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AN ANALYSIS OF THE STRUCTURAL PARAMETERS THAT INFLUENCE

GAS PRODUCTION FROM THE DEVONIAN SHALE. ³⁴ *Annual progress report,*
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THAT INFLUENCE GAS PRODUCTION FROM THE DEVONIAN SHALE

1979 - 1980

ANNUAL PROGRESS REPORT

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INORGANIC GEOCHEMISTRY
AS A HYDROCARBON EXPLORATION TOOL AND PALEOENVIRONMENTAL INDICATOR *

by

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* Abstract. This paper is in press for Revue de l'Institut Francais du Pétrole, 26th International Geological Congress, Paris, France, July, 1980.

This paper will be on Open File at METC sometime in the future.

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Inorganic geochemistry as a hydrocarbon exploration tool and paleo-environmental indicator

NEGUS-DE WYS, J. and RENTON, J.J., West Virginia University, Morgantown, WV,
26th International Geological Congress, Paris, France.

ABSTRACT

Elemental and mineralic analyses are obtained by x-ray fluorescence and x-ray diffraction on well cuttings from 14 wells in the largest gas field in the Appalachian Basin, North America. Percentages of oxides of Al, Si, Mg, K, Fe, Ca, and Si/Al ratio, and percentage of S are related to the Upper Devonian black shale sequence and to the Eastern Kentucky Gas Field. Iso-value maps are related to gas open flow data from ~5000 wells. Sulfur, the oxides of Al and Mg and the ratio of oxides Si/Al show the greatest promise as exploration indicators, from a comparison of computer-drawn maps of the elemental data with contours of density of high producing gas wells. The similarity in patterns is rather striking, especially in view of the limited number of wells used. Mineralic ratios used include 1) Koalinite/Koalinite + Illite, 2) Quartz/Quartz + Koalinite + Illite + Chlorite, 3) Siderite/Calcite + Dolomite + Siderite, 4) Calcite/Calcite + Dolomite, and 5) Chlorite/Chlorite + Koalinite. Paleoenvironmental interpretations are presented for the ~3000 square mile area. Environmental deductions, some based on ongoing coal research at West Virginia University, relate the mineralic ratios to relative marine, non-marine, alkaline, fresh water, proximity to clastic source, and near shore evaporative environments. No great disagreement is found in the map series.

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INORGANIC GEOCHEMISTRY STUDIES OF THE EASTERN KENTUCKY GAS FIELD

by

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October 1979

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ABSTRACT

The Upper Devonian Ohio Shale sequence including the Cleveland, Three Lick, and Upper, Middle, and Lower Huron, and the Mississippian Berea-Bedford sequence are studied by using XRF and XRD on >500 samples from 14 wells from the Eastern Kentucky Gas Field. Elements studied are Mg, Al, Si, P, K, Ca, Ti, Mn, Fe, S, Cu, Zn, Sr, Na. Minerals included in the study are chlorite, illite, kaolinite, anhydrite, szomolnokite ($\text{FeSO}_4 \cdot \text{H}_2\text{O}$), quartz, orthoclase, plagioclase, calcite, dolomite, siderite, pyrite, and bassanite ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$). Ratios studied were Si/Al and five mineralic ratios: 1) kaolinite/kaolinite + illite; 2) quartz/quartz + kaolinite + illite + chlorite; 3) siderite/calcite + dolomite + siderite; 4) calcite/calcite + dolomite, and 5) chlorite/chlorite + kaolinite.

The data are examined in terms of average values for total producing sequence, for Ohio Shale sequence and for each stratigraphic unit. Computer-drawn maps, using six contour levels, are compared with final open flow data patterns from a hand-contour map using ~4750 data points and with maps showing density contours of high-producing wells.

A striking pattern match is shown by several elemental maps with the high-producing well density maps. The mineralic ratios run are perhaps best used as paleoenvironmental indicators and interpreters of the elemental complexes.

The predictive and exploration value of such an investigation is obvious.

Changes of given elements and minerals, within and between wells, are shown for comparison across the Eastern Kentucky Gas Field. The pattern relationships are not obvious from the graphs, nor are they from the formation density logs of the wells.

Further refinements of this work are in process. Seventy-two maps on the elemental analysis have been run to date. Mineralic data is in the process of analysis. Further studies will refine data tops and integrate this work with the more comprehensive study of the Eastern Kentucky Gas Field.

INTRODUCTION

The unique puzzle of the occurrence and recovery of gas from the Upper Devonian shales has long been an enigma to geologists. The depositional environment of the highly organic black shale has aroused considerable debate. Preservation of concentrated organic material is of prime importance. This could occur in a wide range of water depths. Source of organics could be terrestrial, marine, or a combination of both. The necessary anoxic bottom conditions are also derived by a variety of models. Swager (1978) has suggested that the pycnocline theory of Byers (1977) and the thermocline (quasi-estuarine circulation) theory of Heckel (1977) could be modified to fit paleoenvironmental conditions for the Devonian-Mississippian shale sequence.

Recovery of the gas once formed appears closely related to fractures, other factors being equal (Hunter and Munyan, 1935; McFarlan, 1943; Shumaker, 1978; Negus-de Wys, 1979). Many fractures are filled or partially filled with predominantly calcite or pyrite.

The differences in paleoenvironment and fracture filling may be reflected in well cutting analyses. With this concept in mind well cuttings from fourteen wells in the Eastern Kentucky Gas Field are being analyzed for sixteen elements, one elemental ratio, thirteen minerals, and five mineralic ratios.

The structural setting of the Eastern Kentucky Gas Field is shown in Figure 1. (Shumaker, 1977; Negus-de Wys and Shumaker, 1978) Figure 2 shows the basement structure for the field area only. The Rome Trough is the dominant basement feature cutting across the northern section of the field in an east-northeasterly direction. The Floyd County Channel extends from the south in a northerly direction between the Perry County Uplift on the west and the Pike County Uplift on the east. Figure 3 shows the basement interpretation from Bouguer gravity, suggesting an intersection of the Rome Trough by the channel or aborted graben (Ammerman and Keller, 1979).

The stratigraphic units included in the study are Berea-Bedford through Lower Huron (Figure 4).

Structure on the Top of the Ohio Shale is shown in Figure 4 (Provo, 1977) and structural-stratigraphic sections through the field in Figures 6, 7, and 8 (Negus-de Wys and R. C. Shumaker, 1978). The latter were constructed from formation density logs. Other sections as noted on the location map are available in the 1978 paper referenced.

Thus the setting for the Upper Devonian shales in the Eastern Kentucky Gas Field is a gentle doming structure, the Paint Creek Uplift, extending south-southeastward into the field, with the Devonian strata thickening to the east.

From 1935-1962 Coleman Hunter studied well cuttings from several counties and published average values for quartz, pyrite, kerogen and bitumen (Hunter and Munyan, 1935). Iso-value lines on these data are shown in Figures 9, 10, 11, and 12. Hunter's estimated ultimate recovery per well is shown by county in Figure 13. The quartz map shows high values to the east; pyrite is high in Floyd County and may extend north; kerogen is higher in Floyd and on to the north as well as in Perry County and to the northwest; bitumen is higher to the northwest and low to the east-southeast; and the estimated recovery contours show an elongate oval configuration with a northeast-southwest axis.

The purpose of the present study is to ascertain whether meaningful geochemical parameters can be identified to better understand the paleoenvironment of deposition of the shale sequence, the relationships within the field, and relate such evidence to gas occurrence and recovery.

DATA

The locations of the wells from which cuttings were analyzed are shown in Figure 14. Analysis was by x-ray fluorescence and x-ray diffraction (Renton, 1979). All elements except sulfur are analyzed as oxides. Figure 15 shows the elements analyzed with Minimum, Maximum, and Mean Values, Variance, and Coefficient of Variance. Variance is the average of the square of the deviations of the measurements about their mean; coefficient of variance is the standard deviation ($\sqrt{\text{variance}}$) divided by its related mean, and is a relative measurement of deviation.

A comparison of Si and Al oxide graphs for the Berea-Bedford through Huron sequence are shown in Figure 16. The wells are arranged from west to east. Figure 17 shows the Si Oxide graphs in the well positions. Field cross sections of the Si-Al oxide ratios are shown in Figures 18, 19, and 20 with stratigraphic units noted.

From these data computer maps were run on the average values of individual stratigraphic units, for the total sequence, and for the Ohio Shale. The map for the Si oxide in the Three Lick unit is shown in Figure 21. As will be seen from production maps (Figure 38), this map correlates very closely with the contoured configuration of density of high producing wells.

A comparison of computer drawn map miniatures is shown in Figure 22 for all units for Si/Al, Al, Si, S, Mg, K, Fe, and Ca. The darkest shade is the highest values, the lightest represents the lowest value. All were run with six levels, not always representing equal increments, due to data range differences.

The maps showing the greatest similarity to the production maps (Figure 38) show highest values in the central area with a northeast trend. A reverse correlation of very light values in this area could also be significant. One of the closest parallels is observed in the Si/Al series for the stratigraphic units as well as Total Sequence and Total Ohio Shale (Figure 23).

The minerals analyzed are shown in Figure 24. Chemical formulas are shown in Figure 25 and the ratio combinations in Figure 26.

The basic environmental interpretations for the ratios are tabulated in Figure 27.

KAOLINITE/KAOLINITE + ILLITE RATIO #1: Based upon our work with coal, the ratio of kaolinite to illite changes depending upon the inferred depositional environment. Kaolinite is an indication of fresh water environments while illite becomes increasingly dominant as the environment becomes more "marine" (alkaline). In the southern Appalachian Basin coals or the western coals that we interpreted as having fresh water origins (lacustrine, alluvial plain), kaolinite makes up 70% or more of the clays. In the northern Appalachian basin, interpreted as being more "brackish," the ratio is about 50:50, while in the Illinois Basin where the coals accumulated in a more "marine" influence, the kaolinite represents about 30-40% of the clays. It might be pointed out that the terms "brackish" and "marine" are relative terms; the most marine conditions under which coal could be preserved would actually be brackish at best. The Kaolinite/Kaolinite + illite ratio in the shale study is being monitored as a possible indicator of marine influence, the shales being considered the product of a poorly preserved peat type environment.

QUARTZ/QUARTZ + KAOLINITE + CHLORITE + ILLITE RATIO #2: This is basically a quartz-clay ratio. The relative abundance of quartz would be expected to increase as the clastic source is approached, i.e., greater proximity to land. This ratio will be so tested.

SIDERITE/CALCITE + DOLOMITE + SIDERITE RATIO #3: Again referring to the coal studies, siderite is correlative with a fresh water dominated environment. This ratio parallels the Kaolinite/Kaolinite + Illite ratio, the siderite only appearing as a dominant carbonate phase when kaolinite represents 70% or more of the clays.

CALCITE/CALCITE + DOLOMITE RATIO #4: The classic carbonate ratio with increased dolomite reflecting near shore (evaporative) environments.

CHLORITE/CHLORITE + KAOLINITE RATIO #5: Based upon the coal studies, chlorite is a marine indicator. There does seem to be a variation in the relative abundance of the chlorite and kaolinite depending upon the depositional geochemistry. This ratio monitors the chlorite portion of the clay suite.

Computer drawn maps for these ratios for the average values for the total stratigraphic sequence are shown in Figures 28, 29, 30, 31, and 32. Interpretation of these maps is in the initial stages at the time of writing this paper. Figures 33 and 34 show stages of interpretation.

Comparison of these maps is made with Final Open Flow data based on ~4750 wells (Figure 35). Hand contoured this data presents a highly complicated pattern (Figure 36). When a trend surface analysis program is run on these data, the 4th order polynomial yields Figure 37. This is similar to the contours resulting from Hunter's 1962 prediction of ultimate recovery per well by county. When the data is contoured by density of wells > .5 MMcf/day/25 square miles and > 1 MMcf/day/25 square miles, Figure 38 results. Comparison with one of the computer maps considered to closely resemble the production configurations is shown in Figure 39, the Si/Al map for the Three Lick unit.

Figure 40 shows a table of the element maps run to date and correlation with contours of density of high producing wells. This is a visual comparison. A statistical analysis is in progress. The Sulfur, Magnesium oxide, Si/Al oxides ratio and Aluminum oxide maps show the highest number of correlations. The Sulfur maps and the combination of Si/Al ratio and Aluminum oxide maps show correlations with all units.

Of the ratio maps, only mineral Ratio 4 shows similarities with the production configurations.

CONCLUSIONS

Based on studies to date:

- 1) Elemental geochemistry shows promise as an exploration tool for field development.
- 2) The Si/Al ratio of oxides, Al oxide, Sulfur, and Magnesium oxide maps show the highest number of correlations with contoured density of high producing wells.
- 3) The Lower Huron shows the highest number of correlations of elemental data with production; the Upper Huron is a close second. The Three Lick shows the least correlation.
- 4) Mineralic ratios are best used for paleoenvironment interpretation. Refinement of interpretation is ongoing. Figures 33 and 34 show the present level of interpretation.

We are presently seeking funding to continue this innovative and promising research. It is hoped that complete mineralic analyses, application of refinement of tops from lithological studies (Negus-de Wys, 1979), further well sample analyses and data analysis will be funded.

This work was initiated with no funding and has received subsequent interim support under DOE contract #DE-AC21-76MC05194 (formerly EY-76-C-05-5194).

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CORRELATION OF COMPUTER MAPS WITH CONTOURED DENSITY OF HIGH PRODUCING WELLS									
Units	Oxides of Si/Al Ratio	Elements (all oxides except Sulfur)							Totals
		Al	Si	S	Mg	K	Fe	Ca	
Berea-Bedford	+	+		+	+	+			5
Cleveland	0	+		+	+	+			5
Three-Lick		0	+	+					3
Upper Huron	+	0	+	+	0	0			6
Middle Huron		1		0	1			+	4
Lower Huron	+	0		+	+	0	0	+	7
Total Sequence	+			+	+		0	+	5
Ohio Shale	+			+	+		0	+	5
Totals	6	6	2	8	7	4	3	4

Figure 2. Structural setting of the Eastern Kentucky Gas Field showing the Rome Trough cutting across the northern part of the field and the Floyd County Channel extending from the south into the center of the field.

Figure 2 Basement structure of the area studied (after Shumaker, 1977).

Figure 3 Basement structure of the area studied from Bouguer gravity (after Ammerman and Keller, 1979). Note extension of Floyd County Channel to intersect the Rome Trough.

STRATIGRAPHIC SEQUENCE

BEREA/BEDFORD	Berea Sandstone and Bedford Shale, undivided
CLEVELAND	Cleveland Member of Ohio Shale of Ohio
THREE LICK	Three Lick Bed of Provo, Kepferle, and Potter, 1977
UPPER HURON	Upper Part of Huron Member of Ohio Shale of Ohio
MIDDLE HURON	Middle Part of Huron Member of Ohio Shale of Ohio
LOWER HURON	Lower Part of Huron Member of Ohio Shale of Ohio

Figure 4 Stratigraphic Units included in study.

Figure 5 Structure on Top of the Ohio Shale (after Provo, 1977).

Figure 6 Structural-stratigraphic section B-B' through the center of the field, southwest to northeast.

CROSS SECTION E'-E **EASTERN KENTUCKY** **GAS FIELD**

J. Negus de Wys May, 1978

Figure 7 Structural-stratigraphic section E'-E through the southwest end of the field, north to south.

Figure 8 Structural-stratigraphic section K'-K through the northeastern part of the field, north to south.

Figure 9 Isolines of data from Hunter (1935) of quartz by county.

Figure 11 Isolines of data from Hunter (1935) of kerogen by county.

Figure 13 Isolines of Estimated Ultimate Recovery/well (Hunter, 1935) by county.

SIMPLE STATISTICS FOR CHEMICAL ELEMENTS

Variable	Weight Percent oxide (except Sulfur)			Variance	Coefficient of Variance
	Minimum	Maximum	Mean		
MN	0.016	0.500	0.051	0.001	66.789
FE	3.590	20.150	8.519	2.679	19.214
S	0.051	8.258	2.364	0.907	40.272
ZN	0.001	0.106	0.013	0.000	72.342
SR	0.000	0.064	0.004	0.000	109.953
NA	0.149	0.730	0.661	0.004	9.660
MG	0.733	4.157	1.428	0.171	29.007
AL	6.000	18.120	14.206	3.333	12.851
SI	48.000	78.300	55.103	7.912	5.105
P	0.102	0.962	0.138	0.009	70.618
K	0.401	8.460	3.354	0.438	19.720
CA	0.155	32.985	1.252	12.565	283.140
TI	0.230	1.160	0.931	0.020	15.043
SI/Al RATIO	2.829	12.102	3.982	0.776	22.113

Figure 15 Table of Simple Statistics for Elements and Ratio Si/Al analyzed.

EASTERN KENTUCKY GAS FIELD

Graph Comparison of Si and Al versus depth

J. Negus de Wys

June, 1979

Figure 16 Comparison of graphs of %Al oxide and %Si oxide. Wells are arranged west to east from left to right.

