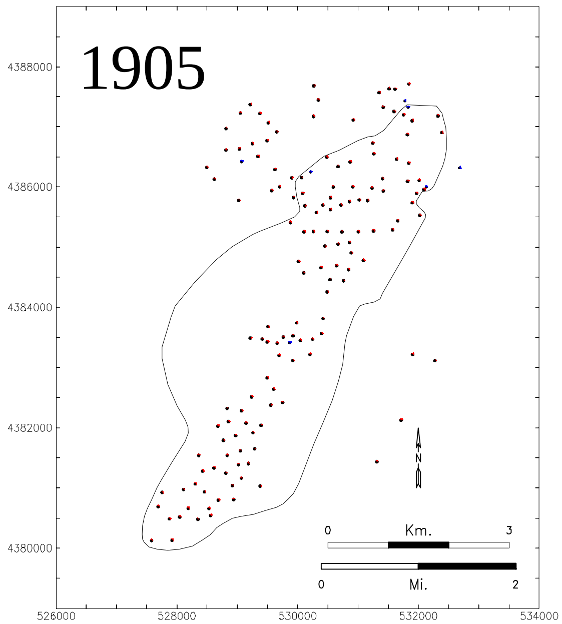


Figure 2. (continued)

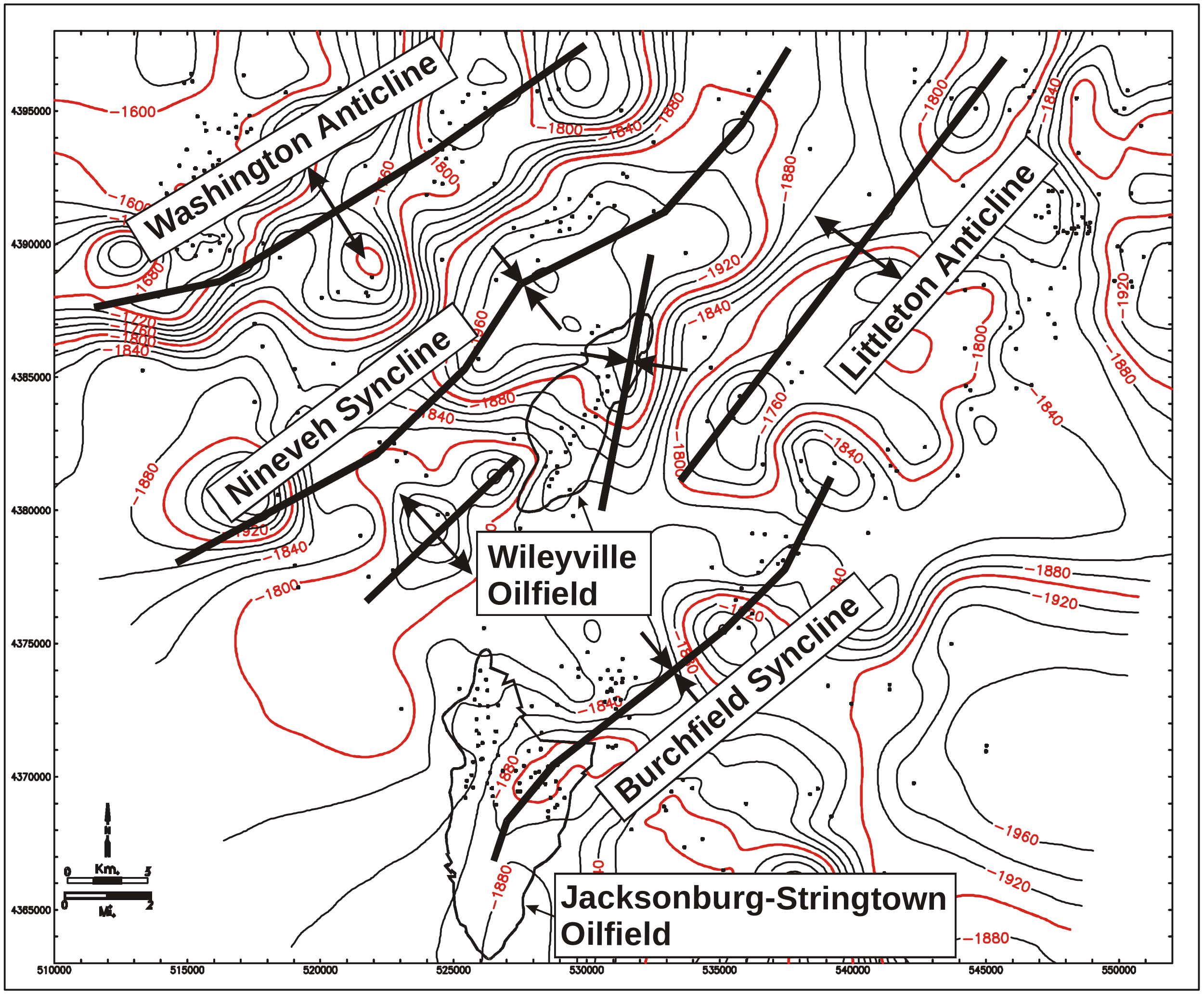


Figure 3. Structural contour map on the the top of the Gordon sandstone in the Wileyville area. Outlines of the Wileyville and Jacksonburg-Stringtown oil fields are superimposed on the map.

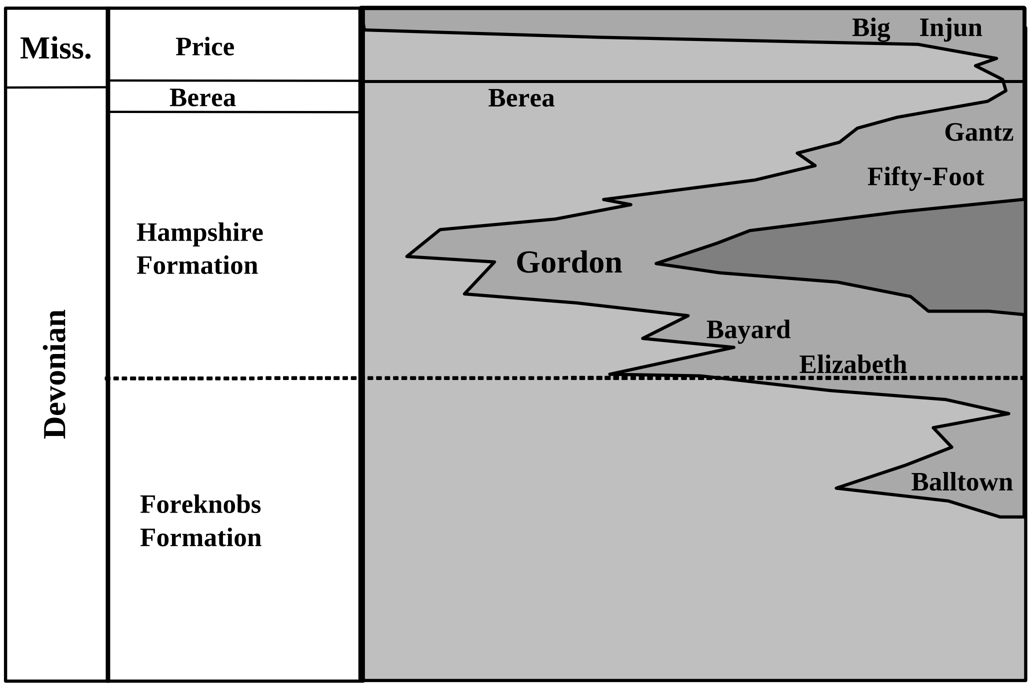


Figure 4. Generalized stratigraphic column for the study area including both outcrop and subsurface terminology.

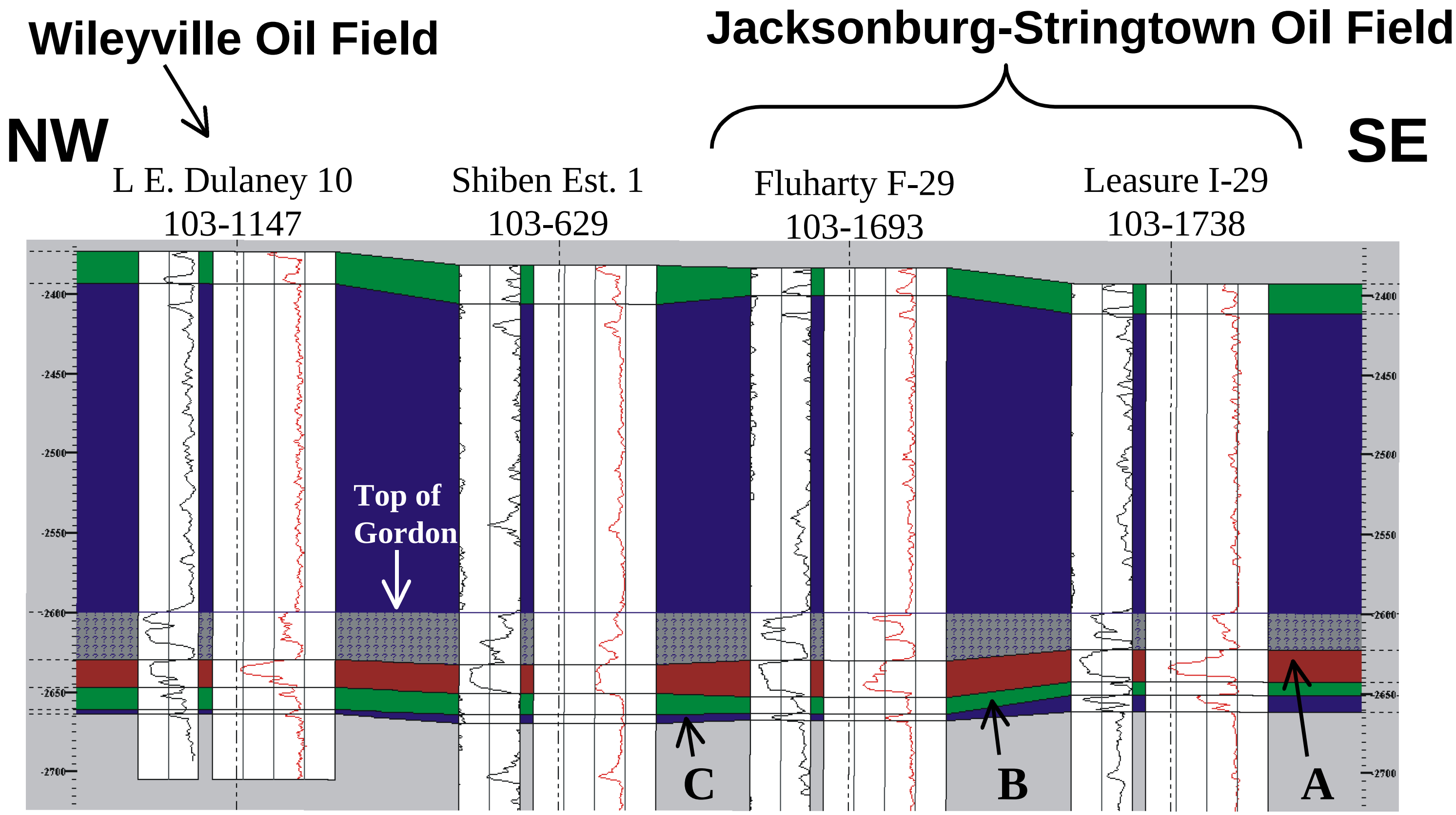


Figure 5. Correlation of Gordon wells in Wetzel County, WV. Datum is the top of the Gordon. The sandy portions of parasequences B and C pinch out to the northwestward of the Stringtown Oilfield. Only Parasequence A is recognizable in the Wileyville Oilfield. The uppermost parasequence comprised of lithofaces Hb serves as a recognizable marker. Gamma ray curves are to the left, density curves are to the right. No horizontal scale implied.