EASTERN KENTUCKY GAS FIELD SOUTHWEST-NORTHEAST CROSS SECTION A-A' OF Si/Al RATIO

J. Negus de Wys June, 1979

Figure 18 Southwest-northeast cross section A-A' through the field with Si/Al oxide ratio graphs. Compare with Figure 6.

EASTERN KENTUCKY GAS FIELD SOUTHWEST-NORTHEAST CROSS SECTION B-B' OF Si/Al RATIO

J. Negus de Wys June, 1979

Figure 19 Cross sections of %Si/Al oxide ratio southwest-northeast B-B'. Compare with Figure 6.

LEGEND for Si/Al RATIO CROSS SECTIONS

- ↓
WELL LOCATION on CROSS SECTION
- B/B TOP of BEREA/BEDFORD
 - O/C OHIO SHALE/TOP of CLEVELAND
 - 3L TOP of THREE LICK
 - UH TOP of UPPER HURON
 - MH TOP of MIDDLE HURON
 - LH TOP of LOWER HURON
 - HB BOTTOM of HURON
 - >4.0 Si/Al OXIDE RATIO
 - STUDY WELLS
 - CORED WELLS

CROSS SECTION C-C' OF
Si/Al RATIO

J. Negus de Wys June, 1979

CROSS SECTION D-D' OF
Si/Al RATIO

J. Negus de Wys June, 1979

Figure 20 Cross section of %Si/Al oxide ratios northwest-southeast C-C' and D-D'. Compare with Figure 8.

PERCENTAGE OF Si OXIDE FOR THE THREE LICK UNIT

1
N

Figure 21. Computer-drawn map for %Si oxide for the Three Lick unit. Highest concentration are the darkest (center and southwest) with second highest to the north-northwest and east central. Lowest areas of concentration are the lightest (west central, northeast, and south central).

* All elements in oxides except Sulfur

Chart of COMPUTER DRAWN MAPS Eastern Kentucky Gas Field

Figure 22

J. Negus deWys

July, 1979

Computer-drawn maps for Si/Al oxide ratio, Al oxide, Si oxide, Sulfur, Mg oxide, K oxide, Fe oxide, and Ca oxide arranged in a table with stratigraphic units and sequences represented.

Figure 23 Computer-drawn maps for Si/Al oxide ratio for stratigraphic units. Left, top to bottom: B/B, C, 3L; center, top to bottom: UH, MH, LH; and right, top to center: total sequence and Ohio Shale. Darkest is highest value, lightest is lowest value.

SIMPLE STATISTICS FOR MINERAL DATA

VARIABLE	Percent Total Integrated Intensity*			Variance	Coefficient of Variance
	Minimum	Maximum	Mean		
ILLITE	0.0	91.4	52.3	189.2	26.308
CHLORITE	0.0	1.9	0.7	0.1	50.586
QUARTZ	4.0	83.3	33.7	119.6	31.085
KAOLINITE	0.0	13.0	0.5	3.2	374.000
SZOMOLNOKITE	0.0	2.2	0.0	0.1	664.617
CALCITE	0.0	68.9	1.3	42.9	522.579
ORTHOCLASE	0.0	2.0	0.0	0.0	469.630
ANHYDRITE	0.0	1.1	0.1	0.1	277.298
PLAGIOCLASE	0.0	2.7	0.9	0.2	42.371
BASSANITE	0.0	4.0	1.9	0.5	36.698
DOLOMITE	0.0	70.5	1.7	67.1	475.066
SIDERITE	0.0	17.5	2.2	2.6	72.945
PYRITE	0.0	13.1	4.8	15.6	49.622
RATIO 1	0.0	100.0	1.3	42.8	515.179
RATIO 2				717.6	34.045
RATIO 3	0.0	100.0	78.7	585.3	267.249
RATIO 4	0.0	100.0	9.1		
RATIO 5					

*May be considered numerically equivalent to weight percent

Figure 24 Table of Simple Statistics for Minerals and Mineral Ratios analyzed.

CHEMICAL FORMULAS FOR MINERALS

ILLITE	$(\text{H}_3\text{O}, \text{K})_y (\text{Al}_4 \cdot \text{Fe}_4 \cdot \text{Mg}_6) (\text{Si}_8 - \text{Al}_y) \text{O}_{20}(\text{OH})_4$ where $y < 2$, usually $y = 1-1.5$
CHLORITE	$(\text{Mg}, \text{Fe}^{+2}, \text{Fe}^{+3})_6 \text{AlSi}_3\text{O}_{10}(\text{OH})_8$
QUARTZ	SiO_2
KAOLINITE	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$
SZOMOLNOKITE	$\text{FeSO}_4 \cdot \text{H}_2\text{O}$
CALCITE	CaCO_3
ORTHOCLASE	KAlSi_3O_8
ANHYDRITE	CaSO_4
PLAGIOCLASE	$(\text{Na}, \text{Ca})\text{Al}(\text{Si}, \text{Al})\text{Si}_2\text{O}_8$
BASSANITE	$\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$
DOLOMITE	$\text{CaMg}(\text{CO}_3)_2$
SIDERITE	FeCO_3
PYRITE	FeS_2

Figure 25 Chemical formulas for minerals analyzed.

RATIO DEFINITIONS

RATIO 1	$\frac{\text{KAOLINITE}}{\text{KAOLINITE} + \text{ILLITE}}$
RATIO 2	$\frac{\text{QUARTZ}}{\text{QUARTZ} + \text{KAOLINITE} + \text{ILLITE} + \text{CHLORITE}}$
RATIO 3	$\frac{\text{SIDERITE}}{\text{CALCITE} + \text{DOLOMITE} + \text{SIDERITE}}$
RATIO 4	$\frac{\text{CALCITE}}{\text{CALCITE} + \text{DOLOMITE}}$
RATIO 5	$\frac{\text{CHLORITE}}{\text{CHLORITE} + \text{KAOLINITE}}$

Figure 26 Ratio definitions.

RATIO	ENVIRONMENT	RATIO MEANING
1. $\frac{Ka}{Ka + III}$	>Ka = fresh water >III = marine or alkaline influence	>Ratio - fresher water <Ratio marine alkaline
2. $\frac{Q}{Q + Ka + III + ChI}$	>Q = clastic source	>Q >Ratio >Ratio - closer to clastic source
3. $\frac{Sid}{CaI + DoI + Sid}$	>Sid = fresh water	>Ratio - fresher water
4. $\frac{CaI}{CaI + DoI}$	>DoI = near shore evaporative environment	<Ratio - near shore evaporative environment
5. $\frac{ChI}{ChI + Ka}$	ChI = marine indicator	>Ratio - more marine

Figure 27 Interpretation of Ratios.

Figure 28 Computer-drawn map of Ratio 1.

Figure 29. Computer-drawn map of Ratio 2.

Figure 30. Computer-drawn map of Ratio 3.

Figure 31 Computer-drawn map of Ratio 4.

RATIO 5

Figure 32 Computer-drawn map of Ratio 5.

Figure 33

COMPOSITE INTREPRETIVE MAP OF RELATIVE ENVIRONMENTS

Figure 34

Figure 35 Final Open Flow Data points.

Figure 36 Hand-contoured map of Final Open Flow based on ~4750 points.


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C123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789
40.16 22 111 00000 5555555 8888888 7777777 777777 888 99 0 1 2 45 34 7 02 46
39.54 1 00 555 7777777 7777777 8888888 888 99 0 1 2 45 34 7 02 46
28.92 99 158 777777 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
35.29 88 777 8888888 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
37.67 77 666 555555 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
37.25 66 555 4444444 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
36.43 6 55 444 3333333 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
35.80 5 44 33333 2222222 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
35.18 5 44 33 2222222 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
24.56 44 33 22222 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
33.94 4 33 2222 111 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
33.31 44 33 222 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
32.69 4 3 222 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
32.07 4 3 22 111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
31.45 4 3 22 11111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
30.83 4 3 22 11111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
30.20 4 3 22 11111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
29.58 4 3 22 11111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
28.96 5 4 33 22 11111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
28.34 5 4 3 22 11111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
27.71 5 4 3 22 11111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
27.09 65 44 3 22 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
26.47 6 5 4 33 22 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
25.85 6 44 3 22 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
25.22 76 5 4 33 22 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
24.60 7 6 44 3 22 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
23.98 76 5 4 3 22 1111111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
23.36 87 65 4 33 22 1111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
22.73 2 6 54 3 22 1111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
22.11 76 5 4 3 22 111 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
21.49 587 5 4 3 22 11 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
20.87 58 65 4 3 22 11 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
20.25 76 4 3 2 11 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
19.62 576 4 3 2 11 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
19.00 55676 4 3 2 1 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
18.38 55676 4 2 11 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
17.76 87 43 2 1 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
17.13 7 3 1 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
16.51 1 32 1 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
15.89 1 65 21 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
15.27 1 65 1 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
14.64 10 65432 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
14.02 0 7654321 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
13.40 0 765 10 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
12.78 0 76 10 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
12.16 0 7 3210 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
11.53 20 7 321 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
10.91 20 7 43 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
10.29 2 7 4 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
9.67 7 4 10 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
9.04 7 1 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
8.42 3197 2 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
7.80 3197 2 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
7.18 197 2 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
6.55 4 2 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
5.93 42 20 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
5.31 20 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
4.69 3 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
4.06 6 1 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
3.44 4 97 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
2.82 520 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
2.20 3 8 8888888 8888888 8888888 888 99 0 1 2 45 34 7 02 46
C123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789

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TREND SURFACE ANALYSIS, 4th order polynomial. Contour level = 0.05 MMcf/day,
contour increment = 0.05 MMcf/day.

Key

etc }
3 }
2 } >.05
1 } increasing
.
datum .05
A }
B } <.05
C } decreasing
etc }

Figure 37 Trend Surface Analysis (4th order polynomial) of ~4000 Final Open Flow data points.

Contours of High Volume Wells
Based on ~5000 Wells
(after Griffith, 1976)

J. Negus deWys
March, 1979

Figure 38 Isolines of density of high producing wells: left - >0.5 MMcf/day/25 square miles, and right - >1 MMcf/day/25 square miles (after Griffith, 1976).

Si/Al

(GRIFFITH, 1976-77)

0.5/25 sq. mi.

CONTOUR OF HIGH VOLUME WELLS

Figure 39 Comparison of Si/Al oxide ratio map with density of high producing wells.

LITHOLOGY STUDIES OF UPPER DEVONIAN WELL CUTTINGS

IN THE EASTERN KENTUCKY GAS FIELD

by

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Department of Geology and Geography

October 1979

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Well cuttings from 14 wells in the Eastern Kentucky Gas Field are studied under reflected light. A comparison of lithology changes across the field and between stratigraphic units is presented.

Fracture indicators are contoured and related to density of high producing wells and other lithologic characteristics. Statistical methods show highly significant correlation between fracture counts and high producing well contours. A table of correlation coefficients is presented for lithologic data and production.

The value of such a field study approach, in more detail, is emphasized for future exploration and evaluation in the production of gas from Upper Devonian Shales in this area.

INTRODUCTION

This study of well cuttings from fourteen wells in the Eastern Kentucky Gas Field is part of a more comprehensive study comparing final open flow values from approximately 4750 wells with geological parameters including structural position on the top of the Ohio Shale, the Ohio Shale thickness, stratigraphy, geochemistry, and fracture data.

Historically, studies of the Eastern Kentucky Gas Field and cross sections through the area have been achieved by using wireline logs, usually formation density logs, in which natural resistivity could be related to the stratigraphic units. Drillers' logs have been used to supplement the existing information, as well as cores from Martin and Perry Counties and more recently one is available from Johnson County. (Provo, 1977; Schwietering, 1977; Wilson, 1977; Negus-de Wys and Shumaker, 1978). The lithology of the main part of the field, however, has remained an interpretation mainly from the wireline logs. Coleman Hunter (1935) studied 700 thin sections from 86 wells, but only general averages by county are reported in his writings on the study. The 700 thin sections are presently under restudy by the present author.

Recently Swager (1978) related radioactivity, biostratigraphy and lithology of the Ohio Shale sequence along the outcrop belt west of the Eastern Kentucky Field and in the Pine Mountain thrust area. Most of his sites were examined by the present author.

The purpose of this study is to look at lithologic changes across the field and relate such changes to other geological aspects as well as final open flow data, in order to better understand the occurrence and production of gas in the Upper Devonian rocks in the field.

The setting of the Eastern Kentucky Gas Field is shown in Figure 1 (after Negus-de Wys and Shumaker, 1978). The Cincinnati arch is situated to the northwest, the Pine Mountain Thrust to the southeast. The Rome Trough extends in an east-northeasterly direction across the northern section of the field with the asymmetrical graben deepening to the east.

Another basement feature, the Floyd County Channel, extends northward through the center of the field (Figure 2, after Ammerman and Keller, 1978) and is interpreted by some as an aborted graben joining the Rome Trough. The Perry County Uplift and Pike County Uplift are situated west and east, respectively, of the Floyd County Channel.

The Paint Creek Uplift with a north-south trend extends into the center of high production from the north and probably was developing through Mississippian and Pennsylvanian time (McFarlan, 1943).

The stratigraphic sequence involved in the study is Berea-Bedford through Lower Huron. (See Figure 3). The Berea-Bedford is treated as a single unit because of the difficulty in ascertaining the separate units in the southwestern area where both units are shaley. Incomplete samples hampered interpretation of the Berea in the eastern part of the field.

DATA

Locations of the fourteen study wells are shown in Figure 4. Well cuttings in the central portion of the field were extremely difficult to locate. Frequently wells penetrate high pressure zones which blow the cuttings out of the well (Hager, 1978). Other stored well cuttings were lost in warehouse flooding. Most cuttings are from cable tool drilling; one is from rotary drilling.

Well cuttings were examined wet using a binocular microscope with 10 x and 30 x magnification. The Mudrock terminology of Folk (1974) was used. See Figure 5. Early in the study it became apparent that the Ohio Shale sequence was predominantly very silty silt-shale in some wells, although this sequence has usually been referred to as "brown shales."

constructing cross sections it was deemed advisable to relate logs to the base of the Huron because of difficulties in correlation, higher in the stratigraphic sequence.

Cross sections A-A', B-B', C-C', and D-D' are shown in Figures 6, 7, 8, and 9. Section A-A' (Figure 6), from southwest to northeast, shows the thickening section to the east. The Berea is 100% shale in the southwest grading into a siltstone with some sand grains in the east and northeast. Some dolomitic cementation is observed in the siltstone. Williamson (1974) interpreted the Berea in West Virginia as a channel sand adjacent to Eastern Kentucky oriented approximately north-south, with proximal bar and distal bar facies farther east. In the Eastern Kentucky Field the Berea is of nearly uniform thickness over the entire area, but does show changing lithology. It resembles more a beach sand in the changing lithology and even thickness.

The Cleveland is a black to dark brown, at times greasy looking, highly organic siltstone in the southwest. It grades into a browner silt-shale and then to brown mud-shale in the east and inter-tongues increasingly with gray clay-shale and mud-shale in the eastern part of the field.

The Three Lick is designated as the upper banded shale by Swager (1978) at the outcrop. This banding of green and gray and brown shale is also apparent in the well cuttings. In some wells, siltier zones are apparent.

The Upper Huron is usually a brown, highly organic mud-shale, and is the lower black shale unit of Swager. The Middle Huron is less organic, siltier, and frequently shows interbedding of gray or green with black shale. The Lower Huron is very highly organic, black to dark brown mud-shale and may show some interbedding. It breaks into blocky rather than platy fragments. In the outcrop it also appeared blockier and less fissile than the Cleveland or other Huron units.

For comparison with the lithological cross sections, similar sections using logs may be compared (Figures 10, 11, and 12) as well as the structural-stratigraphic sections (Figures 13, 14, 15, and 16). These are not identical cross sections, since logs are not available on most of the wells from which well cuttings were used.

In cross section A-A' (Figure 6) the center well appears to be lacking part of the Lower Huron and shows a milky white chert and limestone unit. This is probably Huntersville Chert (Hager, 1978). The chert continues for approximately 75+ feet with a tan-gray sandy, fossiliferous limestone and dark brown sucrose dolomite. Stylolites occur in the limestone. The Boyle cherty limestone observed in some outcrops below the Ohio shale appears similar to the cherty well cuttings. The relationship of the Boyle and Huntersville would appear to be a pertinent problem. This center well shows indications of fracture at 29 different horizons. A normal fault with about 100 feet displacement may cut the well in the Huron, eliminating the lowest part of the Huron and bringing the Huntersville Chert in higher in the section. Such a fault on the side of the Floyd County Channel would not be unreasonable.

Cross section B-B' (Figure 7) north-south through the center of the field shows the thickening of the section to the south. Redbeds occur in the northern two wells, but not in the southern where the sections show more silt. The southern sections also may represent faulted sections. Protosalvinia occurs near the top of the southernmost section (not found in such a horizon in other wells) and repetition appears in the Knott County well suggesting thrust faulting. This is not unreasonable as the Pine Mountain Thrust area is approached.

Fracture indicators include: slickensides, open fractures, filled fractures, fracture sides, and spar. Stylolites occur in the limestone unit in the bottom of the central well with the Huntersville Chert.