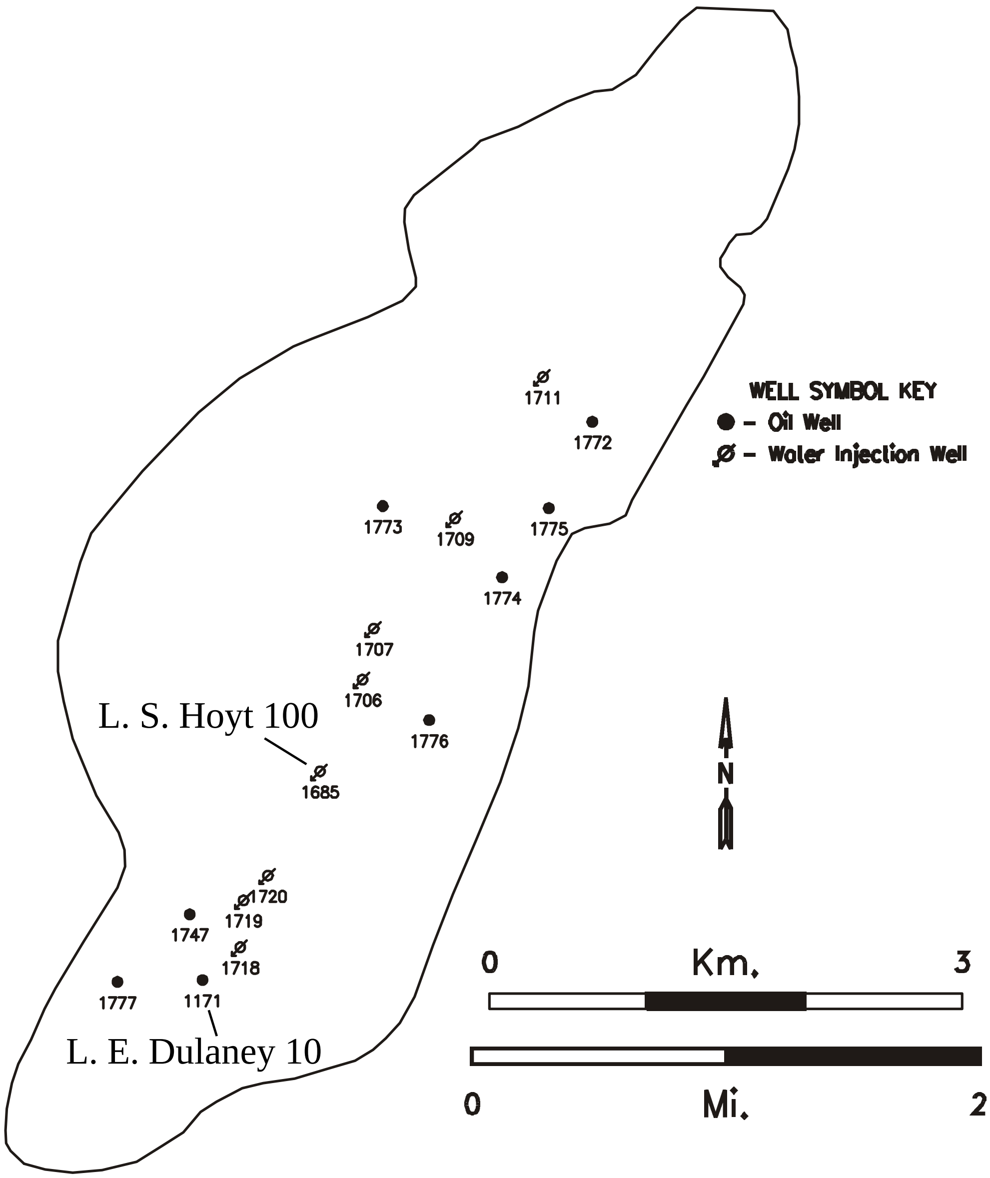


Figure 6. Location of the two cored wells in the Wileyville field (L. S. Hoyt 100 and L. E. Dulaney 10). Also shown are the locations of wells with geophysical logs used used to identify electrofacies.

Figure 7. L.S. Hoyt 100, 3154', Heterolithic bioturbated (*Hb*) Lithofacies with vertical burrow (*Diplocraterion?* sp.).

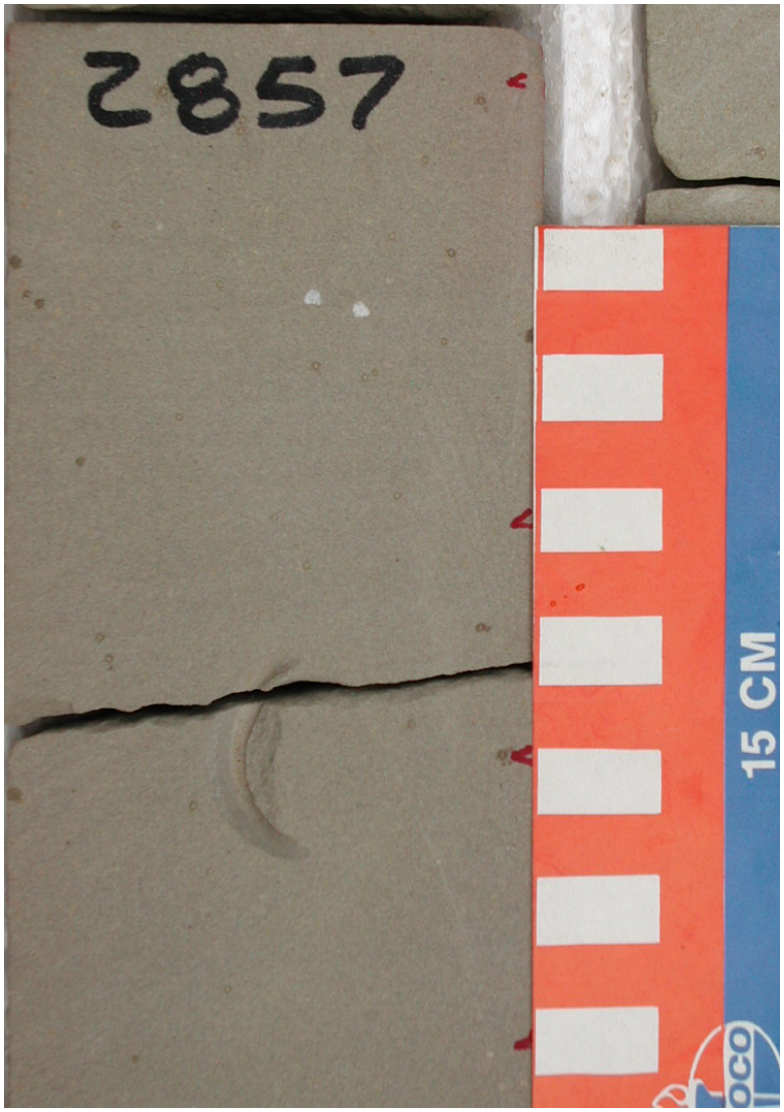


Figure 8. L.E. Dulaney 10, 2857', Featureless sandstone (*Fss*) Litho-facies. Note the absence of sedimentary structures and the presence of isolated quartz pebbles.

Figure 9. L.E. Dulaney 10, 2840', Laminated Sandstone (*Lss*) Lithofacies showing ripple-scale crossbedding.

Figure 10. L.E. Dulaney 10, 2850', Conglomeratic sandstone (*Css*) Lithofacies. Clasts are a combination of quartz pebbles and sideritic shale rip-ups.

CORE/SECTION # L.E. Dulaney #10 (103-1171)
LOCALITY Wetzel Co., WV
Core = Log + 4'

FORMATION : Gordon
DESCRIBED BY: Sheehan and McDowell

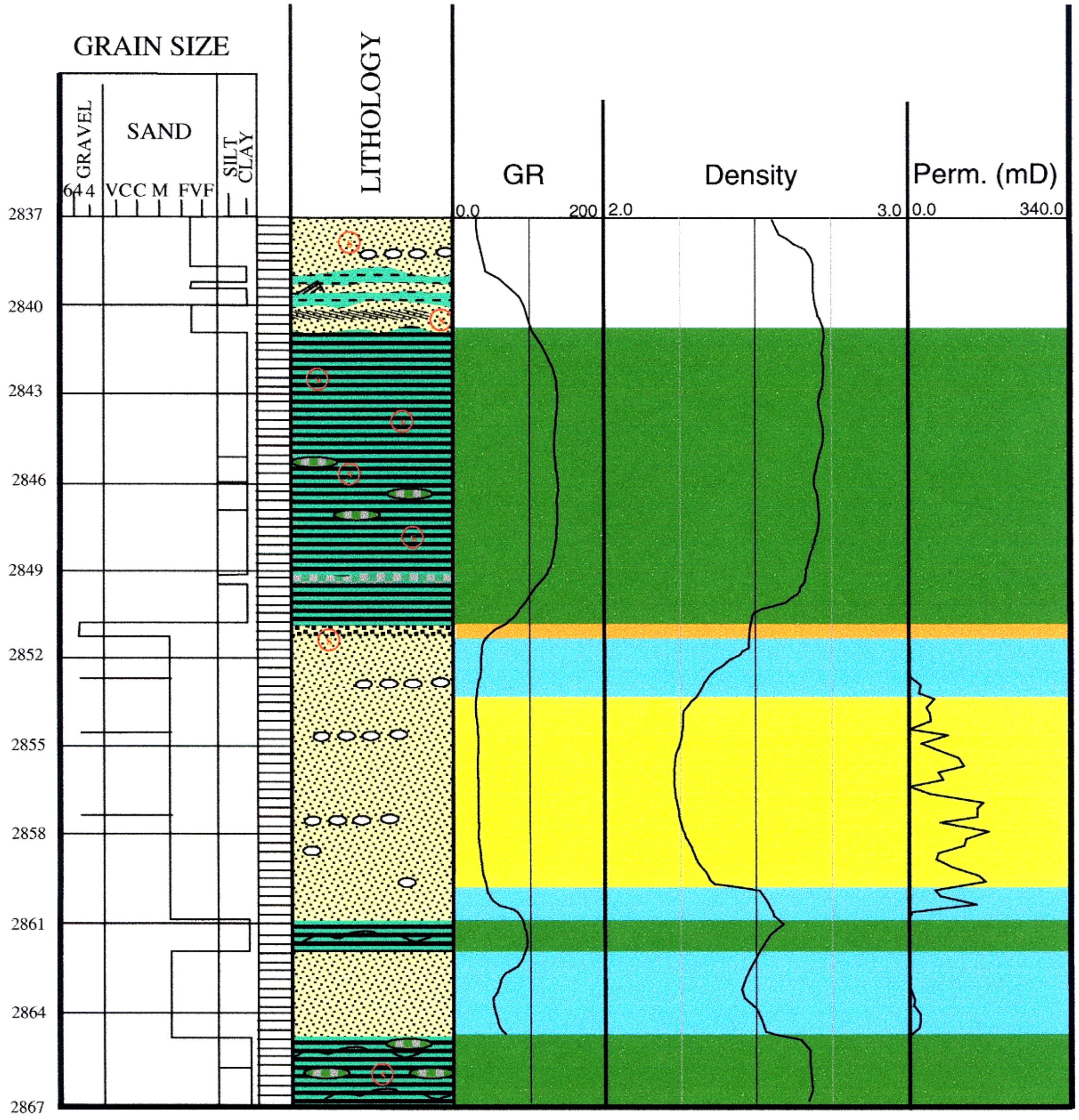


Figure 11. Correlation of L.E. Dulaney 10 core to wireline log. Note the differentiation of *Fss* (yellow) from *Lss* (blue) and *Css* (orange) in log. Lowest bulk density readings correspond to *Fss*. Permeability measured by minipermeameter is shown on the right.

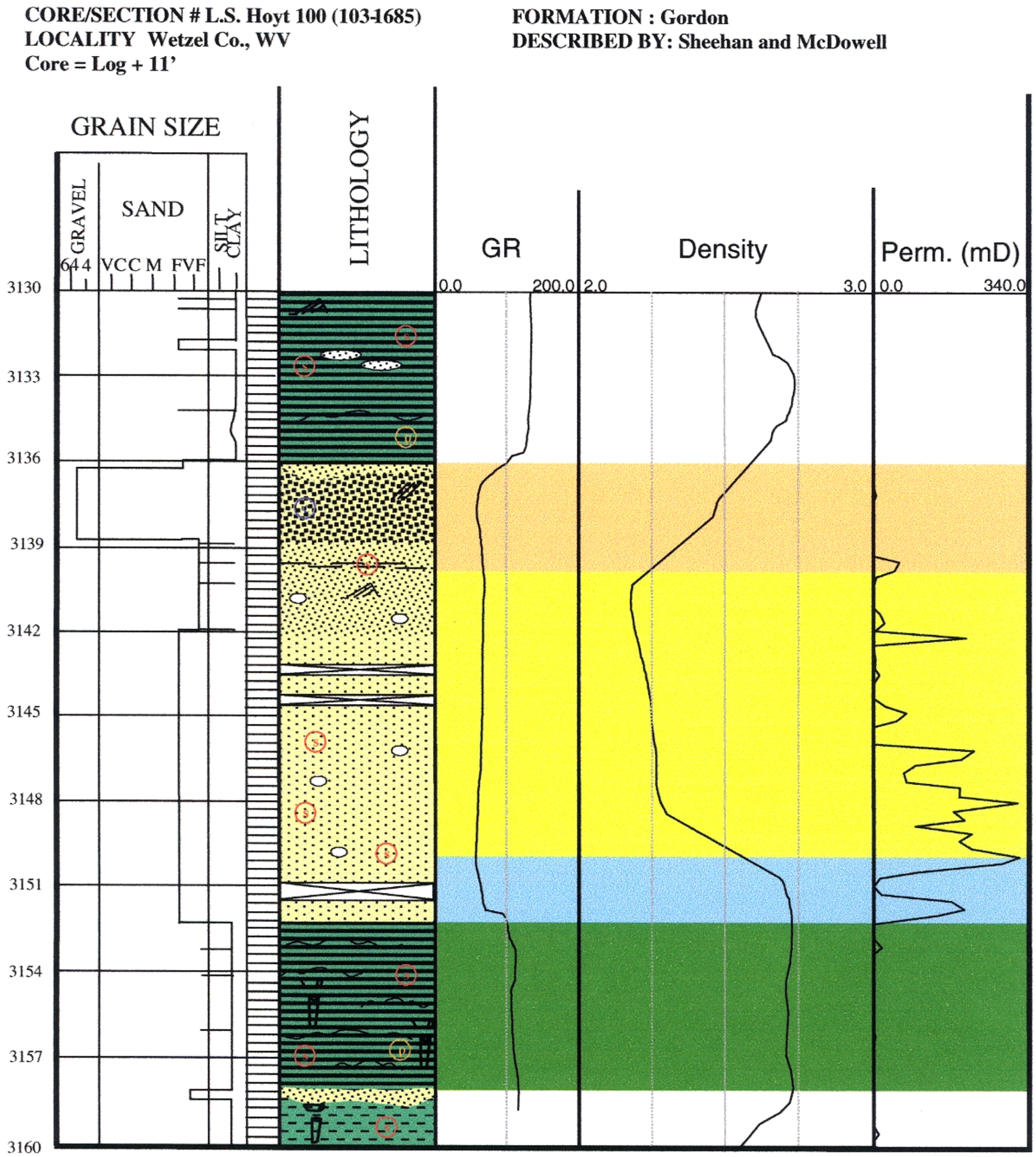


Figure 12. Correlation of L.H. Hoyt 100 core to wireline log. Note the differentiation of *Fss* (yellow) from *Lss* (blue) and *Css* (orange) in log. The lowest bulk density readings correspond to *Fss*. Permeability measured by minipermeameter is shown on the right.

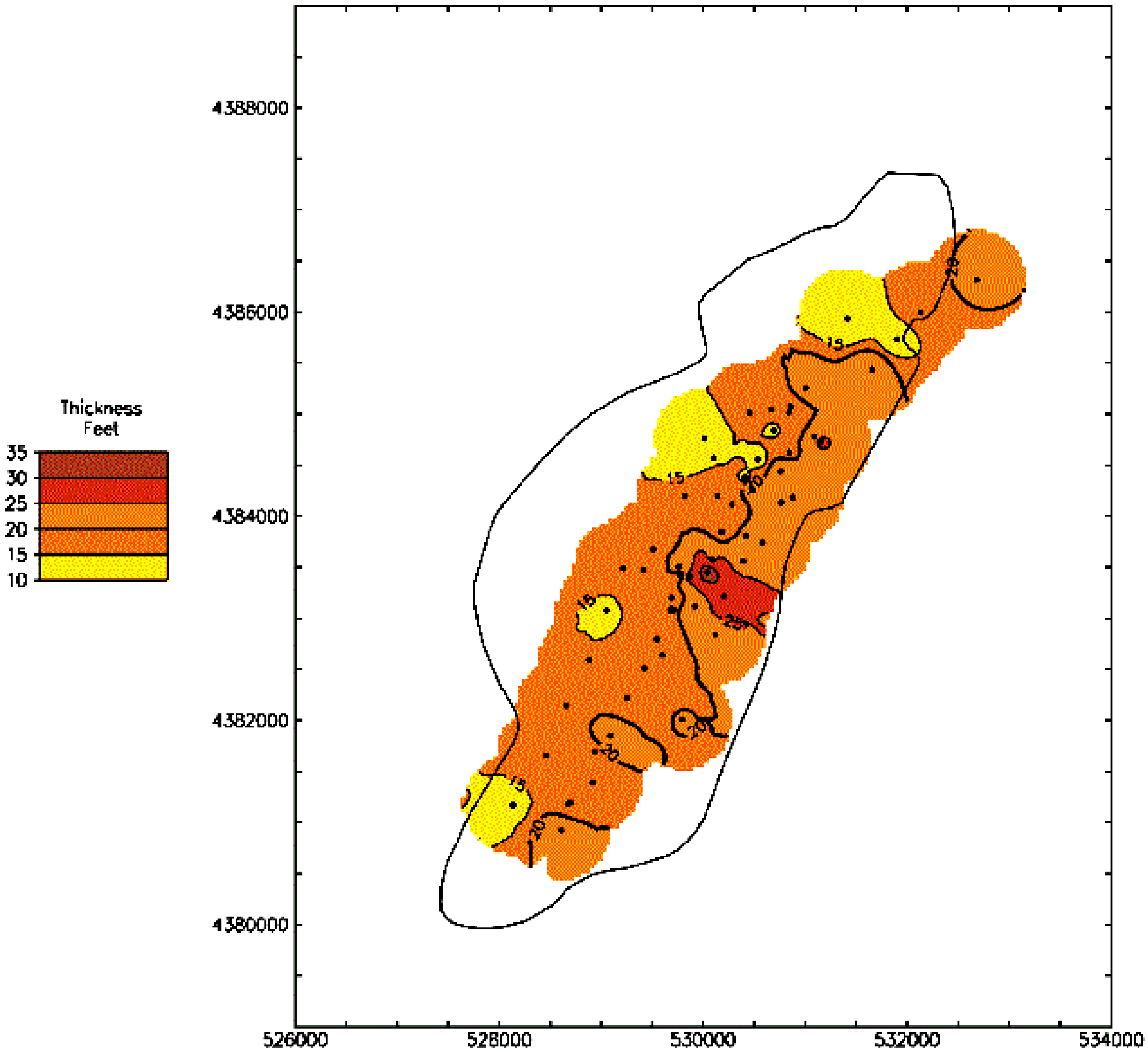


Figure 13. Map of total Gordon thickness for the Wileyville oil field. Outline of the field has been superimposed on the map

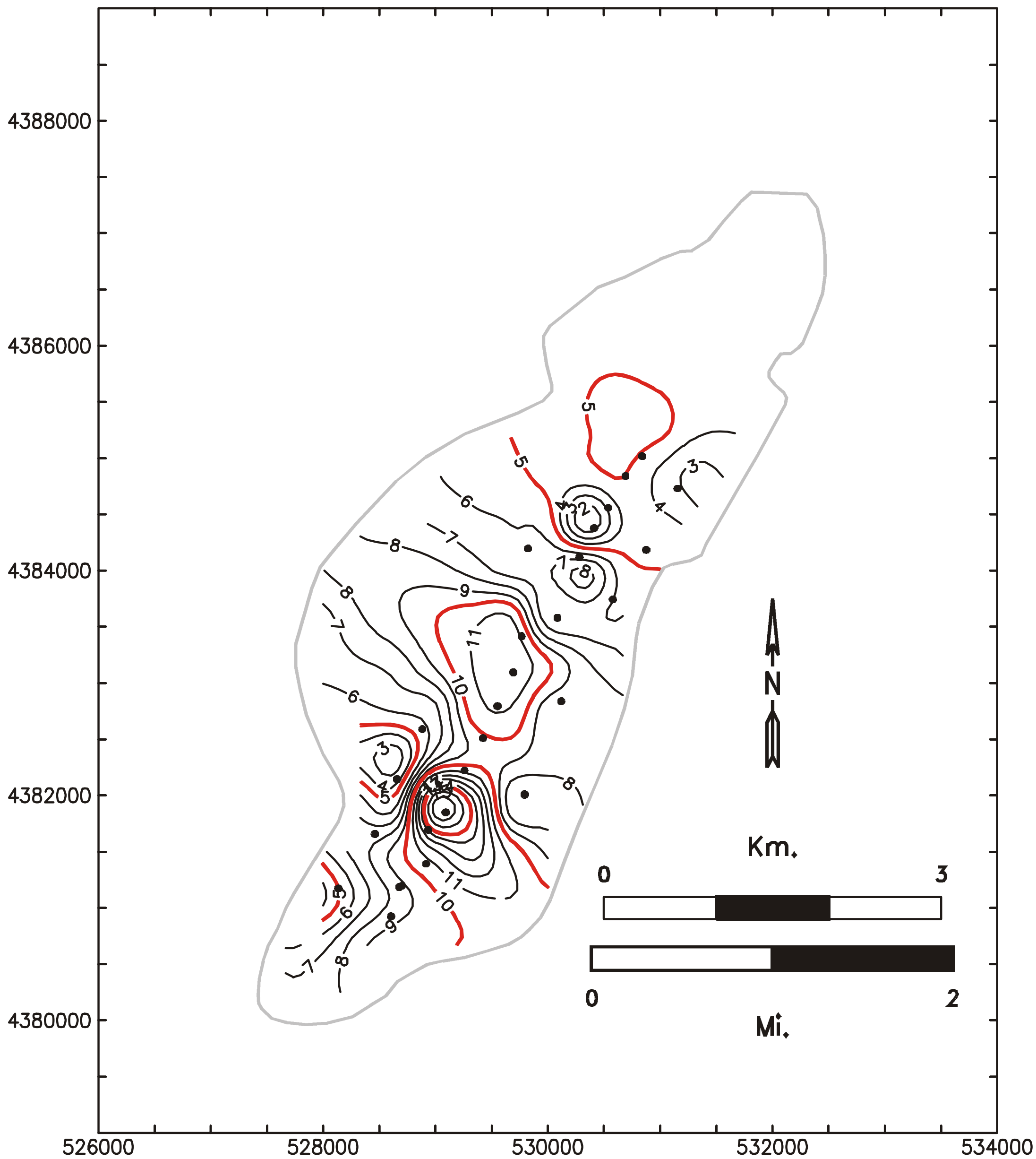


Figure 14. Map of thickness of *Fss* lithofacies within the Gordon for the Wileyville oil field. Contour interval is 1 foot.

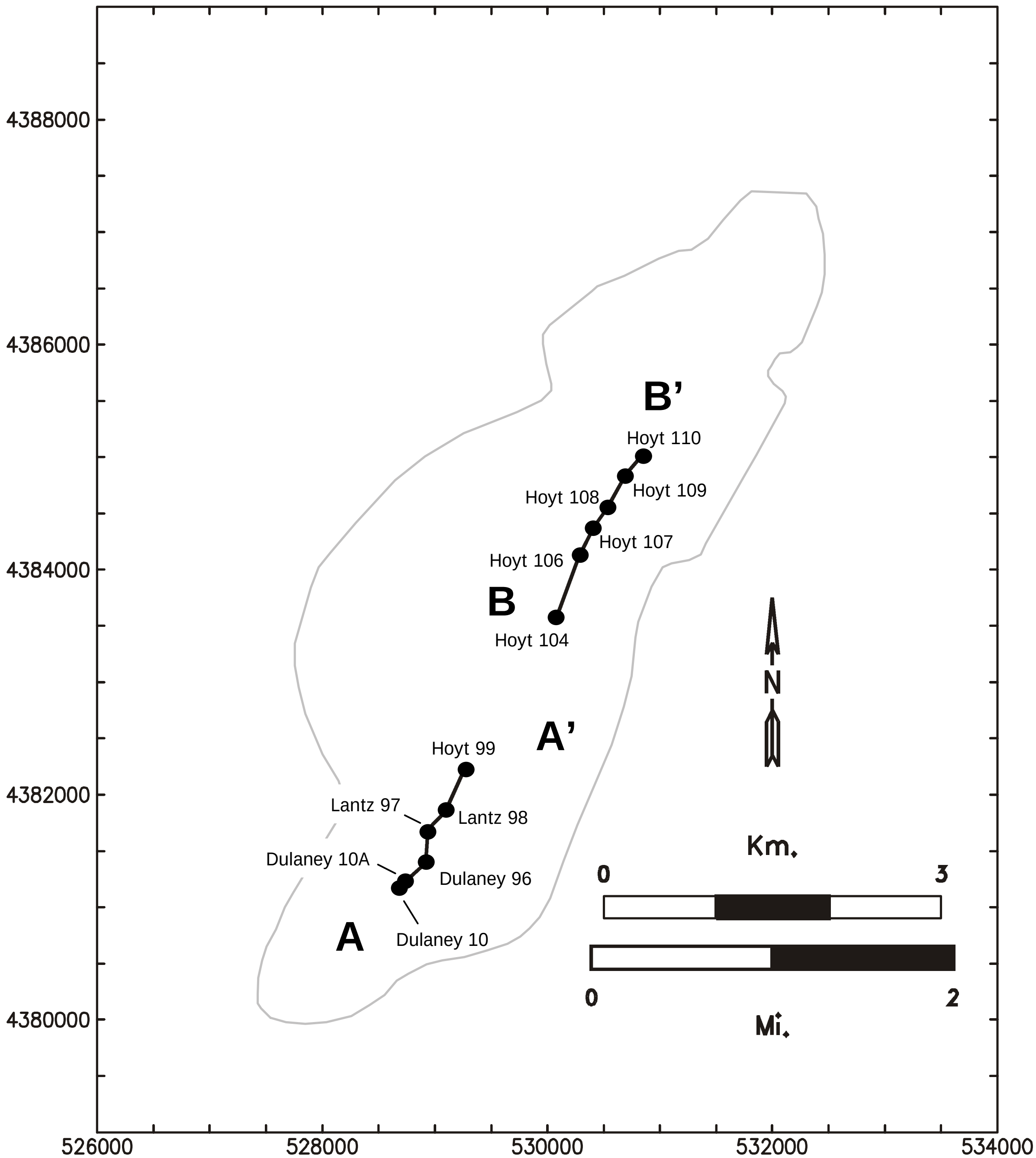
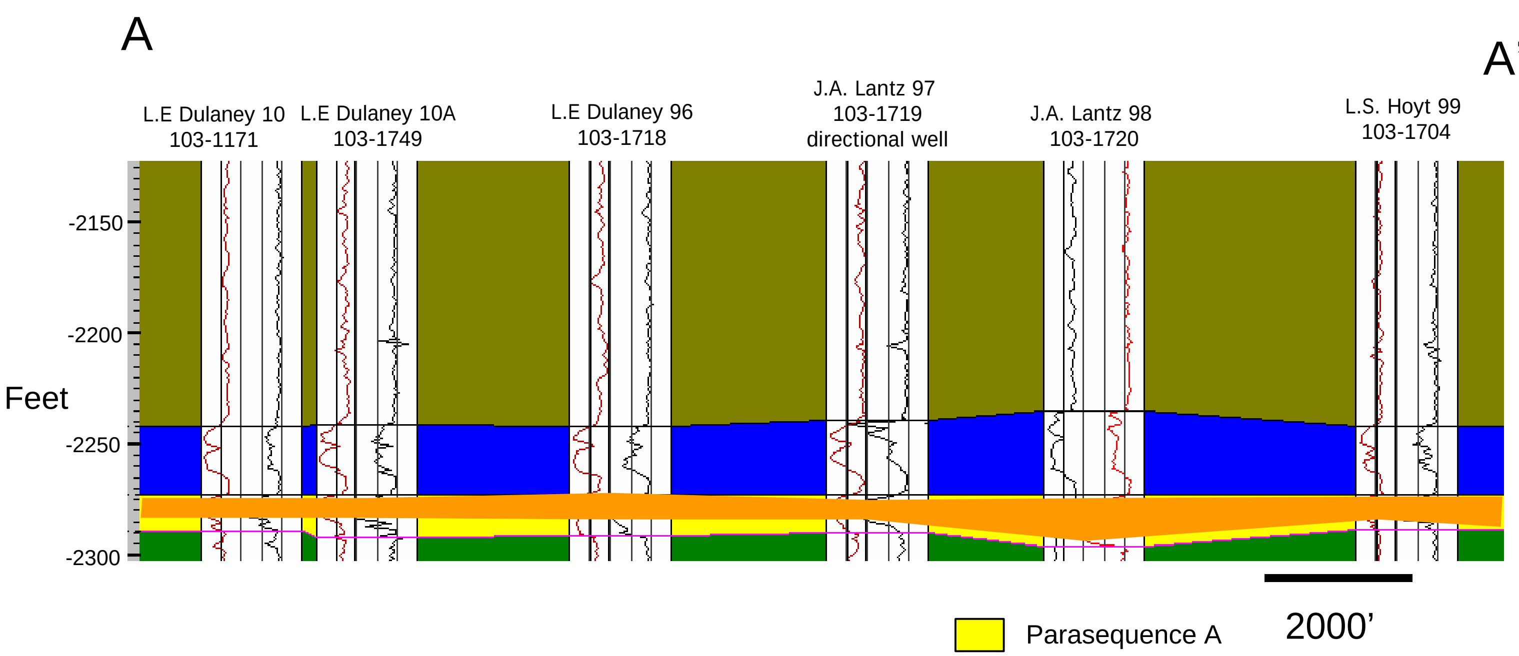