Frequency of fractures was contoured (Figure 17) with results showing strong similarities to contours of densities of high producing wells (Figures 18 and 19, after Griffith, 1976).

Figure 20 shows histograms of observed fractures versus lithotypes, stratigraphic units, structure on top of Ohio Shale, and thickness of total shale. The highest degree of correlation is seen in mud-shale lithology, the Middle Huron unit, -1000 to -1250' (below sea level) on Ohio Shale structure, and a thickness of 500 to 600 feet.

Maps of relative percentage of gray, brown, and green shale in the total Ohio Shale sequence studied (Cleveland-Huron) are shown in Figures 21, 22, and 23. The isopach of black shale is shown in Figure 24 in which a striking resemblance is seen to the trends of the density of high producing wells $\leq .5$ MMcf/day/25 sq. miles. This is also similar to the configuration shown by Harris, deWitt, and Colton, (1978). For comparison with the black shale isopach, the total shale isopach is shown in Figure 25.

Percent shale of total Ohio sequence is shown in Figure 26, which may be compared to percent of silt and sand in Figure 27. Higher silt/sand areas occur in the northeastern section of the field and a patch southwest of field center. If the silt/sand percentage is contrasted, Figure 28 results, showing finer grained clastics to the southwest and coarser material to the northeast. Percent carbonate is shown in Figure 29. It shows a marked similarity to structure on top of the Coniferous (McFarlan, 1943). Percent redbeds of total sequence are shown in Figure 31. An area trending northeast-southwest shows occurrence of redbeds with the highest values to the northeast. This suggests a positive area during late Upper Devonian or preferential currents depositing detrital fragments from higher on the delta.

The results of very scanty data on the Berea-Bedford show the unit to be 100% shale in the southwest, and if the trend is extrapolated, the 50:50 shale:sandstone contour would run through the heart of the gas field. The thickness remains fairly constant over the field. The 1946 isopach map of the Berea-Bedford by Pepper, Demarest, Merrels, and deWitt show the sand in a highly complicated patchy thinning and thickening in the Floyd County area. The 0 isopach would represent 100% shaley facies. The thins are suggestive of small scale doming and basins on the nose of the Paint Creek Uplift. (Figure 32).

STATISTICAL RELATIONSHIPS

Using a stepwise regression procedure for dependent variables D1 (density of high producing wells $>.5$ MMcf/day/25 sq. miles) and D2 (>1 MMcf/day/25 sq. miles) and independent variables: fractures, structure, shale thickness, percent ss/siltstone in total sequence, carbonate %, green shale %, redbeds, black shale thickness, brown shale %, and gray shale %, the following relationships were observed:

1. D1 was best explained by fractures: $R^2 = 83\%$
 Adding redbed occurrence: $R^2 = 92\%$
 No other variables met the 0.5000 significance level for entry into the model.
2. D2 was best explained by fractures: $R^2 = 64\%$
 Adding Brown shale % of total sequence: $R^2 = 92\%$
 Adding structural position: $R^2 = 96\%$
 No other variables met the 5% significance level for entry into the model.
3. A Table of Correlation Coefficients is shown in Figure 33. Significant relationships are boxed.

PALEOENVIRONMENT

Various deep and shallow water environments have been suggested for the Ohio Black and Brown Shales. After studying outcrop sections and well cuttings, the present author suggests the following criteria could collectively indicate shallow water, but which singly would not necessarily rule out deeper water:

1. occurrence of vitrinite
2. dolomite occurrence suggesting supratidal replacement (present day analogue: Coast of Georgia)
3. Lingula and Orbiculoidea
 . Soil horizon top of the Boyle at outcrop
5. Possible channel in shale at outcrop in Estill County, Kentucky
6. Algae (Protosalvinia)
7. Redbeds

8. anhydrite
9. thinning toward basin edge.

CONCLUSIONS

The samples studied indicate a shaley Berea-Bedford unit in the southwest of the field with increasing silt and some sand to the east. The thickness appears fairly uniform.

2. The Ohio Shale shows a high shale content in the southwest with increasing silt and sand to the northeast with one high area to the southwest of the field center. The clastic grain size increases to the northeast.
3. A higher carbonate zone trends northeast-southwest with an enlarged high to the southwest. Red-bed occurrence follows the same trend. This may represent a higher area during upper Ohio Shale deposition time, or a preferential current area bringing in detrital redbed fragments. This area also correlates with the thickest area of the Corniferous.
4. Fractures appear to be most strongly related to:
 - a) mudshale lithology,
 - b) Middle Huron stratigraphic unit,
 - c) 500-600 foot thickness of total shale, and
 - d) -1000 to -1250 (below S.L.) structural elevation of top of Ohio Shale.

Figure 34 shows the outline of the resulting area which may be compared with contours of high density of high producing wells.

5. The higher fractured well in Floyd County may penetrate a normal fault of approximately 100 feet on the west side of the Floyd County Channel. The Ohio Shale is approximately 100-150 feet short. The Huntersville Chert appears to underlie the section.
6. The Knott County well may have penetrated a shallow thrust fault.
7. Positive identification of all Ohio shale units in cuttings is not feasible without other information. More studies of lithology, biostratigraphy, and radioactivity are needed in subsurface (similar to Swager's outcrop studies) to better understand the stratigraphy of the Eastern Kentucky field.

ACKNOWLEDGMENTS

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STATISTICAL ANALYSIS SYSTEM

CORRELATION COEFFICIENTS / PROB |R| UNDER HO:RHO=0 / NUMBER OF OBSERVATIONS

	D1	D2	F	STRU	THICK	SS,SLT	CO ₃	GREEN	SH	R	BLK	BR	GRN
D 1	1.00000 0.00000	0.94827 0.0039 6	0.91249 0.0041 7	-0.37394 0.4086 7	-0.03624 0.9185 7	-0.09827 0.8340 7	0.09781 0.8148 7	0.09554 0.8185 7	0.09467 0.8400 7	0.19476 0.6756 7	0.47123 0.2858 7	-0.28196 0.5401 7	0.02922 0.9504 7
D 2	1.00000 0.00000	0.97668 0.0573 6	-0.12742 0.8094 6	0.21758 0.6788 6	-0.19347 0.7134 6	0.00000 1.0000 6	0.32981 0.5232 6	0.18328 0.7282 6	0.10227 0.8471 6	0.50728 0.3044 6	-0.51729 0.2933 6	-0.08869 0.8833 6	
F	1.00000 0.00000	0.62074 0.1364 7	0.01577 0.9731 7	-0.02853 0.9516 7	0.17582 0.7061 7	-0.04941 0.9162 7	0.03114 0.9471 7	0.48467 0.2658 7	0.27429 0.5517 7	-0.04281 0.9274 7	0.04818 0.9183 7		
STRU	1.00000 0.00000	0.01637 0.9722 7	-0.02146 0.9629 7	-0.08652 0.8537 7	0.03065 0.9480 7	0.01057 0.9421 7	-0.41219 0.3581 7	-0.20786 0.6550 7	-0.19755 0.6711 7	-0.23692 0.6090 7			
THICK	1.00000 0.00000	-0.08801 0.8512 7	-0.07028 0.8810 7	0.80387 0.0293 7	0.08133 0.8624 7	0.36356 0.4228 7	0.00703 0.9881 7	-0.60940 0.1463 7	-0.28995 0.5282 7				
SS,SLT	D 1 DENSITY of HIGH PRODUCING WELLS .5 MMcf/DAY/25 sq. mi.	1.00000 0.00000	0.97501 0.0002 7	-0.26922 0.5593 7	-0.99982 0.0001 7	0.02919 0.9505 7	-0.72244 0.0667 7	-0.15200 0.7449 7	0.79581 0.0323 7				
CO ₃	D 2 DENSITY of HIGH PRODUCING WELLS 1 MMcf/DAY/25 sq. mi.	1.00000 0.00000	-0.28395 0.5371 7	-0.97481 0.0002 7	0.15248 0.7441 7	-0.68439 0.0899 7	-0.16235 0.7280 7	0.75147 0.0515 7					
GREEN	F FRACTURES STRUCTURE on OHIO SHALE	1.00000 0.00000	0.25832 0.5755 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5849 7						
SH	THICK THICKNESS of TOTAL SHALE SEQUENCE	1.00000 0.00000	-0.01470 0.9683 7	0.71640 0.0701 7	0.16776 0.7192 7	0.79714 0.0318 7							
R	SS,SLT PERCENTAGE of SANDSTONE and SILT of TOTAL SEQUENCE	1.00000 0.00000	-0.37963 0.4009 7	0.26670 0.5632 7	-0.36631 0.4198 7								
BLK	CO ₃ PERCENTAGE of CARBONATE of TOTAL SEQUENCE	1.00000 0.00000	-0.28238 0.5395 7	-0.26567 0.5647 7									
BR	GREEN PERCENTAGE of GREEN SHALE of TOTAL SEQUENCE	1.00000 0.00000	-0.15812 0.7349 7										
GRN	R PERCENTAGE of SHALE of TOTAL SEQUENCE	1.00000 0.00000											
	BLK THICKNESS of BLACK SHALE in TOTAL SEQUENCE	1.00000 0.00000											
	BR PERCENTAGE of BROWN SHALE of TOTAL SEQUENCE	1.00000 0.00000											
	GRN PERCENTAGE of GREEN SHALE of TOTAL SEQUENCE	1.00000 0.00000											

5% SIGNIFICANCE LEVEL

Figure 2. Basement Structure from Bouguer Gravity Map (same as Figure 3 in Negus-de Wys and Renton, "Inorganic Geochemistry Studies in Eastern Kentucky Gas Field.")

STRATIGRAPHIC SEQUENCE

BEREA/BEDFORD	Berea Sandstone and Bedford Shale, undivided
CLEVELAND	Cleveland Member of Ohio Shale of Ohio
THREE LICK	Three Lick Bed of Provo, Kepferle, and Potter, 1977
UPPER HURON	Upper Part of Huron Member of Ohio Shale of Ohio
MIDDLE HURON	Middle Part of Huron Member of Ohio Shale of Ohio
LOWER HURON	Lower Part of Huron Member of Ohio Shale of Ohio

Figure 3 Stratigraphic units included in study (same as Figure 4 in Negus-de Wys and Renton, "Inorganic Geochemistry Studies in Eastern Kentucky Gas Field.")

Figure 4 Well locations (large dots) of wells from which cuttings were studied. (Same as Figure 14 in Negus-de Wys and Renton, "Inorganic Geochemistry Studies in Eastern Kentucky Gas Field.")

PETROLOGY OF MUDROCKS (Folk, 1974)

Mudrock (word coined by Ingram) is a general term used herein to cover those terrigenous rocks that contain more than 50 per cent silt and/or clay. The most obvious division of mudrocks is on the basis of texture and structure:

<u>Grain size of mud fraction</u>	<u>Soft</u>	<u>Indurated, non-fissile</u>	<u>Indurated, fissile</u>
Over 2/3 silt	silt	siltstone	silt-shale
subequal silt and clay	mud	mudstone	mud-shale
over 2/3 clay	clay	claystone	clay-shale

Figure 5 Mudrock Terminology from Folk.

Figure 8. Lithological Cross-section C-C', southwestern section of the field, northwest-southeast.

Figure 10. Cross-section B-B', showing formation density logs.

Figure 11. Cross-section E'-E, showing formation density logs.

Figure 12. Cross-section K'-K, showing formation density logs.

Figure 13. Structural-stratigraphic cross-section B-B' through the center of the field, southwest-northeast. (Same as Figure 6 in Negus-de Wys and Renton, "Inorganic Geochemistry Studies in Eastern Kentucky Gas Field.")

Figure 14. Structural-stratigraphic cross-section E'-E through the southwest end of the field, north to south. (Same as Figure 7 in Negus-de Wys and Renton, "Inorganic Geochemistry Studies in Eastern Kentucky Gas Field.")

Figure 15. Structural-stratigraphic section H'-J through the center of the field, northwest to southeast.

Figure 16 Structural-stratigraphic section K'-K through the northeastern part of the field, north to south. (Same as Figure 8 in Negus-de Wys and Renton.)

Figure 17 Iso-value lines of fracture frequencies in wells.

Contours of High Volume Wells
Based on ~4750 Wells
(after Griffith, 1976)

Figure 18A. Iso-value lines of density of wells with final open flow > 0.5 MMcf/day/25 square miles (after Griffith, 1977).

J. Negus deWys
March, 1979

Figure 18B. Iso-value lines of density of wells with final open flow > 1 MMcf/day/25 square miles (after Griffith, 1977).

Figure 19. Histograms of Observed Fractures vs A) Lithotypes B) Stratigraphic Unit C) Structure on Ohio Shale, and D) Thickness of Total Shale.

Figure 20 Iso-value lines of % gray clay-mud shale of total shale sequence.

Figure 21 Iso-value lines of % organic brown silty mud shale of total shale sequence.

Figure 22 Iso-value lines of % green clay shale of total shale sequence.

Figure 23 Isopach of highly organic black mud shale (in feet).

Isopachs of Total Ohio Shale

deWys, 1979

Figure 24. Ohio Shale Isopach Map (after Provo, 1977).

Figure 32 Isopach of Berea-Bedford.

OPTIMUM CONDITIONS

- 1) a) FRACTURE CONTOUR: 30/WELL
b) SHALE THICKNESS: 500-600 FEET (TOTAL)
c) STRUCTURE: -1000 to -1250 on OHIO SHALE
- 2) a) FRACTURES: 10 to 30/ WELL
b) THICKNESS: 500 to 600 FEET
c) STRUCTURE: -1000 to -1250 FEET
- 3) a) FRACTURES: 10/ WELL
b) THICKNESS: 300 to 600+ FEET
c) STRUCTURE: -1000 to -1250 FEET

Figure 33. Comparison of Optimum Total Shale Thickness, Fracture Occurrence, Structural Position on Top of Ohio Shale with Density of Wells > 1 MMcf/Day /25 sq. mi. (Differences noted in non-producing matching lobes of high wells density contour)

POSSIBLE EFFECTS OF PLATE TECTONICS ON
THE APPALACHIAN DEVONIAN BLACK SHALE PRODUCTION IN EASTERN KENTUCKY

by

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October 1979

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POSSIBLE EFFECTS OF PLATE TECTONICS ON
THE APPALACHIAN DEVONIAN BLACK SHALE PRODUCTION IN EASTERN KENTUCKY

by

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ABSTRACT

The sequential development of structural features in the Eastern Kentucky Gas Field is examined in terms of trends and relationships to plate rifting and collision. The trends are compared with open flow gas data.

Three major structural trend directions are apparent from Precambrian time through late Paleozoic plate collision: 1) north-south, 2) northeast-southwest, and 3) east-west. The east-west direction appears to have the highest degree of correlation with gas data, although the field trend is northeast-southwest, and appears to be related to the Paint Creek Uplift.

The field lies in the changing stress field elbow of the collision axes, running northeast-southwest in the more northern part of the Appalachians and changing to a more east-westerly trend south of this point. The interaction of these stress directions on the sediments, buttressed against the Paint Creek Uplift may be a significant factor in the resulting suspected fault patterns, which in turn drain gas from fracture facies in the Ohio shale and where fractures intersect silty zones in the shale.

INTRODUCTION

As a dynamic solution for observed stratigraphic and structural relationships, plate tectonics is in its infancy. The serious objections raised by the Meyerhoffs, Smiley, Boucot, Teichert, Jeffrys, and Dillon in the 1974 AAPG Symposium and subsequent volume, to name but a few, have not been adequately answered nor put to rest. The misfit of paleomagnetic data which would align the continental plates quite differently according to the Upper Paleozoic Equator, has not appeared to deter continuing use of the basic Bullard reconstruction (Figure 1, after Bullard, 1965). If reconstruction of the continental plates in Permian time were to be guided by the data mentioned, a configuration such as Figure 2 could result.

To paleomagnetism, paleoclimatic interpretations, as well as paleontologic and stratigraphic evidence are attributed the bases for the energetic Scotese (1975 and later) map sequences. Nonetheless, these very data are used to refute such movements. Dillon (1974) finds the present position of continents quite compatible with most of the evidence, with no substantial plate movements necessary, while Boucot (1974) finds almost as much evidence for an original super-continent as against one (Figure 3).

However, evidence is amassing for plate tectonic activity and active forces from the east and southeast throughout Paleozoic times (Proceedings, Caledonide Symposium, 1979). Whether or not one embraces extremes of gravity tectonics and thin skinned dynamics of movement (Rogers 1971), the evidence of highlands being eroded and deposited, of volcanics and metamorphism, of fault zones, grabens, and thrusts cannot be refuted. The co-corp

data and interpretation by Harris (1979) at the recent Caledonide Symposium suggest a thrust sheet in the southern Appalachians with possibly no roots. Hatcher (1979) prefers to root the orogeny in the King's Mountain area. The data as yet is scanty and obviously controversial. According to Dickinson (1974) plate tectonics theory offers a more comprehensive explanation of mountain belts than any previous theory. With a realization of this backdrop of confusion, a brief and general recap of some of the evidence is presented in the framework of plate tectonics with specific application to the Upper Devonian gas-producing black shales of eastern Kentucky.