Figure 15. Location of stratigraphic cross-sections.



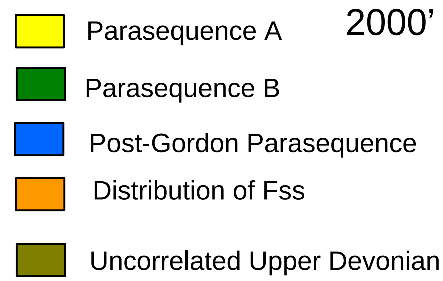


Figure 16. Stratigraphic cross section A-A’. See Figure 15 for the location of the cross section.

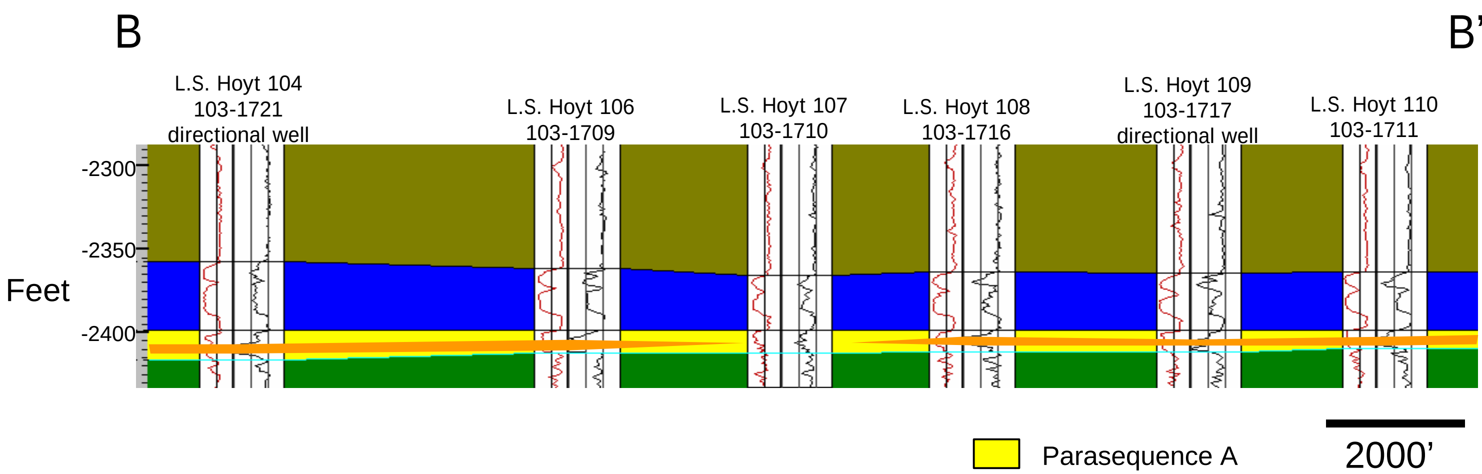


Figure 17. Stratigraphic cross section B-B'. See Figure 15 for the location of the cross section.

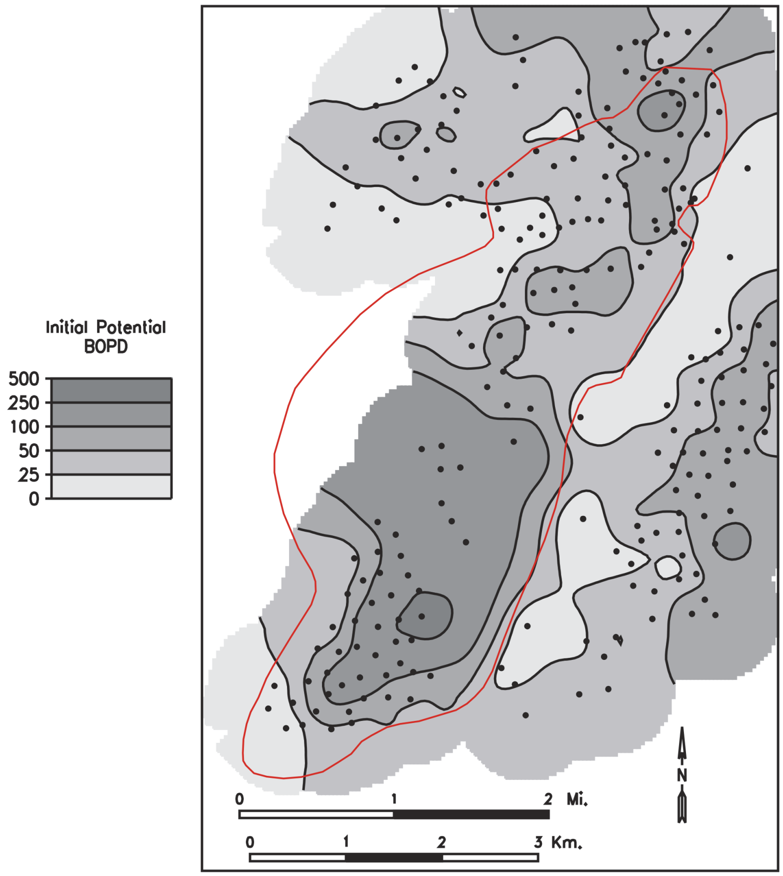


Figure 18. Contour map of oil initial potential in Wileyville oil field and vicinity. Field outline is shown in red.

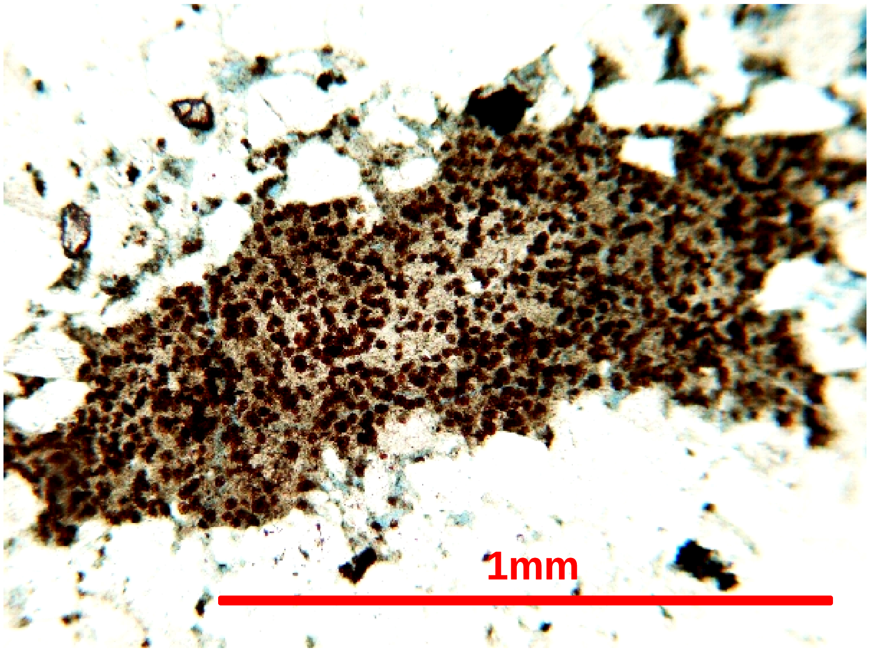


Figure 19a. Sideritic shale clast in a fine- to very fine-grained quartz sandstone from L. E. Dulaney 10 (103-1171) at a depth of 2850.25'; plain light.

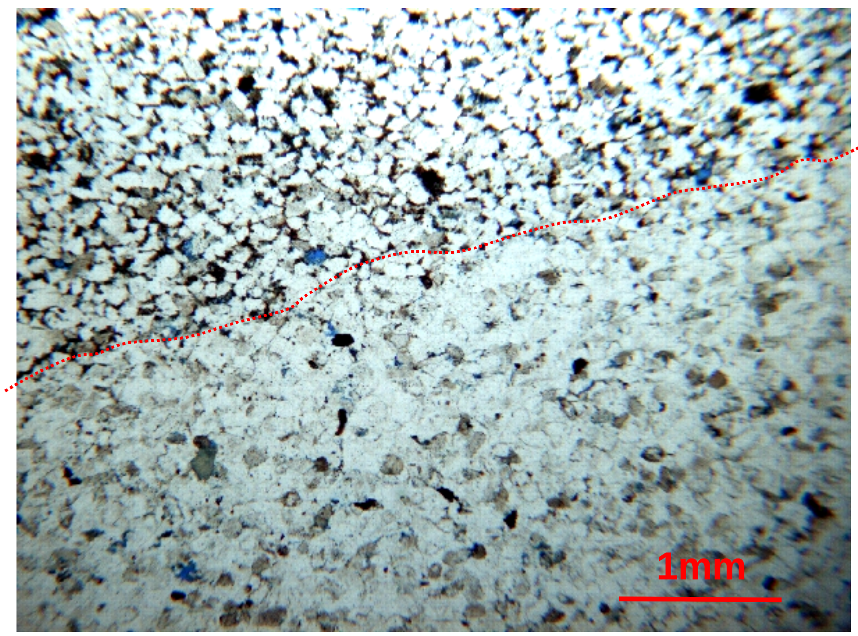


Figure 19b. Siderite front (top of slice above dashed line) in a fine- to very fine-grained quartz sandstone from L. E. Dulaney 10 (103-1171) at a depth of 2852.25'; plain light.

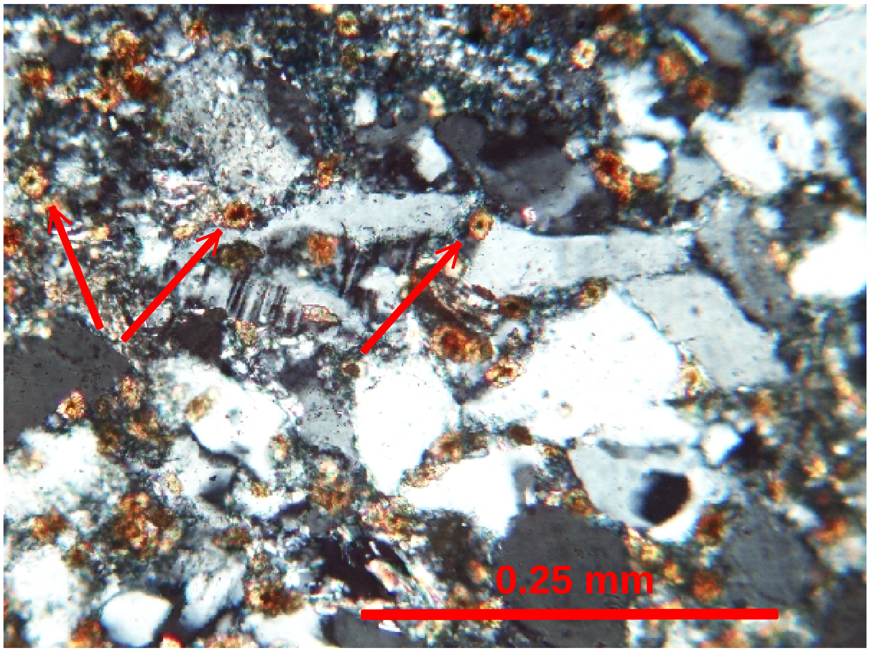


Figure 20a. At higher magnification (25x), siderite *blebs* are seen to be poorly developed rhombs with dark, ferruginous centers. From L. E. Dulaney 10 (103-1171) at a depth of 2840.50'; crossed polars.

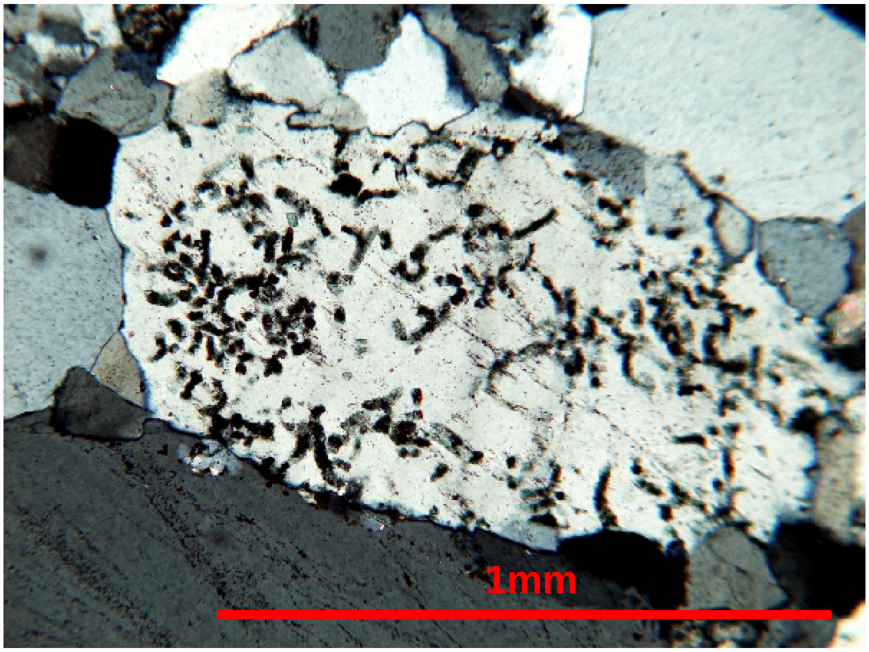


Figure 20b. Vermicular chlorite alteration in a subrounded quartz grain sandstone in a fine- to very fine-grained quartz sandstone from L. S. Hoyt 100 (103-1685) at a depth of 3137.45'; crossed polars.

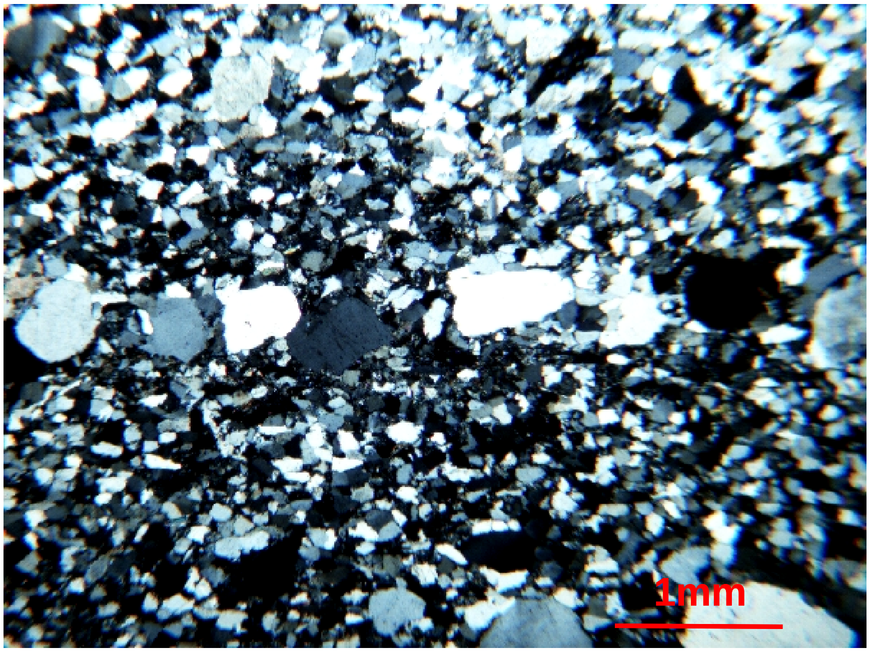


Figure 21a. Layer of moderately well-rounded quartz granules in a fine- to very fine-grained quartz sandstone from L. S. Hoyt 100 (103-1685) at a depth of 3137.45'; crossed polars.

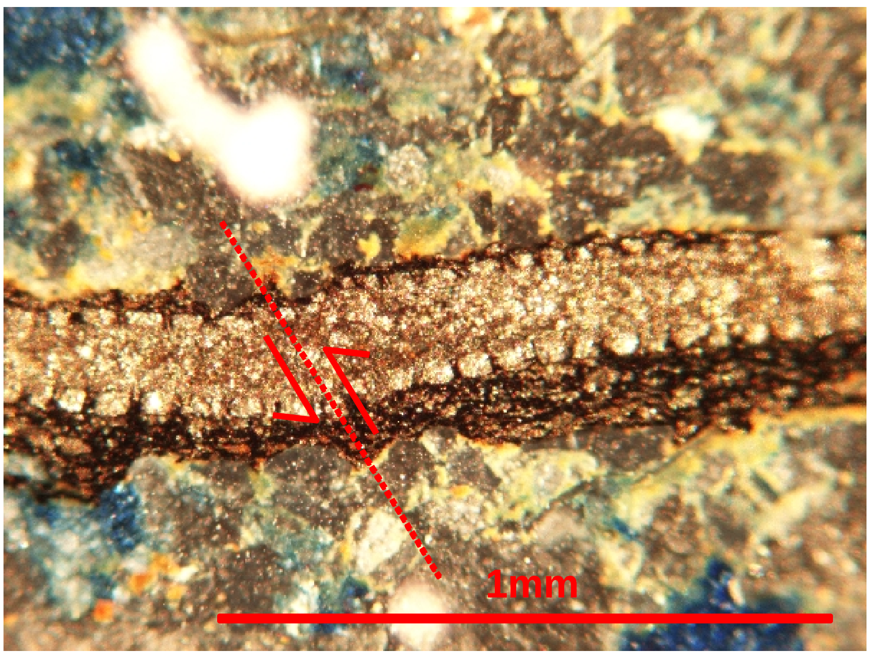


Figure 21b. Pyritized plant fragment showing displacement by a microfault. From L. S. Hoyt 100 (103-1685) at a depth of 3138.05'; reflected light.

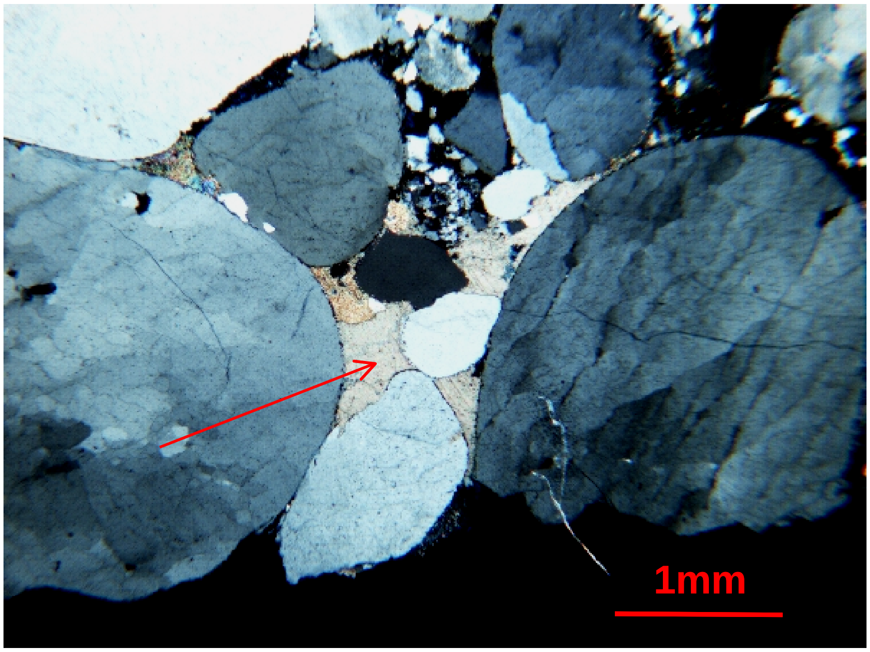


Figure 22a. First-stage, sparry calcite cement filling pore space between well-rounded quartz pebbles. From L. S. Hoyt 100 (103-1685) at a depth of 3138.05'; crossed polars.

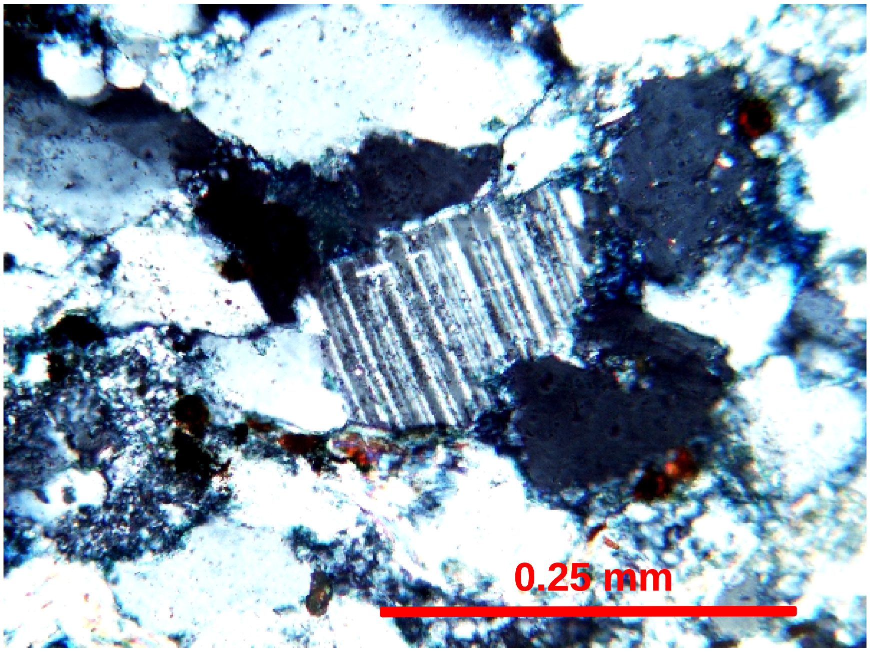


Figure 22b. Intact plagioclase grain showing no secondary porosity. From L. E. Dulaney #10 (103-1171) at a depth of 2838.65'; crossed polars.

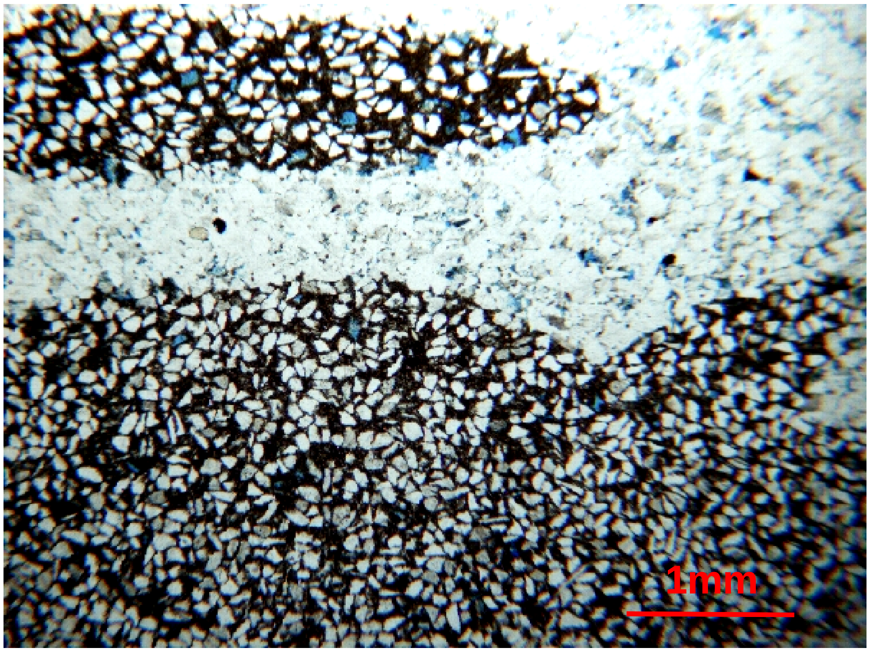


Figure 23a. Clasts of siderite-cemented, fine- to very fine-grained quartz sandstone in a fine- to very fine-grained quartz sandstone from L. S. Hoyt 100 (103-1685) at a depth of 3149.75'; plain light.