Sloss and Speed (1974) investigate relationships between cratonic sedimentation and continental margin tectonism. They suggest that emergent, oscillatory, and submergent cratonic modes are globally controlled by specific types of continental margin tectonism, which are noted to occur simultaneously on several cratons. Thus, in a general way cratonic deposits such as the Ohio shale can be related to plate tectonics (Provo 1977).

In Rogers' (1971) review of global folded mountain chains he notes that "in nearly every case (he) cites, the folded belt in question is composed of a wedge of miogeosynclinal sediments and facies (and verges asymmetrically towards) an older platform or shield, but is backed by a more complicated orogenic core belt, commonly containing metamorphic rocks of the same age as the unmetamorphosed strata in the folded belt. (On the other hand, contemporaneous deformation on the platform, if any, is basement tectonics, as . . . throughout the mid-continent region and as far east as eastern Kentucky)." Rogers looks for the prime motive power for

both uplift and folding in "true lateral compression within the crust, . . . at or near the margin of crustal plates that have been jammed together beside or over down-going slabs of lower crust and mantle."

Cooper (1964), after reviewing 17 Appalachian structures, concludes that there is overwhelming evidence from the strata of subtle tectonic local control of the stratigraphy by structural elements.

Schwab (1971) emphasizes that contrasts in Appalachian sediment composition, texture, dispersal, provenance, thickness, and depositional environment primarily reflect an evolving tectonic framework. He suggests that plate tectonics and sea-floor spreading may provide partial explanation for abrupt removal of eastern source areas and an appreciable expeir-ogenic downwarping of the cratonic margin, i.e., the Chilhowee Group of Lower Cambrian age.

Figure 1. Reconstruction of continental plates during Permian time (Bullard 1965 in Dillon 1974) showing non-matching Permian paleomagnetic latitudes and equator.

Figure 2. A possible reconstruction of plates in Permian time, matching the paleomagnetic equators.

CIRCUM-ATLANTIC CORRELATIONS - EVIDENCE FOR ORIGINAL SUPER-CONTINENT

PERIOD	STRUCTURE	STRATIGRAPHY AND LITHOFACIES	BIOGEOGRAPHY	COMMUNITY
DEVONIAN	NORTHERN HEMISPHERE NEUTRAL	NEGATIVE	NEUTRAL	NEUTRAL
	SOUTHERN HEMISPHERE POSITIVE			
SILURIAN	POSITIVE	NEGATIVE TO NEUTRAL	NEUTRAL	NEUTRAL
ORDOVICIAN	NEGATIVE	NEGATIVE	NEUTRAL	_____
CAMBRIAN	POSITIVE	NEGATIVE	NEUTRAL	_____
SUM	POSITIVE	NEGATIVE	NEUTRAL	NEUTRAL

BOUCOT, 1974

Figure 3. Table of evidence for and against an original super continent (Boucot 1974).

(AFTER MUEHLBERGER, ET AL, 1967)

Figure 4. Orogenic trend lines and ages of geologic provinces (Muehlberger 1967) related to position of study area.

(COLTON 1970)

J. Negus-de Wys 1979

Figure 5. Precambrian basement floor in the Appalachian area (Colton 1970) with position of highest aeromagnetic anomaly and New York-Alabama lineament (King and Zietz 1978 and Zietz 1979); boundary between Grenville metamorphics on the east and unmetamorphosed massive volcanics on the west (Bass 1960); upper Paleozoic hinge line (Arkle 1971); east continental gravity high (ECGH); Rome Trough and study area. The basement contours are in thousands of feet.

Figure 6. A section of the Bouguer Gravity Map covering the study area (Ammerman and Keller 1979) showing Floyd County channel, Rome Trough, Perry County uplift, and Pike County uplift.

Figure 7. Postulated Cambro-Ordovician fault zones along Woodward Fault zone (Silberman 1972), position of dikes at surface, and relation to study area.

Figure 8. North-south cross-section showing thickening of the Rome formation and thinning of Cambro-Ordovician units onto the northern platform. Datum is Top of the Tyrone.

Figure 9. Sequential development of structural features relating to the eastern Kentucky study area. (Pattern-coded map in preparation.)

Figure 10. Plate configurations from Heckel and Witze 1978, used by permission. Reconstruction considers paleoflora, fauna, lithologies, and paleomagnetism.

Figure 11. Plot of relative metamorphic and orogenic intensities with known plutons (Hatcher 1979) and schematic collision relationships of plates (after Odom and Fullager 1953).

(AFTER HECKEL AND WITZE, 1973)

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Figure 13. Isopach map of Devonian clastic sequence, showing area of unconformity at the base of the Devonian, paleocurrent direction, areas of greatest thickness, Brevard zone, shale line, and sandstone line (after Colton 1970).

Isopachs of Total Ohio Shale

deWys, 1979

Figure 14. Isopach of Ohio shale in study area (compiled from Provo data 1977).

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J. Negus-de Wys 1979

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Figure 20. Position of ~4750 gas open flow data points used in study.

Figure 21. Pattern of wells with ≥ 0.5 MMcf/day open flow.

Figure 22. Hand contoured map of ~4750 data points of open flow (MMcf/day).

Figure 23. Linear trends of high open flow, ≥ 0.5 MMcf/day.

Figure 24. Linear trends of low open flow < 0.1 MMcf/day.

Figure 25. Polar plots of cumulative length of total high (A) and total high and low (B) open flow trends.

Figure 26. Trends of fractures in Devonian shale outcrop (Long 1979).

HIGH, MEDIUM, AND LOW PRODUCING AREAS

MUD CREEK AREA, FLOYD CO., KENTUCKY

Figure 27. Area of high production along Floyd County-Pike County border, showing dendritic pattern of lowest production, suggestive of fractures (Hunter and Young 1953).

Figure 28. Detail of Brown shale isopach in Prestonsburg quadrangle showing demarcation of high and low open flow. Changes in isopach thickness (20-30') and small scale anticlinal and synclinal structures do not apparently control recovery (Thomas 1951).

(1)

(11)

C (111) D

Diagrams showing map areas on which the three trend surface analysis programs were run. Arrows indicate 1st degree surface, or major trend, of data. R^2 values, however, are very low, suggesting a low predictive value in the designated direction.

Figure 29. Trend surface analysis results from open flow data.

Figure 30. Fourth degree polynomial trend surface analysis program printout, based on open flow data.

Contours of High Volume Wells
Based on ~4750 Wells
(after Griffith, 1976)

J. Negus deWys
March, 1979

LOW

HIGH

Figure 31. Contours of density of high open flow wells (≥ 0.5 MMcf/day and ≥ 1 MMcf/day after Griffith 1976).

Figure 32: Original shale rock pressures, and changes in the 200 pound shale rock pressure contour: 1935-1951 (Hunter and Young 1953).

Figure 33. Trends of structural features related to trends of open flow.

Figure 34 Major high production trends suggested by final open flow data pattern. En echelon fractures best shown in south-southeast trend. Compression is parallel to linear trend (N-NW). En echelon alignment is parallel to one of the potential conjugate shear fractures under this stress pattern (from Dennis 1972).

σ_1 would be parallel to direction of compressional stress arrows in example shown.

**3-D COMPUTER DRAWN
MAP**

Center of Eastern Kentucky Gas Field

Figure 35. Final open flow data.

CONCLUSIONS

1. The oldest apparent north-south trend in the study area is the Grenville metamorphic front. Later north-south structural features developed in the Cambro-Ordovician and Mississippian times. The Paint Creek Uplift, classed as a north-south trending structure of Mississippian age, appears to exert a general control on the gas accumulation, interpreted from the contours of density of high producing wells. The Floyd County channel, also a north-south feature, is possibly of Pre-Cambrian origin, and may be a saddle or an aborted rift.
2. The oldest northeast-southwest trend is the N. Y.-Alabama lineament which is interpreted by King and Zietz (1978) as a possible Pre-Cambrian suture and buttress for Pre-Cambrian plate collision. The Devonian shale fractures show a preference for this direction in the outcrop area (Long 1979). High open flow trends approach this angle.
3. The oldest east-west trend is observed in the possibly Pre-Cambrian rifting of the Rome Trough area although major movement was in the Cambrian during Rome Formation time. East-west growth faults continued in Cambro-Ordovician times, related to the Woodward fault zone (Silberman 1972). Permian intrusives, including surface dikes, are associated with this area.

The east-west trend is shown by trend surface analysis of open flow data from ~4750 wells. It is also the direction of greatest significance shown in a polar plot of cumulative lengths of high production trends.

4. The three main structural trend directions thus appear to date from Pre-Cambrian times, suggesting a basement involvement with later detached tectonics.
5. The probable subduction-related volcanics and plate collision tectonics appear related to basinal configuration and facies relationships from the cratonic boundary on the west, northwest on to the eastern deltaic sedimentation developing along the collision axis. Bentonite relationships to isopach trends across the basin suggest more rapid subsidence immediately following volcanic activity in the area.
6. The open flow trends appear to suggest a fractured rock sequence or "fracture facies" over the entire study area. Major linear trends of high open flow radiate to the east, southeast from a northeast trending cut-off line for high production. This configuration is suggestive of fault zones, probably draining complex fracture patterns which in turn intersect siltier or sandy zones. The origin of this suggested fault pattern may lie in the interaction of plate collisional stresses from the east, southeast buttressing against the Mississippian Paint Creek Uplift. The constraints on the silty zones in the Ohio shale would be the cratonic Paleozoic epicontinental shelf running through the center of the field and the deltaic toe extending westward into the heart of the study area and causing intricate intertonguing with craton-derived organic sediments.

Thus, the study area suggests an intricate relationship of cratonic sediment supply, structural constraint and resistance, and response to

forces and sedimentation directly resulting from plate collisions. The better the interactions are understood, the better will be the understanding of the complexities of the gas producing "fracture facies" and fault systems intersecting the silty primary reservoirs of the Eastern Kentucky Gas Field.

PRELIMINARY DEPOSITIONAL MODEL
FOR UPPER DEVONIAN HURON AGE ORGANIC BLACK SHALE
IN THE EASTERN KENTUCKY GAS FIELD

by

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and

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May 1980

Preliminary Depositional Model
for Upper Devonian Huron Age Organic Black Shale
in the Eastern Kentucky Gas Field

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ABSTRACT

The constraints on a depositional model are discussed for the Upper Devonian organic black shale facies in the high gas production area of the Big Sandy Gas Field in eastern Kentucky. Commencing with the onlapping lower Huron black shale, which is deposited over a recognizable basal unconformity, the lithology, geochemistry, structural-stratigraphic relationships and production are discussed.

The lower Huron is recognized as the zone of high gas recovery in the Ohio Shale sequence in eastern Kentucky. Since gas recovery is dependent upon natural fracture permeability, this zone may also be the most highly fractured. From gamma-ray logs, this basal black shale shows a characteristically higher natural radioactivity than all other Ohio shale units except the Cleveland shale, which is very similar to the lower Huron shale.

The elemental geochemistry of the black organic lithofacies of the lower Huron is presented. Quartz and illite trends are shown for the lower, middle, and upper Huron. A persistent N-S trend of higher quartz and lower illite is observed to occur through the center of high gas production.

Thin sections from highly organic black shale at the outcrop and in the center of the area of high production in Floyd County are compared with thin sections of subbituminous coal. The abundance of spores, cuticles, and carbonaceous plant fragments is apparent, and very similar to a subbituminous coal.

Study of outcrops of lower Huron black shale to the west of the field area suggest a residual soil horizon at the base of the Huron and channels in the lower Huron black shale.

The highly organic black shale at the base of the Ohio shale sequence is concluded to be the result of transgression of shallow Upper Devonian seas, destruction and deposition of abundant plant growth developing both in shallow water and on low-lying cratonic margins in incipient coal-swamp environments.

Drowning of such growth as evidenced by occurrence of a high density of spores, vitrinitic or woody fragments, and reported occurrence of logs of the largest Upper Devonian plant, the tree-fern Archeopteris, is suggested.

Introduction

Although the Ohio Shale sequence in eastern Kentucky has historically been called "black" or "brown" shales, it is actually composed of several distinct lithotypes and may grossly be characterized by 1) organic brown silty shale, 2) gray mud-shale with vitrinitic or woody fragments, 3) green mud-shale with finely disseminated pyrite, and 4) highly organic black mud-shale (Negus-de Wys, 1979a). It is the highly organic black mud-shale which provides a source rock for Upper Devonian gas in the Big Sandy Field in eastern Kentucky and of which the main producing horizon, the lower Huron shale, is composed (Ray, 1976). In the center of the high-producing area of the field, the black mud-shale intertongues complexly with green mud-shale from the east-northeast, gray shale, and brown silty shale. The gray and green shales appear to thicken to the east and probably represent distal prodelta facies.

The depositional environment of the black muds, which became the Upper Devonian black shales, has been a subject of debate for many years, with the extremes of very shallow water and very deep water (similar to the environment of present day Black Sea muds) being advocated by different authors (Twenhofel, 1939; Moore, 1929; Rich, 1939; Conant and Swanson, 1961). Sparked by interest in the Devonian Shale Gas Program, recent authors have also debated the subject (Provo, 1977; Swager, 1978; Schwietering, 1977). The environment for the black shales in the deeper axial portion of the Appalachian Basin and for those which lie in closer proximity to the deltaic sedimentation to the east and northeast may have been quite different from that on the margins of the craton in eastern Kentucky. See figure 1 for total thickness of Devonian Shale in the Appalachian Basin and figure 2 for thickness of organic black shale.

Data

The Upper Devonian Ohio Shale Formation in eastern Kentucky (table 1) includes the black shale of the Cleveland Member, the green mud-shale of the Three Lick Bed of the Chagrin Shale Member, and the Huron Shale Member, composed of a basal highly organic black mud-shale, a middle Huron silty gray shale, and an upper Huron organic black shale which shows less natural radioactivity on the gamma-ray log than the basal black shale (figure 3). In eastern Kentucky, this shale sequence is deposited over a recognizable unconformity resulting from a period of regression of the shallow Devonian seas. As the seas once again transgressed in lower Huron time, the exposed cratonic margins were probably covered with a lush Devonian plant flora adapted to a warm, moist, and shallow-water environment (McFarlan, 1943).

The paleobotanical inclusions in the shale yield important implications concerning the paleoenvironment. In the Kentucky outcrop areas (figure 4), the common occurrence of Callixylon (now recognized as Archeopteris (figure 5), a tree fern, which commonly attained a diameter > 5 feet and a height of over 150 feet, Gillespie et al., 1979) was recorded by McFarlan (1943). It is the largest Upper Devonian plant. Archeopteris is also found in New York, Pennsylvania, and numerous other localities in the United States and Europe (Andrews, 1961). Logs of Archeopteris have been reported with crinoids attached suggesting the rafting of these logs from a distance (Andrews, 1961). However, there is no need to raft all logs of this largest Upper Devonian tree fern a great distance because of isolated evidence of marine faunal association. Browning (1935) has described the Upper Devonian environment as consisting of islands on the eastern flanks of the Cincinnati arch resulting from fluctuating shallow sea waters. Low land masses farther to the east (toward the eastern Kentucky gas field) were proposed by Browning and by Billingsley (1934) on the basis of thinning of beds, unconformities, and silty horizons. Such islands and land masses could be expected to have been covered with flourishing Upper Devonian flora which encompassed all the major plant groups by this time in plant evolution (figure 6).

McFarlan (1943) noted that 15 other plants besides Callixylon (Archeopteris) are represented in the Huron Shale along the outcrop.

Andrews (1961) notes that unlike most Upper Devonian floras, the Kentucky flora is based entirely on petrified remains and it is of special interest by virtue of the variety of plant forms that are represented, and by the fact that many of the fossils are quite unlike any discovered elsewhere. Over 45 species are now known from the black shales, many of which represent critical stages in evolution of terrestrial pteridophytic and early seed-plant groups.

Tasmanites, the most common spore in the black shales (figure 7), is frequently replaced by pyrite (figure 8) and has been identified by Wall (1962) and Jux (1968) as a cyst of a green alga (figure 9). Tasmanites has a known range of Ordovician to Miocene and has shown remarkable stability in evolution. The closest affinity to a living alga is believed to be with Pachysphaera (figure 10), a green alga which liberates a sac of zoospores that later bursts to produce a free-swimming mobile phase that then develops into the young cyst. Thus, the tasmanitids are now thought to have been cysts of planktonic organisms living in a restricted marine environment, sometimes forming marine peats (Haq and Boersma, 1978). These authors suggest that the vast numbers necessary to produce marine peat must represent "algal blooms" formed in a littoral environment where fresh water run-off had lowered the salinity, and that the common occurrence of Tasmanites in euxinic black shales suggests that "the environment of deposition was a death trap for them."