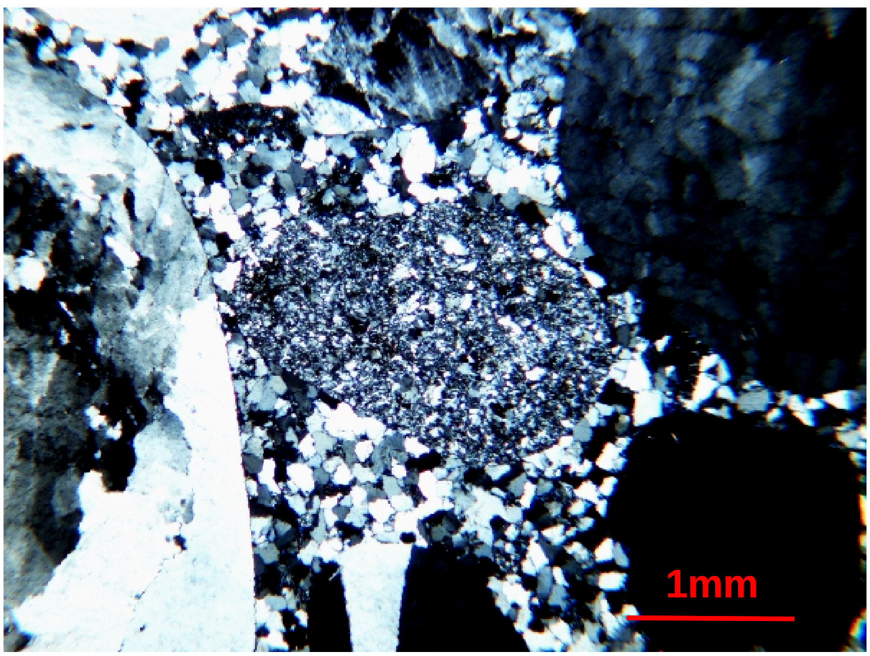


Figure 23b. Well-rounded chert rock fragment in a fine- to very fine-grained quartz sandstone from L. E. Dulaney 10 (103-1171) at a depth of 2852.65'; crossed polars.

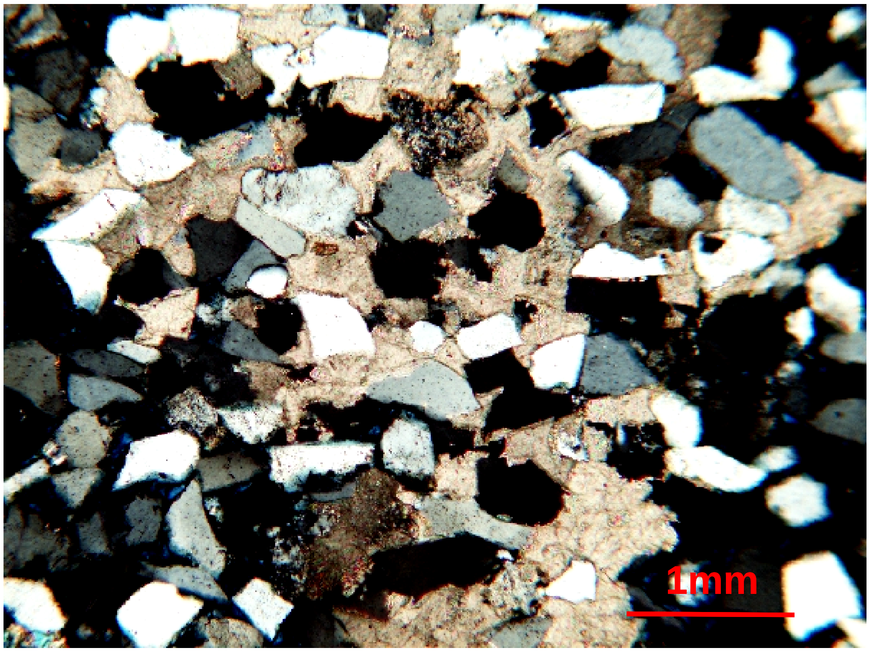


Figure 24a. First-stage, sparry calcite filling pore space in a fine- to very fine-grained quartz sandstone from L. E. Dulaney 10 (103-1171) at a depth of 2857.00'; crossed polars.

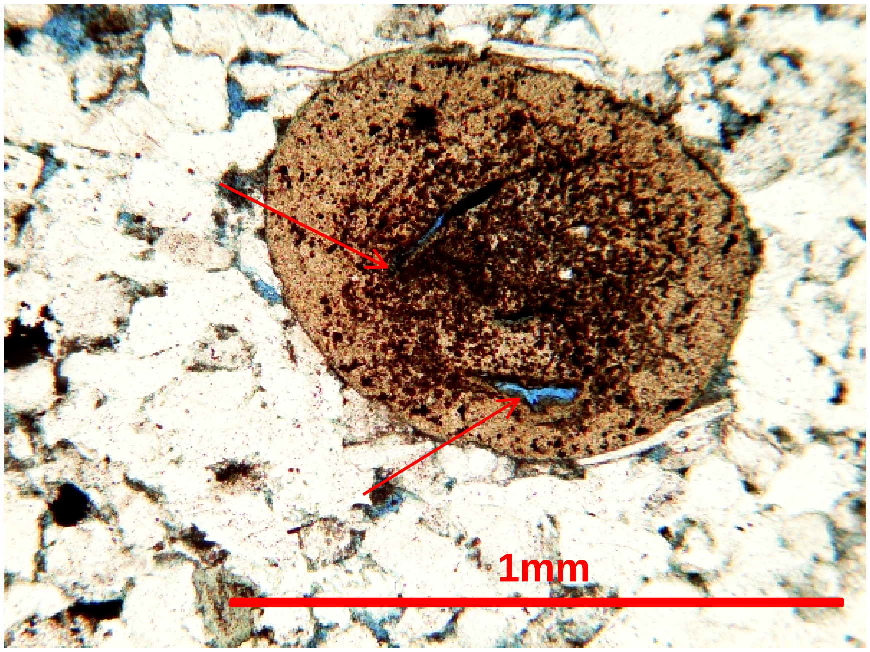


Figure 24b. Phosphatic fecal pellet containing quartz silt and fossil fragments. Secondary porosity (arrows) has developed in voids where calcitic? fossil material has been removed by dissolution. From L. S. Hoyt 100 (103-1685) at a depth of 3137.45'; plain light.

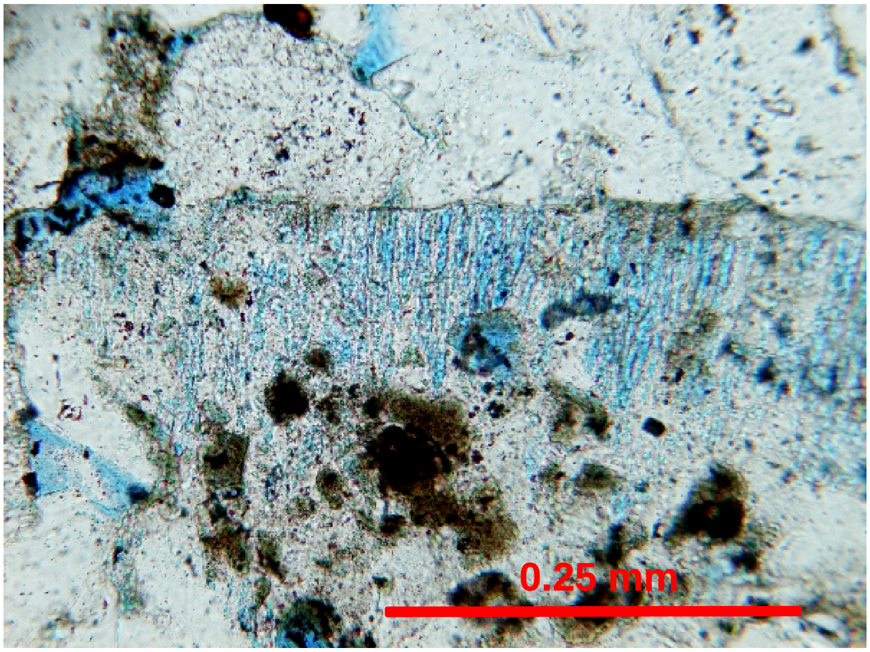


Figure 25a. Highly altered plagioclase grain showing relict twinning. Majority of the grain has been dissolved – secondary porosity is delineated by blue epoxy used to impregnate the rock. From L. E. Dulaney 10 (103-1171) at a depth of 2852.65’; plain light.

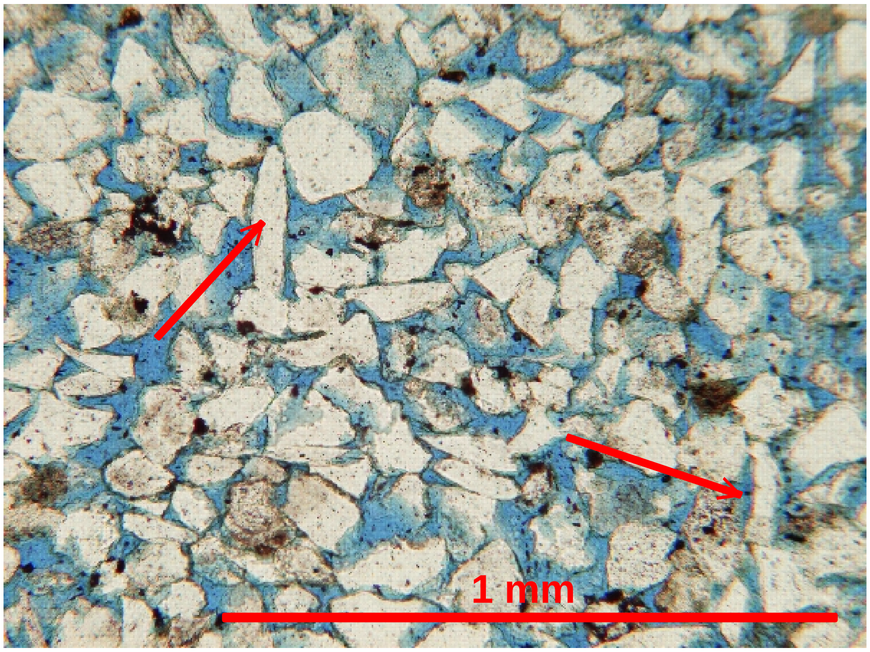


Figure 25b. Elongated quartz grains (arrows) in Featureless sandstone from L. S. Hoyt 100 (103-1685) at a depth of 3148.00’. Bedding is parallel to bar scale. Grains oriented at an angle (90º in this instance) are an indication of bioturbation in sandstones or other sedimentary rocks lacking obvious sedimentary structures.

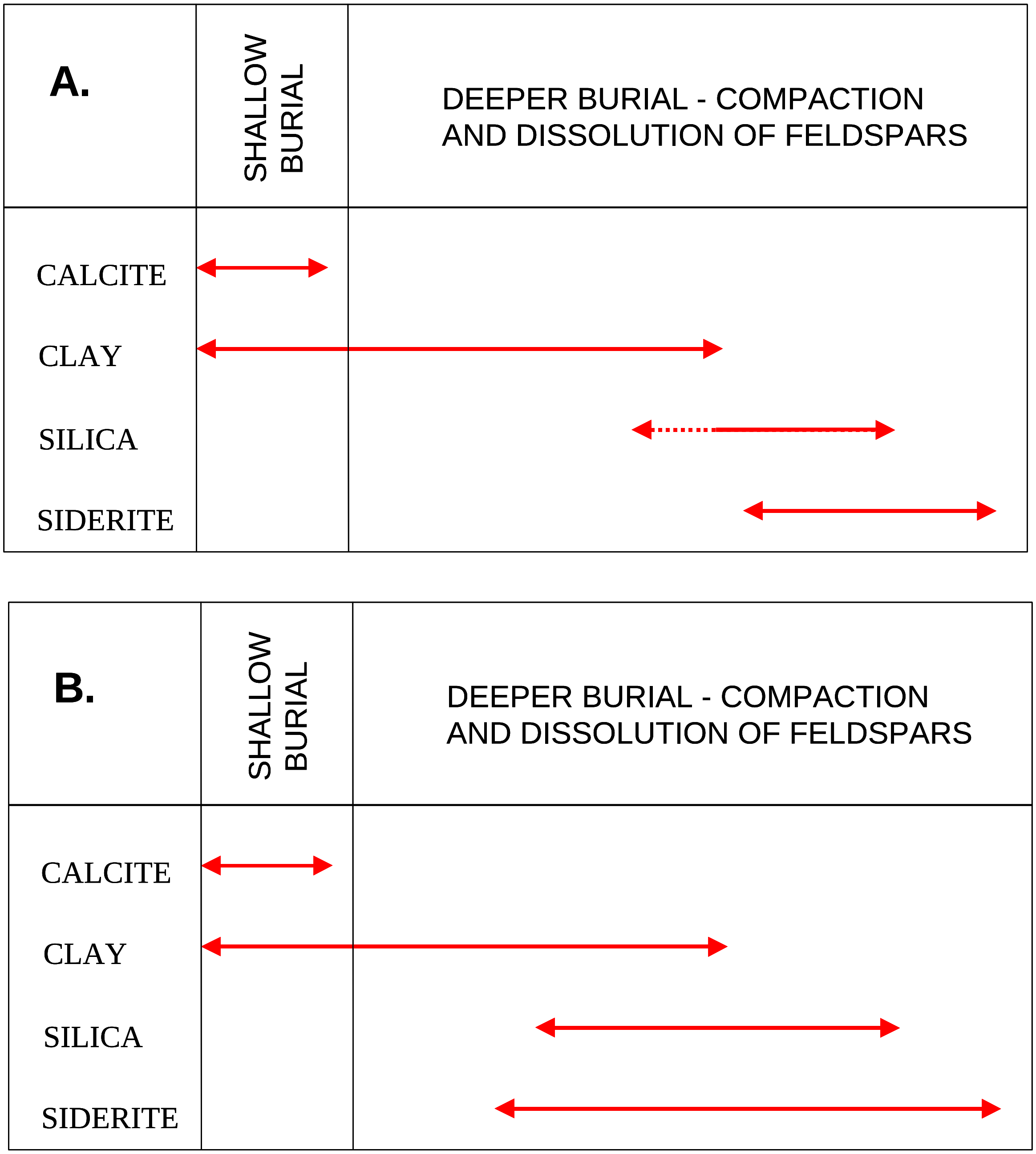


Figure 26. Graphical representation of the timing of cementation in the Gordon sandstone for the Wileyville (A) and Jacksonburg-Stringtown (B) oil fields. In both instances, calcite and clays form the earliest cements, whereas silica and siderite appear later.

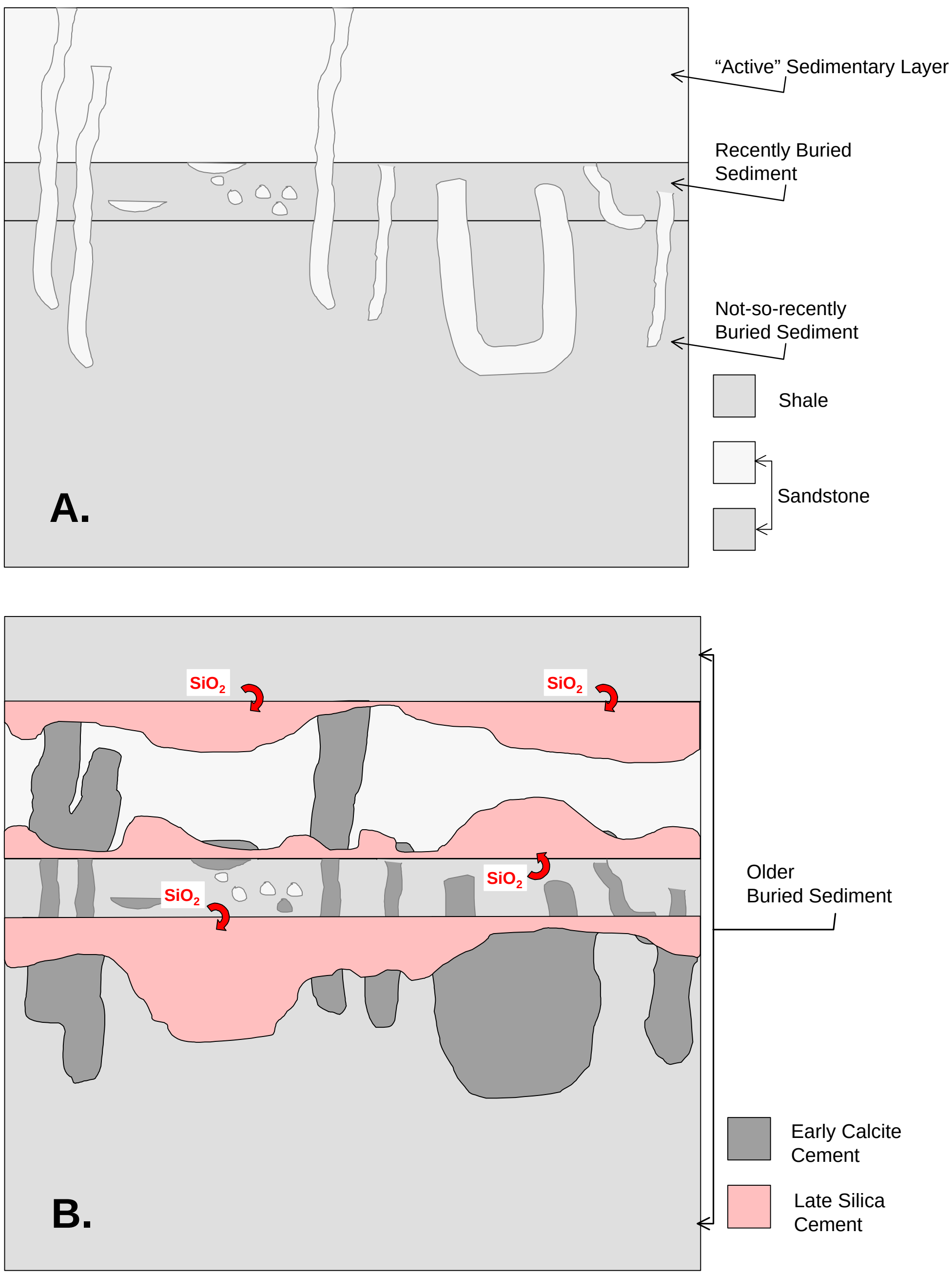
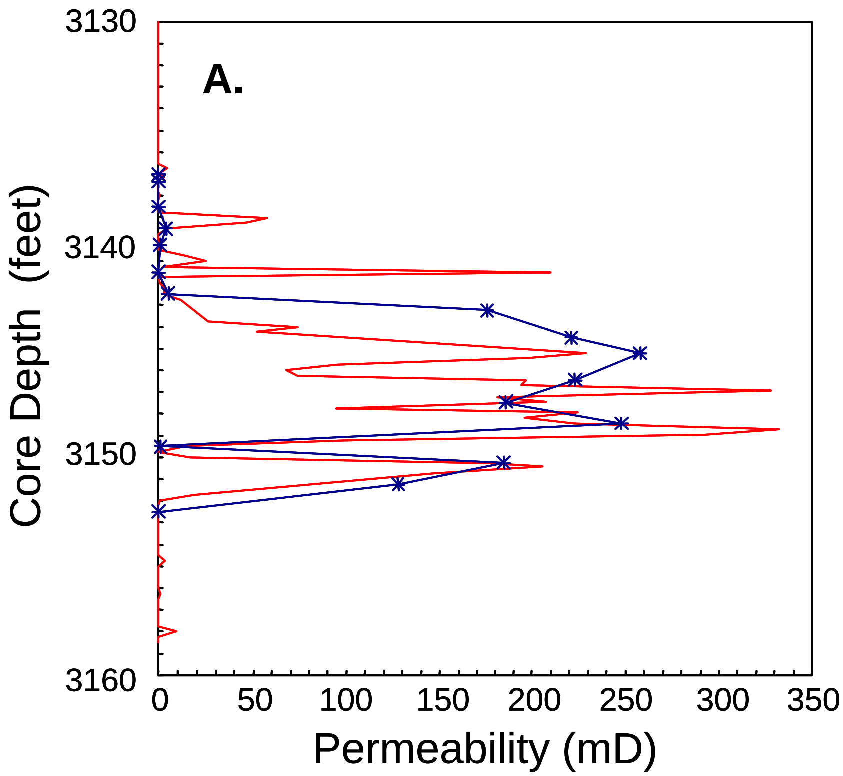


Figure 27. A) Vertical burrows initially allow cementing fluids to migrate between sedimentary layers. These trace fossils are generally concentrated at the tops of beds and are associated with early cementation by calcite. As the density of vertical traces increases, the amount of calcite cementation increases. B) Early calcite cement helps prevents the migration of later cementing fluids between layers of strata. This, in turn, may preserve the permeability within sedimentary layers. *Modified from McDowell and others, 2001.*



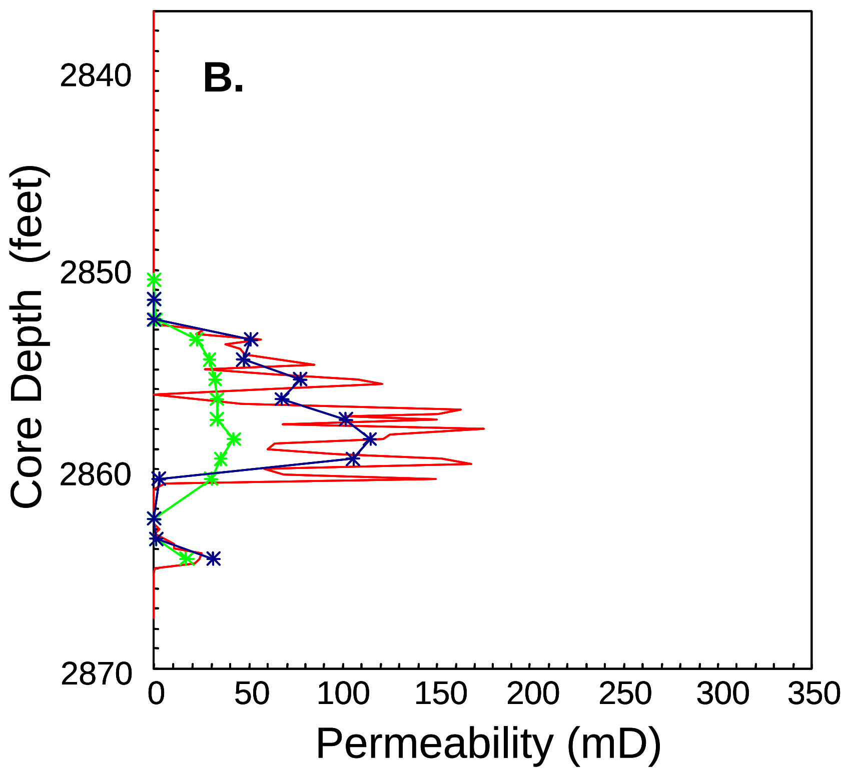


Figure 28. A) Graphical comparison of permeability measured from core plugs (blue) and by minipermeameter (red) for core from L. S. Hoyt 100. B) Graphical comparison of permeability measured from whole core (green), core plugs (blue), and by minipermeameter (red) for core from L. E. Dulaney 10.

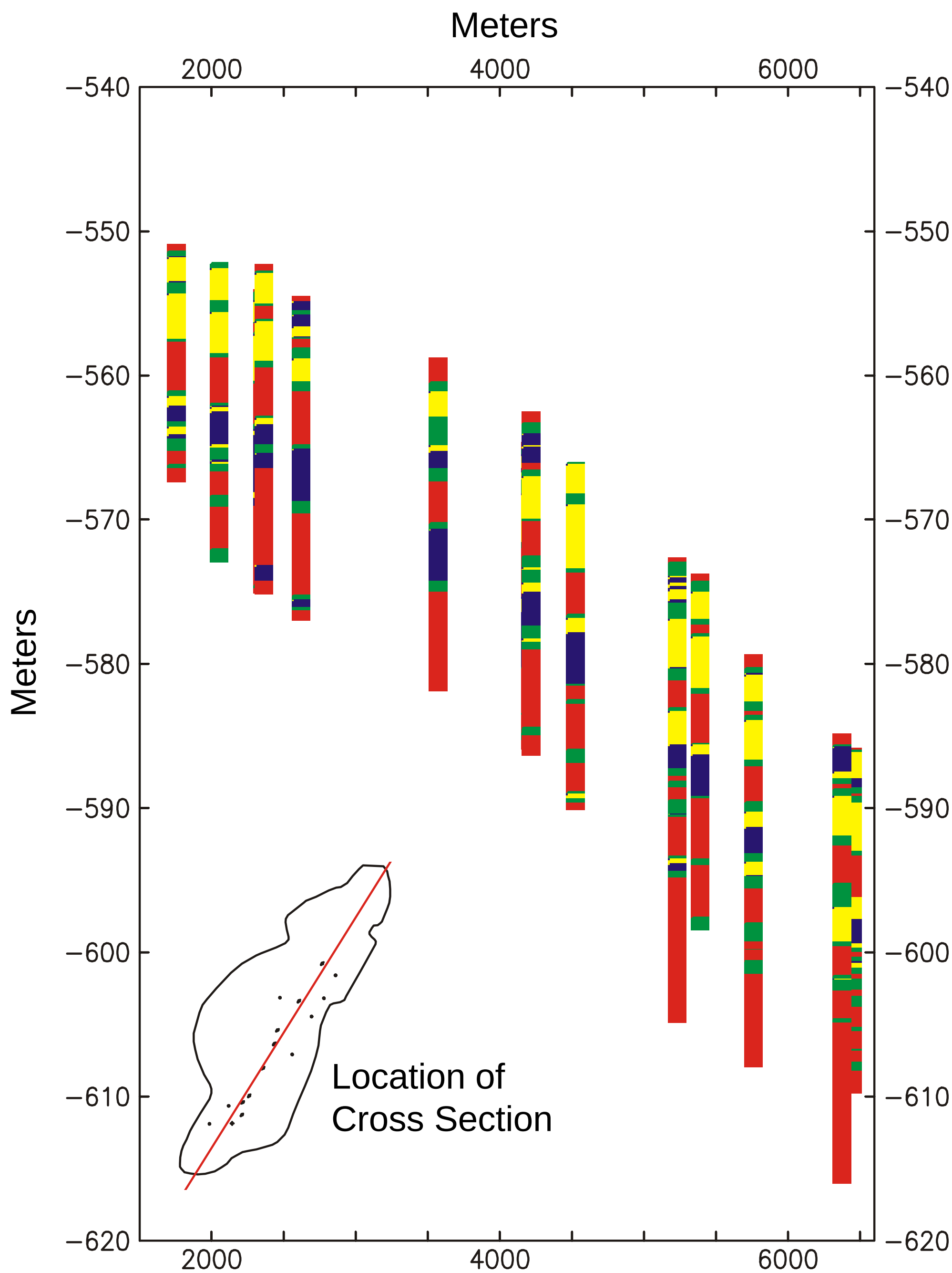


Figure 29. Vertical electrofacies cross section taken along the long axis of the Wileyville oil field – view is to the northwest. Depths and distances between wells are in meters. Wells are placed at their correct subsea elevation; the Gordon interval is observed to deepen to the northeast along the plunge of structure. Color code: Red – Electrofacies 1; Green – Electrofacies 2; Yellow – Electrofacies 3; Blue – Electrofacies 4.