Protosalvinia (figure 11) has been described as occurring commonly in the Middle Huron in a restricted zone (Schopf, 1925; Schwietering and

Neal, 1977). However, Swager (1978) and Provo (1977) have described specimens from a more extended vertical range, from the Three Lick Bed through the lower Huron shale. I also found a wider vertical distribution during the course of lithology studies from well cuttings (Negus-de Wys, 1979b). Protosalvinia is believed to have been a planktonic brown alga and when present in the black shales, is present in vast numbers (figures 12 and 13).

Compared to the other shale lithotypes in eastern Kentucky, the organic black shale shows a very restricted and extremely fine-grained clastic addition. Run off from the craton must have carried very little in the way of clastic material other than swamp plant debris. Fluctuating seas probably continually destroyed marginal swamp growth. Paleocurrents are shown figure 6.

Thiessen (1925), studied thin sections along the outcrop of the black shale and likened them to subbituminous coals (figure 4). The highly organic black shale facies shows a high spore concentration and cuticle from fragments very similar to the fabric of thin sections of Pennsylvanian-age cannell coal (Thiessen, 1925) from the same area (figures 14-19). In the outcrop area a 2" organic soil horizon (or peat) was observed in Estel County at the base of the Huron. Channel scouring was also identified.

From spore counts and total organics from point counts, thin sections showed a range of total organics (75% by volume) which falls within Schopf's definition of coal (figure 20). By comparison with the subsurface the spore count and total organics were slightly lower in the subsurface thin sections than those from the outcrop. Pyrite appears to be higher in the subsurface. (See figures 21 and 22).

From lithology studies, the stratigraphic relationships of the black and brown organic shale facies with the gray and green shales also suggest a western source for the organic facies (Negus-de Wys, 1979a).

The Ohio Shale sequence is almost entirely dark brown silty shale and intertongues to the east and northeast with less organic facies (figure 23). The black shale appears to be thickest in irregular north-south oriented and isolated areas at the westernmost edge of the delta complex (Petroleum Task Force, 1979; Harris, deWitt, and Colton, 1978). Paleogeography is shown in figure 24 after Conant and Swanson (1961). Thus, the accumulation does not show a genetic relationship to the delta plain facies, but a distal prodelta relationship against the cratonic margin. This cratonic marginal shoreline concept is illustrated in figure 25 showing the regional isopachous map of the Silurian and Devonian after Freeman (1959). The basin of continuous deposition is to the east of the gas field area. Any contribution of organic material from sub-aerial delta plain-related swamps in the eastern or northeastern area does

not show an intertonguing relationship to the eastern Kentucky area. The Ohio Shale sequence rather becomes more Chagrin-like, i.e., gray and green silty shale, as it is followed toward West Virginia (Negus-de Wys, 1979a). Occurrence of conodonts has been suggested as evidence of marine conditions, along with ostracods, lingulid brachiopods, and stylolinids (Duffield and Warshauer, 1979; Warshauer and Duffield, 1979). The proposed model is one of fluctuating shallow marine seas constantly destroying incipient shallow water and terrestrial swamp growth by addition of fine clastics and sea water invasion, i.e., periodically a mudflat environment with a fine interbedding of fresh and brackish water swamp detritus with more marine sediments. Separation of marine tongues from the fresher water facies would have to be done on a very careful paleontological biostratigraphic basis, which is presently being proposed.

To the south of the study area, studies substantiate the proposed model. Breger (1979), in his study of Chattanooga Shales (facies equivalent to the south), concludes a terrestrial or land plant origin is indicated by kerogen/carbon studies, i.e., a coal swamp type of environment. Breger (1979, p. 26) concluded that "in effect, the Chattanooga Shale may be viewed as high-ash, low-rank coal." With the contribution of terrestrial plant material to the Chattanooga muds established, and based on studies of peat from the Everglades in Florida, Breger further concluded that slow anaerobic degradation of cellulose by methanogenic bacteria would be expected to result in the formation of methane that would then dissolve in other organic compounds in the sediment. In depositional environments where there is significant aquatically derived organic detritus contributed to the sediment, ethane, propane, and higher gaseous hydrocarbons would be expected. Thus, the occurrence of source quantities of methane and a depositional environment allowing a significant contribution of terrestrial plant detritus are correlatives.

In this context, the isovalue lines of density of high gas producing wells (based on ~5000 wells) is of interest, and suggests in itself that this is where the terrestrial plant debris accumulated (figure 26). Indeed if we again look at the regional isopach of highly organic black shale, the ≥ 400 foot thick area is generally in the location of the Big Sandy Gas Field.

A geochemical study of the black shale interval within the field was conducted consisting of 900 samples from 14 wells distributed throughout the field (see figure 27). Elemental and mineralogical analyses were performed by x-ray fluorescence and x-ray diffraction (tables 2 and 3).

The primary objective of the study was to determine whether or not a correlation existed between gas production and any compositional parameter or combination of parameters. The basis for production comparison was the final open flow data as presented in figure 26. If such associations could be shown, then they may serve as the basis for a geochemical model which could in turn be used as a geochemical exploration tool within this black

shale sequence in particular, and hopefully, within black shale sequences in general.

In order for the primary objective to be realized, however, the patterns of compositional variability throughout the field must be shown to be non-random. Although there is no way to statistically test a pattern for randomness or the lack of randomness, random patterns are characterized by numerous closures. Patterns which show dominant directional (linear or near linear) contours can be considered non-random, as can patterns which show only a few large closures, although obviously proof that the latter is non-random is not as definite as the former. Another indication of non-randomness of a pattern is if the same basic pattern can be observed in overlying or underlying stratigraphic units, i.e., if the pattern shows a definite vertical component. Some of the patterns of compositional variation for the elemental and mineralogical data are shown in figures 28 - 32. None of the figures show an extensive number of closures; the patterns range from dominant linear or sublinear patterns (figure 31) to single large closures (figure 30). In some cases the patterns do show a vertical continuance through successive stratigraphic units (see figures 28,29). The patterns appear to be non-random, i.e., they show real compositional variation within the black shale unit.

A comparison of the final open flow pattern and the individual compositional variation patterns indicate that in several cases there is a marked similarity. The final open flow pattern is generally a NE-SW trending oval pattern. It can be observed that illite and those elements associated with the illite lattice show a similar trend. The match is not perfect and may well be because of the significant difference in the individual observations from which the patterns are generated. The similarity in overall trend and the coincidence of the high final open flow with the highs and lows of the compositional patterns is deemed significant. The association and influence of the clay mineral assemblage in general and the illite component in particular upon the generation and migration of hydrocarbons has been reported in the literature (Espitahe, 1980).

Another reasonably good match of patterns are those for calcium and magnesium (figure 31). These elements are contained largely in carbonates which are assumed to be present in this field area largely as fracture fillings. The positive correlative between calcium and magnesium with the maxima of final open flow may reflect an increased fracture density in the black shale interval. Isovalue lines of frequency of fracture occurrence (based on well cutting study) are shown in figure 33 for comparison. Because most shale production in this area is known to be from fracture porosity, this appears to be a reasonable interpretation.

Other trend patterns such as that for quartz do not match the pattern for final open flow gas data. These patterns may be more correlative with the overall sedimentology in depositional geochemistry of the system

rather than with hydrocarbon occurrence and generation. The elemental trends for S, Si, and Sr would probably also fall in this category (figure 32).

Paleoenvironmental interpretations based on geochemistry at this point would be premature. The regional distribution of the black shales is reasonably well known despite the arguments that persist concerning whether the shales represent shallow or deep-water sedimentation. The authors are of the opinion that the black shales in eastern Kentucky represent sedimentation on a shallow broad cratonic platform with much of the sediment derived from western land sources supplemented by inorganics concentrated in the parts of plants that grew in shallow water and the lowlying western land masses, a minor addition of prodelta sediments from the east-northeast is postulated for eastern Kentucky during the lower Huron time. The organic material is thus considered to be derived largely from these western sources and not rafted from the eastern highlands.

The area under consideration in eastern Kentucky represents a relatively localized segment of the broad western cratonic shelf on which shallow water sediments were accumulating in lower Huron time. This areal restriction on the data places constraints at this time on paleoenvironmental interpretations of the observed compositional variations in the data.

The problem is further complicated by the fact that, based upon the more regional studies of others, the area appears to be located on the highland between the shoaling shallow water to the west and the deepening water to the east. This is illustrated by the intricate interfacing of the various shale facies within the area. Paleoenvironmental interpretations of the geochemical data must, therefore, await the development of a more regional compositional data base, which is presently being accumulated.

Conclusions

In eastern Kentucky, the highly organic black shales of the Upper Devonian Huron Member appear to be the result of concentration of plant detritus, much of which is of terrestrial origin, with added fine clastics, probably the result of repeated marine invasion of marginal cratonic swamp areas. The high density of spores in the highly organic black shale facies is comparable to that in cannel coal and does not appear to change appreciably from the outcrop area to the center of the eastern Kentucky gas field. High methane accumulation as well as abundant plant determinations are suggestive of marginal swamplands rather than open sea conditions. Such a model is not in contradiction with more regional considerations. Geochemical interpretations to date confirm such an interpretation.

Since these paleoenvironmental conditions produced the largest gas field in the Appalachian Basin, further identification of such conditions may be useful in gas exploration. See table 4 for suggested depositional environment for eastern Kentucky.

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TABLES

1. Stratigraphic sequence
2. Elemental data ranges for Huron Shale
3. Mineralic data ranges for Huron Shale
4. Depositional environment of black shale
(after Trask, 1951) with additions from
this paper for the Upper Devonian organic
black shales in eastern Kentucky

STRATIGRAPHIC SEQUENCE

BEREA/BEDFORD	Berea Sandstone and Bedford Shale, undivided
CLEVELAND	Cleveland Member of Ohio Shale of Ohio
THREE LICK	Three Lick Bed of Provo, Kepferle, and Potter, 1977
UPPER HURON	Upper Part of Huron Member of Ohio Shale of Ohio
MIDDLE HURON	Middle Part of Huron Member of Ohio Shale of Ohio
LOWER HURON	Lower Part of Huron Member of Ohio Shale of Ohio

TABLE 1

TABLE 2: ELEMENTAL DATA RANGES FOR HURON SHALE

Element (Al oxides except sulfur)	Lower Huron	Middle Huron	Upper Huron
Si	51.70 - 58.50%	51.27 - 55.50%	52.71 - 57.20%
Ca	0.52 - 19.18	0.36 - 1.41	0.46 - 1.93
Al	8.37 - 16.60	13.54 - 15.97	12.37 - 15.65
Fe	5.53 - 10.13	7.52 - 10.23	6.77 - 10.09
K	2.21 - 4.21	3.18 - 4.26	2.82 - 3.74
S	1.89 - 3.4	1.59 - 4.65	0.68 - 3.62
Mg	1.29 - 2.93	1.21 - 1.89	1.07 - 1.47
Ti	0.34 - 0.92	0.81 - 1.01	0.75 - 1.06
Na	0.41 - 0.70	0.59 - 0.70	0.59 - 0.71
P	0.116 - 0.626	0.11 - 0.14	0.11 - 0.16
Mn	0.03 - 0.07	0.03 - 0.07	0.02 - 0.11
Zn	0.008 - 0.02	0.009 - 0.034	0.007 - 0.017
Sr	0.002 - 0.016	0.003 - 0.011	0.0 - 0.007

TABLE 3: Mineralic Data Ranges for Huron Shale*

Minerals	Lower Huron	Middle Huron	Upper Huron
Illite	31.9 - 79.7%	44.3 - 63.1%	41.3 - 61.9%
Quartz	13.6 - 39.2	24.5 - 43.2	27.8 - 44.4
Pyrite	2.2 - 8.2	2.8 - 8.7	0.8 - 8.8
Siderite	1.2 - 5.3	0.9 - 3.3	0.1 - 4.2
Bassanite	1.4 - 2.5	1.3 - 2.3	1.4 - 2.3
Dolomite	0.1 - 3.8	0.0 - 1.3	0.0 - 3.7
Plagioclase	0.0 - 1.1	0.6 - 1.2	0.7 - 1.5
Chlorite	0.3 - 1.3	0.3 - 1.2	0.3 - 1.1
Orthoclase	0.0 - 0.4	0.0 - 0.7	0.0 - 0.6
Anhydrite	0.0 - 0.3	0.0 - 0.2	0.0 - 0.4
Calcite	0.0 - 24.8	0.0 - 1.0	0.0 - 1.3
Kaolinite	0.0 - 1.0	0.0 - 0.5	0.0 - 1.9
Szmolnokite	0.0 - 0.1	0.0 - 0.2	0.0 - 0.4
RATIOS	(1) 0.0 - 0.2	0.0 - 0.0	0.0 - 0.0
	(2) 0.3 - 0.5	0.3 - 0.5	0.3 - 0.5
	(3) 0.0 - 0.9	0.4 - 1.0	0.4 - 1.0
	(4) 0.0 - 0.9	0.0 - 0.6	0.0 - 1.0
	(5) 0.8 - 1.0	0.8 - 1.0	0.4 - 1.0

*Percent represents percent of total integrated intensity. The use of one decimal place is not meant to indicate level of precision, which is probably $\pm 10\%$.

TABLE 4: Depositional Environment of Black Shale
(Trask, 1951 review, AAPG, as presented in Conant and Swanson, 1961)

Black shale is characterized by:	To account for these features the following inferences could be considered:	The stratigraphic relationships of black shale suggest deposition:
<ol style="list-style-type: none"> 1. Shaly structure, commonly fissile or thin-bedded, 2. Very fine-grained size of constituent particles, 3. High organic content, 4. Black or dark color, 5. Uniform character throughout considerable areal and vertical extent, 6. Absence, scarcity, or dwarf nature of fauna, 7. Low content of calcium carbonate, relatively high content of iron sulphide and varying quantities of phosphate and iron carbonate. 	<ol style="list-style-type: none"> 1. Deposition in a basin, marine or brackish, in which subsurface water is stagnant and is in a state of reduction, 2. Long continued density stratification of water in basin, 3. Orogenic quiet for material length of time, 4. Narrow seaward outlet of basin, 5. Shallow sill at outlet, or basin located in warm-temperature or warm climate, 6. Intermediate depth of basin, but depth probably is not critical, 7. Adequate replenishment of surface water to support abundant life, 8. Warm-temperature and humid or semi-humid climate, 9. Relatively rapid rate of supply of terrigenous constituents, 10. High initial water content of sediments with resulting compaction of order of 90 percent, 11. Low relief of land adjacent to sea. 	<ol style="list-style-type: none"> 1. On the seaward rather than on the landward side of geosynclinal basins, 2. At a time materially in advance of final orogenic destruction of the geosyncline.

Additions from this paper for the Upper Devonian highly organic black shale in eastern Kentucky

1. Terrestrial plant dominance in organic material,
2. Highly diverse flora: >45 plant species,
3. Relatively high spore content, similar to cannel coal,
4. Stratigraphic relationships show black shale tongues extending into the basin and finely interbedded with gray shales,
5. Marine conodonts, ostracods, styliolinids and foraminifera. The entomozoid ostracodes appear to be benthic, and do not occur in the black organic shale facies;
6. Occurrence of Lingula, a brachiopod which today characterizes shallow, intertidal waters,
7. A relatively high Si content of ~52 - 59%, and a low Al content of ~8 - 17%,
8. Widespread occurrence of probably penecontemporaneous dolomite (dispersed rhombs and rhombs inside spores).

1. Proximity to or a part of swamp type environment,
2. Unique highly diversified plant ecological niches available during a time of explosive plant evolution,
3. Marginal shallow water to swamp depositional environment near cratonic margins, with recurrent flooding by marine waters or marginal swamp environment,
4. A shoreline interface of black organic muds with marine silt addition; possibly low energy cratonic runoff,
5. Supratidal to intertidal evaporative conditions.

1. With a western constraint of cratonic margin,
2. With an eastern constraint of prodelta sediments,
3. Resulting in complex inter-tonguing of black and gray shales in eastern Kentucky,
4. Although on the seaward side of the deltaic sedimentation, black shales occur on the cratonic landward western side of the basin,
5. Very low energy shoreline or near shore environment,
6. Fluctuating transgressive, regressive shallow seas, probably with periods of mudflat sub-aerial exposure along the craton margins.

Figures (not available at this time)

1. Total thickness of Devonian Shale in the Appalachian Basin (after Petroleum Task Force, 1979).
2. Thickness of Devonian age organic rich (black) shale from gamma ray logs (after Petroleum Task Force, 1979).
3. Stratigraphic cross section SW-NE through the Big Sandy Gas Field in eastern Kentucky.
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THE ANATOMY OF A LARGE DEVONIAN BLACK SHALE GAS FIELD

by

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THE ANATOMY OF A LARGE DEVONIAN BLACK SHALE GAS FIELD

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ABSTRACT

The gas occurrence and production from approximately 5000 wells is compared with lithofacies changes and other stratigraphic features, structural development, and fracture occurrence in the largest Upper Devonian black shale gas field in the Appalachian Basin, North America. Lithology studies suggest complex depositional history of craton-derived organic muds intertonguing with distal, deltaic, fine gray silts and green mud-shale. Two bentonite zones indicate volcanic activity prior to more intense basinal subsidence. Fracture frequency is contoured over the field area. Structural development is related to continental plate rifting and collision. Three major structural trends persist from the Pre-Cambrian; north-south, northeast-southwest, and east-west. Production studies of open flow data from 5000 wells in this 3000 square mile area include computer-drawn contours, trend-surface analysis pattern interpretation, and polar plot trends of high production. A series of radiating high fracture of fault zones is suggested. Gas recovery appears to be governed by fractures intercepting siltier zones in thick sequences of highly organic black shale in the area of greatest complexity of intertonguing. The relative importance of the different parameters is discussed and assessed, using statistical correlations. The methods of analysis and model of field conditions may be applicable to other shale basins.

Introduction

The "Big Sandy" gas field is located in eastern Kentucky on the western flank of the central Appalachian Mountains, at the junction of two orogenic trend directions. Figure 1 shows the study area in relationship to the Precambrian orogenic provinces in North America. The area studied covers about 3000 square miles.

The gas in the eastern Kentucky field is produced primarily from fractures in the Upper Devonian black shale of the Ohio Shale sequence. The field is situated at the distal terminus of deltaic sedimentation originating to the east and northeast. These fine clastics intertongue complexly with black organic muds primarily derived from the west and north. Figure 2 shows the field location in eastern Kentucky relative to the epicontinental shelf and the aeromagnetic anomaly of King and Zietz. The areas of oil and gas accumulation lie directly to the northwest of this anomaly, which also shows up in gravity data.

The basement in the field area is dominated by a trough reaching a depth of -16,000 feet in the northeast, and which trends in a north easterly direction across the northern edge of the field. At nearly 90 degrees to this trough, known as the Rome Trough, the Floyd County Channel extends northward to, and perhaps into, the trough. The channel is flanked on the east and west by slight uplifts. Figure 3

shows a three-dimensional block diagram of these basement features. Figure 4 shows the sequential development of structural features. The area of the Rome Trough shows continued activity up to the present time, but with the major development occurring in Cambrian time.

Evidence for the major development of this trough is seen in the thickened sequence of Cambrian sediments caused by growth of the asymmetrical graben at that time (Figure 5).

Structure and Stratigraphy

Present structure on top of the producing horizon, the Ohio Shale, shows a north-south trending uplift which broadens to the south, southeast (Figure 6). This structure, known as the Paint Creek Uplift, appears to exert a major control on gas accumulation in the field as will be shown later.

Ohio Shale sediments thicken to the east (Figure 7) with a N-S strike to the nearly parallel isopachous lines.

Cross sections drawn from gamma-ray logs in the field indicate a relatively constant thickness of sediments in the southwest (Figure 8) which increases in thickness from 300' to 900' across the field to the northeast (Figure 9). Complex intertonguing of silty zones with organic zones is suggested by the gamma-ray log signature. The lower Huron, the basal shale in the sequence, shows especially high natural radioactivity. Figure 10 shows the relatively constant thickness at the northeastern end of the field, but thicker than the section in the southwest.

Cross sections developed from lithology studies on well cuttings confirm the complex intertonguing of black, gray, green, and brown silty shales. The highly organic black mud shale is thicker in the center of the field; the green and gray shales are more dominant to the east and northeast (Figure 11).

Bentonite zones below the base of the Ohio Shale and at the base of the Cleveland black shale at the top of the Ohio Shale sequence are evidence of volcanic ashfalls immediately prior to thicker black shale deposition and increased basinal subsidence in the eastern and north-eastern parts of the field.

Studies of relative percentages of the different shale types suggest the green clay shale source may be to the northeast (Figure 12). The area of thickest black shale is located off the nose of the Paint Creek Uplift (Figure 13). The gray shale which commonly contains vitrinite or woody fragments is most dominant in the southwest central portion of the field, suggesting perhaps a northwestern source (Figure 14). The brown, frequently very silty, mud-shale is lowest to the east and more dominant to the northwest, west and southwest. This silty organic shale is also suggestive of a western cratonic source.

The present structure on the Pennsylvanian Fire Clay Coal (Figure 15) indicates uplift occurring in the southeast and hinging along a NE-SW trending synclinal axis known as the eastern Kentucky syncline (Figure 16). The northern part of this syncline is part of the Rome Trough. This syncline is interrupted by the N-S trending Paint Creek Uplift, which forms a saddle or barrier between what results in a northeastern basin and southwestern basin. The tectonic movements involved in the formation of these features were probably instrumental in developing highly fractured zones related to the nose of the Paint Creek Uplift, the eastern Kentucky syncline, and the uplift to the southeast.

Thrust sheets in the southeast, i.e., Pine Mountain thrust sheet,

and the southeastern uplift are related to plate collision interactions along the continental plate margins, commencing after Devonian sedimentation.

The changes in depositional and present attitudes of the Fire Clay coal relative to the black shales indicate uplift of the black shales at the extreme NW and SE of the field area, but downwarp in the extreme NE and SW, with the hingeline for uplift along the eastern Kentucky syncline and the saddle for downwarp provided by the Paint Creek Uplift (Figure 17).

The plot of fracture frequencies based on data from lithology studies and core data shows the highest concentration of fractures along the central portion of the eastern Kentucky syncline and off the nose of the Paint Creek Uplift (Figure 18).

Gas Occurrence and Recovery

Pressure decline plots of the 200 pound isopressure contour show the contour moving away from the center of high production in the period plotted: 1935-1951. This is evidence of an interconnected gas reservoir in the field (Figure 19).

For a comparison of the gas isopotential (an indication of gas occurrence and production) the final open flow data from 4750 wells were analyzed. Well distribution is shown in Figure 20.

A histogram of the open flow data shows a nearly asymptotic curve with 0.06 MMcf per day as the economical cutoff for "dry" holes (Figure 21). The tail of this histogram extends out to > 8.6 MMcf per day but only includes 19 wells between 2.4 and 8.6 MMcf per day (Figure 22).

Contours of high producing wells per 25 square miles, representing a density value of wells producing at a given rate, show the greatest concentration of higher producers centered in south-central Floyd County with a N-E trend (Figure 23). The western boundary of high production is fairly straight, but irregular, linear projections are apparent to the north, east and southeast.

Contouring of the open flow data results in a highly complex configuration (Figure 24), suggestive of a coalescence of many smaller fields.

Trends of open flow configurations plotted from Figure 24 show multidirectional trends both in low open flow and in the high open flow patterns (Figure 26), resulting in Figure 27. These trends suggest higher fracture zones extending in bands radiating off the nose of the Paint Creek Uplift and sharply cut off along a line parallel to the eastern Kentucky syncline.

A comparison of cross sections is shown in Figure 28. The section through open flow data (#3) shows higher values over the area of structural high on the Paint Creek Uplift, even though the dip of the strata is only 30-50 feet per mile. Black shale lithotype is thickest over this central area of high production, and greater complexity of intertonguing of gray, green, brown, and black shales occurs in the central portion of the field.

The geochemistry cross sections which are not discussed in this paper, also show abnormalities in the central area.

Summary

In conclusion, the Big Sandy Field, which is estimated to be capable of producing 2 trillion cubic feet of gas from the present 5000 wells, represents a highly complex structural-stratigraphic gas trap. It may be considered a coalescence of many smaller fields, but in general shows the high gas concentration and recovery from fractures to be related to the interaction of southeastern uplift hinged along the eastern Kentucky syncline and abutting against, and interrupted by the Paint Creek Uplift. Thicker organic black shales and complex intertonguing with silty zones providing a "fracture facies" are undoubtedly important factors in gas recovery from the Upper Devonian black shales in the largest gas field in the Appalachian Basin.

Acknowledgement

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Figure 1. Geological provinces and orogenic trend lines. (after Muehlberger, *et al.* 1967). The location of study area is shown by rectangle. Province ages are in billions of years.

Figure 2. Field location relative to the epicontinental shelf (after Price in Lafferty, 1941), the New York-Alabama Lineament (King and Zietz, 1978), Grenville metamorphic front (Bass, 1960), Cincinnati Arch, and oil and gas occurrence. Contours are of thickness of early Paleozoic clastics.

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Figure 4. Sequential structural development.

Figure 5. Evidence of major development of the Rome Trough in Cambrian time (after Dever, et al., 1977).

Figure 6. Structure on top of the Ohio Shale (after Provo, 1977).

Isopachs of Total Ohio Shale

deWys, 1979

Figure 7. Isopach map of total Ohio Shale.

Figure 9. Stratigraphic cross section B-B', southwest to northeast through the field center, showing log traces of natural radioactivity from the formation density logs. Intertonguing of the black and gray shales in the Cleveland are usually related to the changes in natural radioactivity. The black shale in the Cleveland is shaded gray.

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Figure 12. Map showing iso-value lines of percent green clay-shale of total shale sequence.

Figure 13. Isopach map of highly organic black mud-shale (in feet).

Figure 14. Map showing iso-value lines of percent gray clay- to mud-shale of total sequence.

Figure 15. Map showing iso-value lines of percent organic brown silty mud-shale of total shale sequence.

Figure 16. Structure on top of the Fire Clay coal (after McFarlan, 1943). Note: Northeast-southwest trend of syncline interrupted by the N-S trend of the Paint Creek Uplift; the northeast basin is deeper than the southwest basin; this is the area (NE) where the "Corniferous" limestone isopach suggests an early basin; and this northeastern area is suggested by geochemistry to be an area of marine tidal influence. Age of structural development is indicated in parentheses.

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Figure 18. Map of observed frequency of fracture horizons in wells studied.

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Figure 21. Histogram of all wells used in computer-mapping (4138). Figure 22 shows tail of histogram representing only 19 wells.

Figure 22. Histogram tail of Fig. 21 showing highest value 19 wells. Note histogram must be broken twice on the horizontal scale.

Contours of High Volume Wells
Based on 4750 Wells
(after Griffith, 1976)

J. Negus deWys
March, 1979

Figure 23

Contours of density of high producing wells (after Griffith, 1976). Contours represent number of wells $\geq .5$ MMcf/day/25 square miles (left) and ≥ 1 MMcf/day/25 square miles (right). These figures may be interpreted as the area of gas accumulation with recovery details smoothed out. Note pattern irregularities suggesting linear peripheral extensions.

Figure 24. Hand-contoured map of open flow data with three contour levels, using 4750 wells. The highest value areas are shaded to enhance the pattern of higher open flow. Circled dots are locations of wells used in lithology and geochemistry studies.

Figure 25. Trends of high open flow data taken from Figure 24.

Figure 26. Pattern resulting from connecting all wells with $\geq .5$ MMcf/day where not contra indicated. This should be compared with Figure 20 in order to recognize the density of data and constraints of such density imposed on this pattern.

Figure 27. Pattern of open flow basic fracture band trends from Figure 26. Compare with Figures 6 and 16.

Figure 28. Comparison of similar cross sections.

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THE COTTAGEVILLE (MOUNT ALTO) GAS FIELD, JACKSON
COUNTY, WEST VIRGINIA: A CASE STUDY
OF DEVONIAN SHALE GAS PRODUCTION

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INTRODUCTION

One of the oldest gas-producing intervals in West Virginia (and for the most part in all of the Appalachian basin) is the thick shale sequence in the western one-third of West Virginia referred to by drillers as the "Devonian Shales" or simply "Brown Shales". Organic shales within this thick section have yielded low-volume gas production for nearly 50 years from shallow-depth wells.

Under contract EY-76-C-05-5194 from the United States Department of Energy, Morgantown Energy Technology Center with West Virginia University, a comprehensive examination of Devonian shale natural gas production characteristics in the Cottageville gas field (Mount Alto) was undertaken in the winter of 1977 (Figures 1 and 2).

The purpose of this study was to evaluate gas production characteristics of the Devonian shales in the Cottageville field and surrounding areas. The objectives of this study were threefold. The first objective was to establish gas production configurations. This was accomplished by studying gas test-flow rates and/or gas-production rates. The second objective was to determine and define the stratigraphic interval(s) of gas production. And the third objective was to attempt to determine if fractures control production and if other structural or stratigraphic parameters affect production characteristics. Delineating the interrelationship of these parameters that affect production could lead to increased drilling activity in this gas field and possibly to further exploration and establishment of other potential shale fields.

Fig. 1. Location - Cottageville gas field.

REVIEW OF PERTINENT LITERATURE

Only recently has any investigation dealt with production mechanisms and characteristics of this gas field. Martin and Nuckols (1976) first attempted to characterize production at Cottageville by correlating geophysical logs with organic lithologies and gas production. Published later that year, Larese (1976) and Larese and Heald (1976) petrographically analyzed samples from a core in the southwestern portion of the gas field (West Virginia Permit Number Jackson - 1369). In late 1977, Nuckols presented a paper at the "First Annual Devonian Shale Symposium" (1977) that laid the groundwork for structural and production studies. During this same year, Patchen (1977) completed a regional subsurface stratigraphic and production study that included the Cottageville gas field. Early in 1978, de Wys and Shumaker (1978) completed a pilot study on the methodology in the analysis of gas production data.

GEOLOGY

STRATIGRAPHYGeneral Survey

The surface sediments of the Cottageville area are Permian in age (Figure 3). The Gilmore Sandstone is the youngest unit of the Dunkard Group found within this area. This massive sandstone along with the upper, middle, and lower Rockport Limestones often cap ridges in northeastern Jackson County. Other topographically prominent surface rocks of this area include the Nineveh Sandstone and the Upper Marietta Sandstones. The Dunkard Coal is represented in this area by a very thin impure coal seam; and the Nineveh Coal, which is stratigraphically younger, is also thin but of a better grade (lower ash).

The Monongahela Formation is the youngest formation of the Pennsylvanian Series, and is also the most economically significant. The Waynesburg, Sewickley, and Redstone Coals are also economically valuable coal units within the Monongahela Formation. The Pittsburgh Coal is the oldest coal measure of this series, and is economically perhaps the most valuable. Within the Cottageville area, these coal units are represented by very thin beds. The underlying Conemaugh Formation contains the Connellsville Sandstone, Saltsburg Sandstone, Bakerstown Coal, and the Upper Mahoning Sandstone. Stratigraphically underlying the Conemaugh Formation is the lower Freeport Sandstone; this is the most distinctive lithologic unit in the Allegheny Formation. The Pottsville Formation, which

GENERALIZED GEOLOGIC COLUMN				
SERIES	GROUP OR FORMATION	IMPORTANT ROCK UNITS	ROCK COLUMN	DRILLERS TERMS
PERMIAN	DUNKARD	Gilmore SS		Gilmore Coal
		Rockport LS		Nineveh Sand
		Nineveh Coal		Jollytown Sand
		Dunkard Coal		Hundred Sand
		Jollytown Coal		Washington Coal
PENNSYLVANIAN	MONONGAHELA	Waynesburg Coal		Uniontown Coal
		Sewickley Coal		Redstone Coal
		Pittsburgh Coal		
	CONEMAUGH	Connellsville SS		Morgantown Sand
		Bakerstown Coal		Saltsburg Sand
	Mahoning SS			
	ALLEGHENY	Lower Freeport SS		Burning Springs Sand
				Gas Sand
	POTTSVILLE	Salt Sands		1 st Salt Sand
	MISSISSIPPIAN
			3 rd Salt Sand	
MAUCH CHUNK		Maxton SS		Ravencliff Sand
				Lower Maxon Little Lime
GREENBRIER		Greenbrier Limestone		Big Lime
		Big Injun SS		Keener Sand
POCONO	Squaw SS
	Weir Sand		Sunbury Shale	
		Berea SS		
DEVONIAN
	OHIO SHALE	Lower Huron Member		BROWN SHALE
	JAVA			
	WESTFALLS			
	ONONDAGA			Corniferous LS
				Oriskany Sand
	HELDERBURG			

Fig. 3. Generalized geologic column of the Cottageville area (after Byrer, Trumbo, and Rhoades, 1976).

contains several sandstones known as the Salt Sands (First, Second, and Third Salt Sands), is the oldest formation of Pennsylvanian age in this area. The Mauch Chunk Formation (Upper Mississippian) contains the Maxton Sandstone. Below this sandstone is the Greenbrier Formation which contains the Big Lime and Keener Sandstones. The lowest formation of the Mississippian Series is the Pocono, which contains the Squaw, Weir and Berea Sandstones.

The subsurface Devonian shales include all of the fine grained clastic rocks that occur between the top of the Middle Devonian Onondaga Limestone and the bottom of the Lower Mississippian Berea Sandstone. At the top of the shale, it includes Bedford Sandstone equivalents in adjacent areas of Ohio and Kentucky (Patchen, 1977). In West Virginia, the thick shales are restricted to the western one-third of the state; whereas, the coarser clastic Catskill redbeds and the various Hampshire and Chemung sandstones and siltstones are present to the east. The term "Brown Shales," although often used as a synonym for Devonian shales, is correctly restricted to darker organic shales within the massive shale sequence to the west (Martin and Nuckols, 1976). These darker shales (dark gray to black), which are more organically rich and more radioactive than the gray and greenish-gray, sandy, silty shales that encompass them, usually occur within the lower half of the shale sequence.