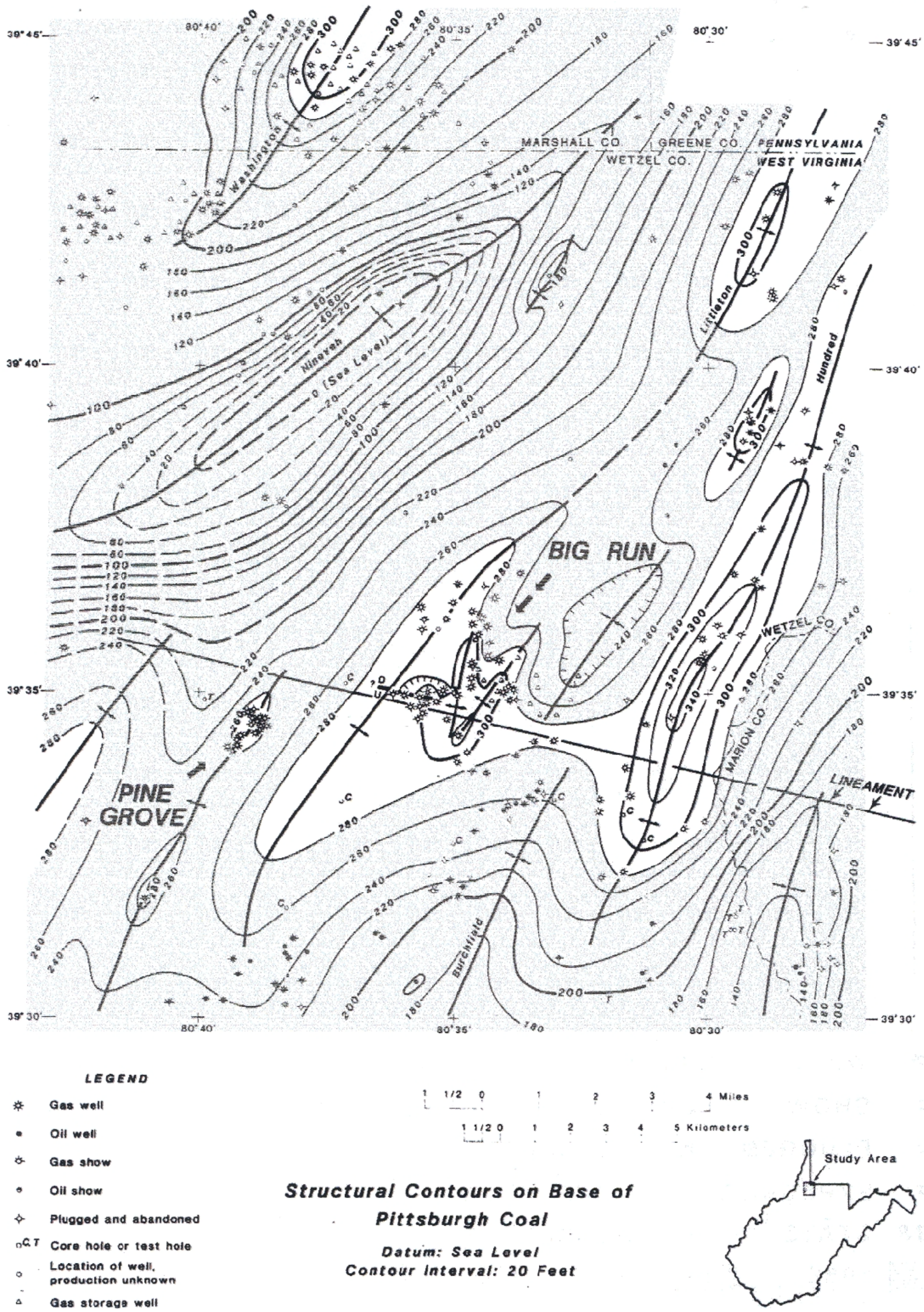


Figure 30. Structural contour map on the base of the Pittsburgh Coal in the Wileyville area. Anticlinal features, gas wells, and wells with gas shows are marked. Areas in which the Pittsburgh Coal may be wet are shaded. ***Modified from Patchen and others, 1991, Fig. 6, p. 14.***

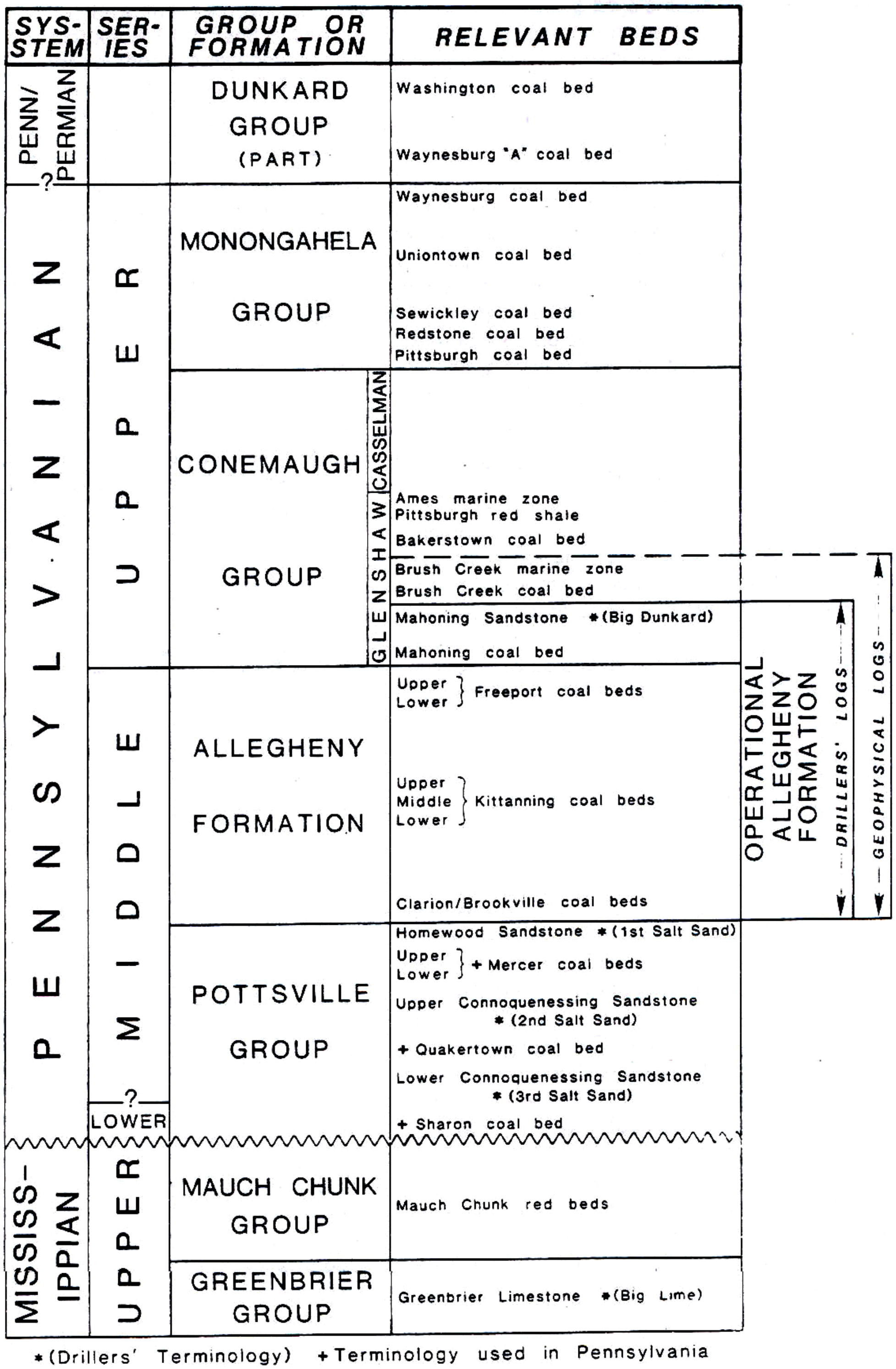


Figure 31. Stratigraphic chart for the uppermost Mississippian and Pennsylvanian in the Wileyville area. Named coal units are listed. ***Modified from Bruner and others, 1995, Fig. 1, p. 2.***

Table 1a. Summary of petrographic analyses of 30 thin sections from the Gordon interval in the Wileyville field. Results for individual lithofacies and the Gordon as a whole are shown.

Facies	Mean Grainsize (mm)	Mean Grainsize (phi)	Monoxtal. Quartz	Polyxtal. Quartz	Sec. Quartz	Feldspar	Primary Porosity	Secondary Porosity	Phyllosilicates	Opaques	Clays	Other
css	1.328770	-0.166434	64.00%	13.08%	7.28%	1.50%	7.08%	0.68%	0.48%	0.15%	2.75%	3.00%
fss	0.126727	2.982198	63.54%	4.13%	0.85%	4.80%	16.33%	1.65%	0.32%	0.21%	6.55%	1.61%
hb	0.155600	2.690119	60.00%	4.00%	13.80%	8.00%	1.15%	2.80%	0.70%	0.35%	6.85%	2.35%
lss	0.177827	3.009967	58.40%	6.73%	8.73%	4.78%	2.89%	0.93%	1.13%	0.46%	4.44%	11.49%
Gordon	0.302740	2.583381	60.97%	6.46%	6.16%	4.58%	7.92%	1.27%	0.74%	0.33%	5.11%	6.46%

Table 1b. Summary of petrographic analyses of 33 thin sections from the Gordon interval in the Jacksonburg-Stringtown field. Results for individual lithofacies and the Gordon as a whole are shown.

Facies	Mean Grainsize (mm)	Mean Grainsize (phi)	Monoxtal. Quartz	Polyxtal. Quartz	Sec. Quartz	Feldspar	Primary Porosity	Secondary Porosity	Phyllosilicates	Opaques	Clays	Other
css	1.363200	-0.288020	60.68%	20.10%	1.96%	1.82%	4.44%	0.66%	0.65%	1.15%	3.90%	4.56%
fss	0.160400	2.734950	60.92%	8.94%	1.32%	3.38%	14.58%	1.80%	1.52%	0.40%	6.08%	0.98%
hb	0.339780	1.859370	61.96%	10.22%	0.40%	2.10%	0.40%	0.32%	0.40%	0.33%	6.11%	17.71%
lss	0.130450	2.961570	62.75%	12.40%	1.90%	3.33%	4.77%	1.48%	2.36%	0.36%	5.46%	5.15%
Gordon	0.540770	1.717320	61.69%	13.55%	1.45%	2.59%	4.95%	0.99%	1.25%	0.59%	5.27%	7.61%

Table 2a. Summary of the petrophysical characteristics of the four Gordon electrofacies in the Wileyville field.

Electrofacies	Mean Gamma Ray	Mean Bulk Density	Mean Permeability	Mean Grainsize
1	122.04	2.70	0.20001	Fine Sand
2	73.34	2.58	10.30922	Very Coarse Sand
3	37.67	2.55	10.15289	Medium sand
4	51.89	2.28	90.70200	Fine Sand

Table 2b. Summary of the petrophysical characteristics of the four Gordon electrofacies in the Jacksonburg-Stringtown field.

Electrofacies	Mean Gamma Ray	Mean Bulk Density	Mean Permeability	Mean Grainsize
1	142.30	2.69	0.00208	Coarse Silt
2	75.28	2.55	1.55785	Fine Sand
3	40.59	2.52	2.66181	Coarse Sand
4	45.85	2.36	30.01643	Medium Sand

Table 3a. Summary of calculations of coal-bed methane potential for the Pittsburgh and Sewickley coals.

	AREA	AREA	COAL THICKNESS	VOLUME	COAL DENSITY[1]	DESORBED GAS[2]	GAS POTENTIAL
	feet^2	acres	feet	acrefeet	tons/acrefoot	ft^3/ton	BCF
Wileyville Field	183720895.10	4217.65					
Pittsburgh_7'	122568095.01	2813.78	7	19696.43			
Pittsburgh_5'	61152800.09	1403.88	5	7019.38			
Pittsburgh_Total	183720895.10			26715.81	1800	150	7.21327
Sewickley_1'	75224512.99	1726.92	1	1726.92			
Sewickley_3'	59055966.42	1355.74	3	4067.22			
Sewickley_5'	49440415.69	1135.00	5	5674.98			
Sewickley_Total	183720895.10			11469.11	1800	150	3.09666
[1] Coal Density from Kelafant and others, 1988, Table 8 - High-volatile Subbituminous Coal							
[2] Desorbed Methane potential from Kelafant and others, 1988, Figure 41 - High-volatile Subbituminous Coal							
at burial depths between 500' and 1000'							

Table 3b. Summary of calculations of coal-bed methane potential for the combined coals of the Allegheny Group.

	AREA	AREA	COAL THICKNESS	VOLUME	COAL DENSITY[1]	DESORBED GAS[2]	GAS POTENTIAL
	feet^2	acres	feet	acrefeet	tons/acrefoot	ft^3/ton	BCF
Wileyville Field	183720895.10	4217.65					
Allegheny_10'	18676487.73	428.75	10	4287.53			
Allegheny_15'	83234004.87	1910.79	15	28661.85			
Allegheny_20'	80348783.03	1844.55	20	36891.08			
Allegheny_25'	1461619.485	33.55	25	838.85			
Allegheny_Total	183720895.10			70679.32	1800	200	25.44455
1 Coal Density from Kelafant and others, 1988, Table 8 - High-volatile Subbituminous Coal							
[2] Supplied by Doug Patchen							