The Devonian shales occupy the same stratigraphic position as six clastic formations in the eastern outcrops of West Virginia: the Marcellus Shale (a black organic rich shale); Hamilton siltstones and shales (some of which are dark); the Harrell Formation (a second black or dark gray shale that contains the Tully Limestone Member

near its base); the Brallier siltstones and shales (some of which are dark); the Chemung (greenish, gray, and brown sandstones, siltstones, and shales); and the Hampshire Formation (Catskill facies-redbeds with sandstones, siltstones, and shales, mostly of nonmarine origin). The thickness of this entire Devonian clastic section ranges from less than 1,000 feet in the southwestern West Virginia gas fields to more than 7,000 feet in the subsurface area (Figure 4) of northcentral West Virginia, and up to 10,500 feet in the eastern outcrop area (Patchen, 1977). However, the interval that is occupied by black or dark brown organic shales makes up approximately 17 per cent of the total Devonian shale section in the Cottageville field. This is assuming that an average of 350 feet of organic brown shale underlies the Cottageville gas field.

As the clastic wedge of dark shales thickens to the east, they occur as a smaller percentage of the total stratigraphic section and at greater drilling depths (Figure 4). Therefore, few wells have been drilled entirely through the Upper and Middle Devonian sequence in the northcentral counties where gas is produced from 17 named Upper Devonian Hampshire (Catskill) and Chemung sandstones (Patchen, 1977). In the southwestern counties, however, gas is produced from several shale zones, usually within the middle of the Devonian shale section (Lower Huron Member of the Ohio Shale Formation). Between these two areas, underlying an area of Mississippian gas production, the key facies change occurs from productive sandstones to organic-rich dark shales. Deep producing intervals as well as shallow ones have had geophysical wire-line logs

Fig. 4. Isopach map of the Devonian shales in western West Virginia and their coarser grained equivalents to the east (from Patchen, 1977).

run in the holes. Historically, the logs have often skipped the shale section, logging only from the Onondaga and Oriskany Formations down to total depth, and from the Mississippian Berea Sandstone up to the surface.

Directly underlying the Lower Huron Member of the Ohio Shale Formation (Figure 3) in the Cottageville field, is a greenish-gray, calcareous, usually nonsilty shale, that is from 300 to 400 feet thick (the Java Formation and upper part of the Westfalls Formation; Figure 3). This is a persistent zone that can be traced from eastern Kentucky (where it is referred to as the "Big White Slate" by drillers), northward to Wood County, West Virginia, a distance of more than 100 miles. The lower-most dark shale (Westfalls Formation) thickens and splits from west to east, and probably is equivalent to dark shales in the Hamilton Formation below the drillers' Tully, and the Harrell and lower Brallier Formations above the Tully. The upper dark organic shale zone (correlated with the Lower Huron Member of the Ohio Shale Formation) also thickens and splits toward the east, and appears to interfinger with the Riley-Benson zone (Martin and Nuckols, 1976). Dark shales within the Riley-Benson zone are identical to dark shales in the brown shale zone to the west (Cheema, 1976).

For the most part, these regional correlations and lithologic subdivisions, based entirely on well sample descriptions, are confirmed by gamma ray log stratigraphy. The dark brown to black, organic-rich brown shales that produce in western West Virginia (Lower Huron Member of the Ohio Shale Formation) appear

to be more radioactive on gamma-ray logs than the lighter gray, often silty shales to the east. Martin and Nuckols (1976) have traced the radioactive shales in the lower part of the Lower Huron shale zone (Zone II) into the Benson zone of eastern West Virginia.

Stratigraphic Cross Sections

Within the Cottageville gas field, two stratigraphic cross sections were constructed to better illustrate the relationship of subsurface Devonian formations (Figure 5). Cross section A - A' (Figure 6) was constructed along the general strike of the gas field and is approximately 6.8 miles in length. Cross section B - B' (Figure 7) trends normal to the gas field and is approximately 5 miles in length. On these cross sections, five separate stratigraphic units were differentiated: top of the Mississippian Berea Sandstone, the Middle Devonian Lower Huron Member of the Ohio Shale Formation, the Middle Devonian Java Formation, the Middle Devonian Westfalls Formation, and the top of the Middle Devonian Onondaga Limestone.

Of primary economic importance, is the occurrence of organic shales within the upper (Zone III) and lower (Zone II) portion of the Lower Huron Member of the Ohio Shale Formation (Figure 8) and the lower part of the Westfalls Formation (Zone I). These organic shale zones were first recognized by Martin and Nuckols (1976) to be the significant shale producing zones within the Cottageville gas field. Another significant feature of the cross

Fig. 5. Location of stratigraphic cross sections (see Figs. 6 and 7 for depicted cross sections A - A' and B - B').

Fig. 6. Stratigraphic cross section A - A'.

SCALE:

Horizontal: 1" = ~ 4,800 feet

Vertical: 1" = ~ 560 feet

Fig. 7. Stratigraphic cross section B - B'.

Fig. 8. Gamma ray log portraying organic rich shale zones (II and III) of the Lower Huron Member of the Ohio Shale Formation with gas shows from 37 wells drilled within the Cottageville field (from Martin and Nuckols, 1976).

sections is the occurrence of an unconformity in the lower part of the Westfalls Formation. This unconformity has been discovered by Schwietering (personal communication, 1977) to be very extensive throughout the State of West Virginia.

Isopach Maps

To facilitate a better understanding of the stratigraphy of the Cottageville gas field, a series of isopach maps for different stratigraphic intervals were constructed (Figure 8). The following four maps of different horizons were constructed from drillers' logs and geophysical logs (Figures 9, 10, 11 and 12).

- I. Isopach map of the total Devonian shale sequence from the top of the Mississippian Berea Sandstone to the top of the Middle Devonian Onondaga Limestone (Figure 9)*.
- II. Isopach map of the Lower Huron Member of the Ohio Shale Formation (Figure 10).
- III. Isopach map of Zone II in the lower portion of the Lower Huron Member of the Ohio Shale Formation (Figure 11).

*Difficulty was encountered in determining accurately the bottom of the Mississippian Berea Sandstone and the top of the Devonian shale. Therefore, the top of the Berea was selected since the overlying Sunbury Shale-Berea Sandstone contact can easily be recognized from geophysical logs and drillers' logs in this region.

Fig. 9. Isopach map of total Devonian shale.

Fig. 10. Isopach map of the Lower Huron Member of the Ohio Shale Formation.

Fig. 11. Isopach map of organic shale Zone II of the Lower Huron Member of the Ohio Shale Formation.

Fig. 12. Isopach map of organic shale Zone III of the Lower Huron Member of the Ohio Shale Formation.

IV. Isopach map of Zone III in the upper portion of the
Lower Huron Member of the Ohio Shale Formation
(Figure 12).

Correlation between drillers' logs and geophysical logs at times can be tenuous. Drillers' logs were made by personnel that had little to no geological training; whereas, geophysical logs quantitatively evaluate geological formations. Therefore, correlation of subsurface units with drillers' logs can only be attempted when there are striking lithologic differences that normally cannot be made when minor stratigraphic changes occur. Experience and cross checking of geophysical logs and drillers' logs show that the intervals selected do have a fair degree of reliability.

I. Isopach Map of Total Devonian Shale (Figure 9).

Within the Cottageville field, the total Devonian shale thickness ranges from 1,869 to 2,335 feet with an average thickness of 2,102 feet. In comparison to the entire geologic column, this shale section comprises approximately 19 per cent of the total geologic section from the basal Cambrian sediments to the surficial Permian sediments. Seismic data from this area indicates that the basement is approximately 11,000 feet deep. Within the map area (Figure 9), the shale sequence gradually thickens from west to east. This thickening is a direct reflection of an overall sediment wedge that thickens eastward as the center of the Appalachian basin is approached. An important factor in this thickening to the east is the proximity of the Rome trough to the area of study. Within a few miles to the east of the gas field,

the deepest part of the Rome trough (personal communication with Consolidated Gas Supply Corporation Exploration Department, 1979) can be found, which has greatly affected sedimentation and structural conditions in this region.

Two important features can be seen on Figure 9. Just east of the shale field there appears to be an abrupt thickness change. This benchlike feature ranges in width from 3,000 feet to 7,000 feet with a thickness change of approximately 60 to 90 feet. The area within and west of the shale field proper has a broad, fairly uniform thickening pattern. A second thickness change in the northeast portion of the map area has a linear east-west thickening trend. This thickening may be directly related to faulting that has increased the shale section in this area. However, no direct evidence of a fault can be presented to support this suggestion.

II. Isopach Map of Lower Huron Member of the Ohio Shale Formation (Figure 10).

This stratigraphic sequence has been the primary producer of Devonian shale gas in the Cottageville field. Found within this unit are two areas of concentrated organic shale (Figure 8). As can be seen from Figure 10, this shale interval ranges from 369 to 502 feet in thickness across the map area with an average thickness of 436 feet. In general, the shale zone thickens from west to east. However, it is by no means a uniform thickening. An unusual thickening near the center of the map area has approximately 40 feet

of thickening compared to the immediate surrounding area. This feature may possibly be a direct reflection of faulting or paleotopographic changes within this area.

III. Isopach Maps of Organic Shale Zones II and III within the Lower Huron Member of the Ohio Shale Formation (Figures 11 and 12).

Two isopach maps were constructed of the lower (Figure 11) and upper (Figure 12) organic shale facies found within the Lower Huron Member of the Ohio Shale Formation. Of particular importance (relative to gas production), is the isopach map of the lower organic shale, Zone II (Figure 11). This lower organic zone (II) is the major gas-producing horizon within the field and ranges in thickness from 116 to 277 feet across the map area with an average thickness of 197 feet. The contours tend to form an irregular pattern with an overall strike trend to the northeast. Near the center of the map area (approximately the center of the shale field) several linear thickening trends may have been produced by faulting, filling of topographic lows relative to the underlying unconformity, or slumping. However, a selection of which is more probable cannot be supported by any known data.

Somewhat similar to the lower organic zone is the upper organic zone (Figure 12). This zone (III) ranges in thickness from 45 to 120 feet across the map area with an average value of 83 feet. Once again, the contours appear to form an irregular pattern with some linear thickening trends that may be associated with faulting or old paleotopographic changes.

Geochemistry

Several detailed analytical studies of the composition of two shale cores from the Cottageville gas field have been completed (Larese and Herald, 1976; Byrer, Trumbo, and Rhoades, 1976; and Lamey, Bialobok, and Childers, 1978). Geochemical analyses were performed on core samples at selected intervals from a 287-foot section of oriented core from the L. A. Bailer well (Jackson - 1369; Figure 2) and a 420-foot section of oriented core from the W. L. Pnnell well (Jackson - 1371; Figure 2). The cored interval from Jackson - 1369 (Figure 13) was from 3,410 to 3,500 feet and from 3,600 to 3,797 feet with a 100-foot interval that was not cored. The upper cored interval contained Zone III organic shales of the Lower Huron Member of the Ohio Shale Formation, while the lower cored interval contained a partial section of Zone II organic shales of the Lower Huron Member. The original objective of the L. A. Bailer well was to entirely core organic shale Zones II and III of the Lower Huron Member of the Ohio Shale Formation. However, approximately 48 feet from the bottom of Zone II, the coring bit encountered a gas flow of approximately 4MMcf/d. At this point, coring was discontinued and the core was retrieved. The core interval from Jackson - 1371 (Figure 14) was from 3,220 to 3,690 feet, with a continuous oriented core from just above Zone III organic shales to just below Zone II organic shales of the Lower Huron Member of the Ohio Shale Formation.

Fig. 13. Logs of core well No. Jackson-1369 (from Byrer, Trumbo, and Rhoades, 1976).

Fig. 14. Logs of core well No. Jackson-1371 (from Byrer, Trumbo, and Rhoades, 1976).

Of interest to exploration and production aspects of the Devonian shale were the organic analyses performed on these two cores. Contained within a detailed report by Lamey, Bialobok, and Childers (1978) were the following analyses:

- 1) Organic and mineral carbon content for well no. Jackson - 1369,
- 2) Organic and mineral carbon content for well no. Jackson - 1371,
- 3) Thermal chromatographic analysis and relative composition of the carbon number fraction for well no. Jackson - 1369, and
- 4) Thermal chromatographic analysis and relative composition of the carbon number fraction for well no. Jackson - 1371.

From these detailed analyses, Tables 1 and 2 were constructed. A comparison of these tables shows a remarkable difference in organic carbon content between the two wells. Well no. Jackson - 1369 in the southwest part of the gas field has an average organic carbon content of 2.11 weight per cent for the Lower Huron Member, while well no. Jackson - 1371 (5 miles to the north) has an average organic carbon content of 1.28 weight per cent. This difference may be attributed to either poor sample selection (no correlation sampling) or to less organic material in the Devonian section of well Jackson - 1371. A comparison of the relative amount of oil fractions for each well finds some fluctuations in the overall average values, but

ORGANIC ZONATION ANALYSIS

Stratigraphic Interval	Average Organic and Mineral Content		Average Relative Amount of Oil Fractions (%)			
	Organic Carbon (Wt. %)	Mineral Carbon (Wt. %)	$\leq C_{12}$	$C_{13}-C_{20}$	$C_{21}-C_{26}$	$\geq C_{27}$
Lower Huron Member of the Ohio Shale Formation	2.11	0.35	47.9	25.3	16.3	11.1
Zone III of the Lower Huron Member	2.51	0.03	49.2	23.4	17.9	10.8
Zone II of the Lower Huron Member	3.41	0.18	49.1	23.4	17.0	10.5
Interval Between Zones II and III of the Lower Huron Member	0.41	0.85	45.5	29.18	14.6	12.1

Table 1. Organic and mineral carbon content, thermal chromatographic analysis results and relative composition of the carbon number fraction for well no. Jackson - 1369. Core depths are directly correlated with geophysical log data(modified from Lamey, Bialobok and Childers, 1978).

ORGANIC ZONATION ANALYSIS

Stratigraphic Interval	Average Organic and Mineral Content		Average Relative Amount of Oil Fractions (%)			
	Organic Carbon (Wt. %)	Mineral Carbon (Wt. %)	$\leq C_{12}$	$C_{13}-C_{20}$	$C_{21}-C_{26}$	$\geq C_{27}$
Lower Huron Member of the Ohio Shale Formation	1.28	0.27	44.2	30.8	16.1	8.9
Zone III of the Lower Huron Member	1.30	0.36	39.7	33.2	18.1	9.05
Zone II of the Lower Huron Member	1.70	0.27	45.8	29.1	15.6	9.56
Interval Between Zones II and III of the Lower Huron Member	0.84	0.19	47.2	30.0	14.7	8.1

Table 2. Organic and mineral carbon content, thermal chromatographic analysis results and relative composition of the carbon number fraction for well no. Jackson - 1371. Core depths are directly correlated with geophysical log data (modified from Lamey, Bialobok and Childers, 1978).

generally both wells are rich in C_{12} or lighter hydrocarbons (approximately half of the fraction) with fewer amounts of C_{13} to C_{27+} hydrocarbons.

In addition to these analyses, a gas sample from well no. Jackson - 1369 was analyzed for its molecular composition. This analysis was performed by the Mobil Oil Corporation of Denver, Colorado, for Consolidated Gas Supply Corporation of Clarksburg, West Virginia. The results of this analysis are listed below:

<u>Component</u>	<u>Mole %</u>
Carbon Dioxide	.081
Nitrogen	1.570
Methane	81.312
Ethane	10.850
Propane	4.415
I-Butane	.281
N-Butane	1.035
I-Pentane	.179
Hexane	.073
Heptanes +	<u>.060</u>
Total Distribution	100.000

STRUCTURE

Regional Structure

Physiographically, the Cottageville gas field lies in the Appalachian Plateau province of the Appalachian mountain system. On a regional scale, the geologic structure of the Appalachian Plateau consists of a broad asymmetrical synclinorium. The southeast limb is the steepest in the synclinorium which plunges northeastward parallel to the general trend of the Appalachians. Subsurface structure mapping indicates a series of doubly plunging broad folds whose trends generally follow the folds in the Valley and Ridge province to the east. At the surface the strata are nearly horizontal, particularly in the western portions of the Plateau. Spencer (1969) notes that in much of the Appalachian Plateau the folds typically are 50 miles in length and, in some instances, are as much as 100 miles long. Occasionally, these folds form en échelon patterns, and in many cases, the folds plunge abruptly.

In the vicinity of Cottageville, the Geological map of West Virginia (Cardwell, 1968) shows relatively short (six to eleven miles) synclinal structures to the northeast, east, and south. To the west of these folds, including the gas field area, distinctive folds are not evident. The folds to the south of the field show trends of N 70° E to N 80° E, while those to the east are aligned approximately N 25° E, and those to the north are aligned several degrees west of north.

A mega-structural feature within this area is the Rome trough (Figure 15) that comprises a valley rift system on the

Fig. 15. Brown shale gas fields, thickness of brown shales (from deWitt, et al, 1975), and approximate position of the Rome trough in West Virginia. Thick areas of dark organic-rich shale that overlie this Cambrian fault block may be the area of greatest potential for new exploration (from Patchen, 1976).

Pre-Cambrian basement. This Cambrian (possibly Pre-Cambrian) age feature has influenced sedimentation and structural regimes from early Cambrian time up to Silurian and possibly Devonian time. The western boundary of this feature may possibly consist of faults that may have been reactivated throughout time, thus causing warping and fracturing of overlying sediments (Martin and Nuckols, 1976). Figure 16 shows the basement structure as interpreted from magnetic intensity values in the Cottageville area (de Wys and Shumaker, 1978). The basement contours approximately parallel the Rome trough and give an appearance of parallel blocks. Martin and Nuckols (1976) postulate that fractures in the Cottageville area resulted from reactivation movement of the basement fault blocks comprising the western boundary of the trough.

Subsurface Structure

To facilitate an understanding of the possible mechanism for fracturing shales, three structure maps and eight structural crossing sections were constructed (Figures 17 to 22). Structure maps were drawn on top of the Mississippian Berea Sandstone, bottom of the Middle Devonian Huron Member of the Ohio Shale Formation, and the top of the Middle Devonian Onondaga Limestone. The Berea structure map was drawn on top of this horizon as the bottom of the overlying Sunbury Shale (Coffee Shale) is easily recognized on drillers' logs and geophysical logs.

Fig. 16. Cottageville field setting in relationship to basement structures and magnetic intensity contours (from deWys and Shumaker, 1977).

Fig. 17. Structural contour map on top of the Mississippian Berea Sandstone.

Fig. 18. Structural contour map on the bottom of the Middle Devonian Lower Huron Member of the Ohio Shale Formation.

Fig. 19. Structural contour map on top of the Middle Devonian Onondaga Limestone.

Fig. 20. Structural cross sections A - A' and F - F'.

Fig. 21. Structural cross sections B - B', D - D', and G - G'.

Fig. 22. Structural cross sections C - C', E - E', and H - H'.

The Berea structure map (Figure 17) exhibits a total relief of 394 feet across the map area with a subsea elevation change of from -1,261 to -1,655 feet from northwest to southeast. Two interpretations were made of this horizon: (1) a contour interval of 20 feet was chosen and then a map was constructed (Figure 17); and (2) a map with a contour interval of 10 feet was constructed. The first map (contour interval 20 feet) shows the general northeast strike of the structure with a surface dipping somewhat uniformly to the southeast along with some bending and meandering of the contour intervals. However, the second map (contour interval 10 feet) portrayed a very different structural picture. The strike of the structure was generally the same, but this contour interval appeared to create a multitude of inferred cross-strike faults (Nuckols, 1978) and a steepening of dip to the southeast in some areas (especially from -1,410 to -1,540 feet). However, due to the questionable control of formation tops and bottoms from drillers' logs, a map contour interval of 10 feet may not be realistic. In addition, direct evidence of faulting could be detected from these logs. An apparent change in dip or a monoclinial flexure feature (from -1,420 to -1,540 feet) could readily be detected on both map interpretations, but is most readily apparent on structural cross sections A - A', B - B', and C - C' (Figures 20, 21 and 22).

A second structural map constructed on the bottom of the Lower Huron Member (Figure 18) shows a relief of 638 feet across the map area with a subsea elevation change from -2,974 to -3,432 feet (from northwest to southeast). Two interpretations were also made of this horizon: (1) a map was contoured on an interval of 20 feet

(Figure 18), and (2) another was contoured on a 10-foot interval. The first map (contour interval of 20 feet) exhibited features similar to those seen on the first Berea structural map (Figure 17). The second Lower Huron structure map exhibited a multitude of cross-faults similar to those seen on the second Berea map (also the faults were discounted due to the above mentioned reasons). Again, a monoclinial flexure feature was observed on both contour interval maps from -2,990 to -3,610 feet. This feature can readily be seen on structural cross sections D - D' and E - E' (Figures 21 and 22). The monoclinial structural feature was found to have approximately 120 feet of relief on the Berea map (Figure 17) and approximately 170 feet of relief on the bottom of the Lower Huron map (Figure 18).

A third structural map was constructed on top of the Middle Devonian Onondaga Limestone (Figure 19). Within the map area, the Onondaga has a total relief of 825 feet with a subsea elevation change from -3,218 to -4,043 feet (from the northwest to the southeast). With limited data available in the shale gas field proper, a truly accurate picture of the previously mentioned anomalistic structure could not be determined. However, in isolated areas of the map, there appears to be unusual monoclinial features (as seen on the Berea and Lower Huron structure maps). These features can be seen on structural cross sections F - F', G - G', and H - H' (Figures 20, 21 and 22).

The following conclusions and correlations can be derived from these structure maps and cross sections:

- 1) Previous investigations had not recognized the low relief structure or the presence of any structure within the Cottageville gas field.
- 2) Trending almost parallel to the gas field trend (from northwest to southeast) are low monoclinal flexure structural features. These features can be seen on Figures 17, 18 and 19 and are especially evident on the structural cross sections.
- 3) The monoclinal flexure structural features may be the near-surface reflection of basement-associated faults that may be dying out in the Devonian shale and lower Mississippian sediments (Sundheimer, 1978).
- 4) Increasing relief of monoclinal flexure features with depth and general increasing dip of the structure maps with depth (394 feet of structural relief across the map area for the Berea Sandstone, 638 feet of structural relief across the map area for the bottom of the Huron Member, and 825 feet of structural relief across the map area for the Onondaga Limestone) indicate a rapid thickening of the sedimentary section to the east.

Subsurface Fracturing

Probably the single most important gas production mechanism in the Cottageville field is fracture porosity and permeability. Location of fractured shales can be greatly assisted by knowledge of the main causes of fracturing. Overbey, et al, (1974) considered the following causes:

- A. Causes of fractures directly in the shales.
 - 1. Differential compaction around a sand body contained in a larger shale unit.
 - 2. Sedimentary features associated with reef growth.
 - 3. Abrupt facies change and a change in the physical properties of the rock.
 - 4. Fractures produced in carbonate units beneath an unconformity surface as a result of jointing and solutioning along joints in karst zones.
 - 5. Gravity sliding of certain types of sediments to produce landslides and slumps later buried by younger sediments.
- B. Causes of fractures in shales inherited from basement rocks and propagated vertically.
 - 1. Continental drift movements associated with horst and graben faulting produced during opening and closing of the ocean floors.
 - 2. Gravity faulting due to loading of formations from sediment accumulation (growth faults).

Direct evidence of shale fracturing has been documented in one cored Devonian shale well (Jackson - 1369) from the Cottageville field. Mineral-lined fractures were found to be restricted to Zone II of the Lower Huron Member (Figure 23) in an interval extending from 3,720 to 3,796 feet in depth (Byrer et al, 1976). However, the greatest concentration of fractures occurred from 3,720 to 3,730 feet (Byrer et al, 1976) that correlated with gas shows on the temperature log of the well. There appeared to be considerable dispersion in the orientation of mineral-lined fractures in this core (Figure 24); however, three directions predominate: N 40° to 50° E, N 10° to 20° W, and N 80° to 90° W.

Larese and Heald (1976) examined four samples with veins of minor mineralization along fractures from the core interval 3,720 to 3,730 feet in well Jackson - 1369. They found that dolomite was the exclusive vein material except for very small amounts of calcite occurring with dolomite from one sample (3,729.5 feet). The maximum width of most veins measured was 1.5 mm. The vein material in all the samples from well no. Jackson - 1369 only partially filled the fractures, leaving vuggy openings. Dolomite lining these openings formed saddle-shaped rhombohedrons that were built with overlapping plates resembling a shingled roof. Calcite crystals were more pointed and occurred in the form of scalenohedrons with the typical habit of dog-tooth spar. The openings along the veins were found to be generally connected, thereby creating a high permeability.

Fig. 23. Columnar section of the Jackson-1369 well depicting cored intervals and subdivision of the Devonian shale section as interpreted from geophysical logs. Core depths are not corrected to ground level (from Larese and Heald, 1976).

Fig. 24. Orientation of fractures in core samples from the pay zone interval (3,720' and 3,796') of the Jackson-1369 well. The majority of fractures measured were mineral-lined. Source of data - Royal J. Watts, USERDA - MERC (from Larese and Heald, 1976).

In one specimen from the core, Larese and Heald (1976) found several minute shears that were observed to be within the shale matrix. These shears were found to be commonly associated with pyrite nodules and were apparently developed as a result of adjustment around the nodules with fracturing of the enclosing shale. Although they noted very minor amounts of dolomite along the fractures, the majority of the shears lacked mineral linings and appeared tight and impervious.

PRODUCTION

INTRODUCTION

The Devonian shales do not possess a uniform potential for gas production throughout their entire distribution. Western regions of the Appalachian basin are richest in gas production, because this area offered the best depositional conditions in which an abundance of organic material was deposited. However, areas of greater shale thickness are not necessarily richer commercial gas producers than those areas with thinner shale zones. For example, even though southwestern West Virginia is underlain by a thinner Devonian shale sequence (than what is found in the northeastern portion of West Virginia), it produces considerably more Devonian shale gas than the thicker sequences. Hence, it is evident that exploratory studies (such as the one for Cottageville) of the Devonian shale in the entire Appalachian basin should not be based on a specific thickness alone. Caution should be exercised in basing gas estimates on a uniform gas content per cubic foot of shale, unless such estimates represent a carefully weighted mean value for different regions of the Appalachian basin.

The low porosity of the Devonian shales makes them a very poor reservoir rock. However, enormous quantities of gas are estimated to be dispersed within the quadrillions of cubic feet of shales. The low permeability of the shales makes them potentially excellent sealing or source rocks, and therefore accumulations of hydrocarbons within fissures, joints, or other fractures will remain sealed within this shale reservoir (if the fractures are limited stratigraphically).

One of the main problems in a resource evaluation study of the Devonian shales is to determine more accurately the thickness and extent of the various organic Brown shales in West Virginia and to accurately calculate their organic content, amount of gas in place, and "producible" reserves. To accomplish this, it will first be necessary to conduct individual field studies to ascertain if the productive Brown shale sections are the same from well to well and field to field, and to determine the importance of intervening lighter-colored shales in gas production. Many of the Brown shale fields (Figure 25) merge together, especially near the Kentucky border, and many produce from other formations as well (co-mingled production is very prevalent). Toward the north, however, there are several isolated fields in Putnam County, and another still farther north in Jackson County (Cottageville).

The success ratio (wells that produce enough gas initially for individual operating companies to economically produce) for Devonian shale gas wells within these established southern fields is very high, exceeding 90 per cent (compared to 95 + % for Cottageville). Initial open gas flows are often low, averaging only 350 thousand cubic feet per day, while per well reserves are estimated at 350 million cubic feet (MMcf) by Brown (1976), assuming 150-acre spacing between wells. At drilling depths in this area (southwestern West Virginia), Devonian shale wells are considered to be marginally economic at current well costs and gas prices (1978). A significant point that is made when discussing the potential of the Devonian shales as a future gas source is that the calculated recoverable

Fig. 25. Gas fields with production from the Brown shale in southwestern West Virginia. Production extends northward from Cabell County into Ohio, and southwestward from Wayne and Mingo Counties into the Big Sandy Field, eastern Kentucky (from Patchen, 1976).

reserves per well are less than 10 per cent of the calculated gas in place in the darker, organic-rich shales (Brown, 1976). This low recovery rate is believed to be due to the manner in which the gas is locked within the shales and the way it is transmitted from the rocks to the well bore. Gas is thought to be held in the shales in three ways: (1) as free gas within fractures, (2) adsorbed on fracture surfaces, and (3) absorbed within the shale matrix in large shale blocks between fractures (Brown, 1976; Bagnall and Ryan, 1976). Free gas within fractures is the first to be produced to the well bore, followed rather quickly by adsorbed gas on fracture surfaces.

It can, therefore, be inferred that gas production from the shales is controlled by the presence of fractures within the shales. Presumably the higher initial flow wells intersect more fractures and produce free gas and adsorbed fracture gas at higher rates than wells that intersect fewer fractures. Once the flush production is over (production from free and adsorbed fracture gas), the larger blocks of shale between fractures yield their absorbed gas very slowly to the fractures and then to the well bore. At this point, the decline curves are nearly horizontal and remain so for many years as this type of gas continues to bleed off very slowly. Wells intersecting more fractures should thus level off at higher flow rates than wells intersecting fewer fractures.

FACTORS GOVERNING NATURAL GAS ACCUMULATIONS

The organic material within the shales is the main source for production of natural gas and oil hydrocarbons. Economic accumulations of gas in any given area are dependent on the forces governing primary and secondary gas migration and the types of gas traps in the area. Primary gas migration consists of the transfer of the gas from the source rocks to the reservoir rocks; whereas, secondary migration consists of rearrangement of the gas within the reservoir rock and accumulation into traps to form producing pools (such as Cottageville). Clark (1934), Lahee (1934), Lalicker (1949), Levorsen (1954), McCoy and Keyle (1934), Rich (1934), Torrey (1934), and others have published extensive discussions on the mechanisms of gas migration. These include: (1) compaction, (2) capillarity, (3) differential specific gravity, (4) hydrostatic pressure, (5) gas pressure, (6) cementation, (7) diastrophic movements, and (8) pressure from volume increases when some salts are precipitated from solution. Knowledge of primary and secondary gas migration mechanisms is of great importance in the exploration for gas traps. Once the traps have been found, migration mechanisms are still important in determining the gas transfer process from the trap into the well bore.

Theoretically, most gas molecules occupy the intergranular vacancies of the shale matrix (primary porosity gas). From these highly dispersed sites, gas molecules are transferred into nearby fractures. A successfully located well intersects many

fractures of the interconnected fracture network. Therefore, once a gas molecule enters a fracture, it is driven toward the well by a pressure gradient.

Accumulations of gas in the Devonian shales may, for all practical purposes, be classified into two major categories as follows:

- 1) Unfractured shales
- 2) Naturally fractured shales

Gas Occurrence in Unfractured Shales

The gas contained in unfractured shales occupies the intergranular pores of the shale matrix. These are the pores constituting the primary, intergranular or original porosity. The mechanism for gas production from unfractured shale is predominantly diffusion. Little work has been done on diffusion of natural gas in shales. Schlettler (1976) theoretically calculated a depletion thickness of 1.5 centimeters over a period of 1 year with a diffusion constant equal to 1.10^{-17} cm²/sec. From these calculations, it is apparent that it takes a great deal of time for intergranular gas molecules to migrate even a very short distance. Thus, commercial production from virgin shales will most likely require extensive induced fracturing (for example, hydraulic fracturing). This situation apparently exists outside the Cottageville field proper where less fracturing has occurred (see discussion on Subsurface Structure).

Gas Occurrence in Fractured Shales

Many shale formations contain natural open fractures and, therefore, potentially, have a high secondary porosity. The rock

separation or displacement in these shales consists of fissures, joints, bedding partings, and faults. These rock voids offer an excellent system of circulation channels for gas, drastically reducing the need for induced fracturing of the shales around the well. Production experience from naturally fractured shales has shown that shooting (in the past) or hydrofracturing (currently) greatly enhances the well-flow rates. Shooting and hydrofracturing increase the degree of fracture interconnection and, consequently, the drainage volume around the well.

GAS FIELD SETTING

The Devonian-age formations that underlie the Cottageville gas field are approximately 2,300 feet thick. The Middle and Upper Devonian shales comprise the upper 2,100 feet of that section. The upper contact of the Devonian shales is placed at the base of the Mississippian Berea Sandstone, and the lower contact at the top of the Middle Devonian Onondaga Limestone. Within this predominantly shale section, are found light grey to brown-black shales, light to medium grey siltstones (and very rarely white to light grey sandstones) and an unconformity in the lower part of the Westfalls Formation. Of the different shale lithologies, the dark organic-rich shale zones occupy approximately 350 feet or 17 per cent of the entire shale section. These highly organic shale zones occur in three stratigraphically distinct portions of the shale section and are easily recognizable on gamma ray and density logs (Figures 6, 7 and 8). The upper two organic zones (Zones II and III) are found within the Lower Huron Member of the Ohio Shale Formation. These two organic-rich zones are mainly composed of dark brown-black shales, but occasionally have light-to-medium grey shale and siltstone interbeds. Separating the lower and upper organic shale zones of the Lower Huron Member are lithologies of light-to-medium grey shale and siltstone with an occasional thin organic shale bed. Within the Cottageville gas field, Zones II and III have an average combined thickness of 250 feet and are the main reservoirs for Devonian shale gas production. Below these two organic zones of the Lower Huron Member,

is a third organic zone found in the Westfalls Formation. Like the younger shales found in the Huron, this organic-rich shale has interbeds of light-to-medium grey shale and siltstones. This organic-rich shale has an average thickness of approximately 100 feet, but has rarely produced any gas within the Cottageville area.

Regional east-west correlations of the Devonian shale sequence (Schwietering, 1979) indicate the absence of deposition of the Huron organic-rich shale zones just east of the Cottageville field (Martin and Nuckols, 1976). The gradual facies change of the organic shales to the east seems to coincide with the western edge of the Rome trough (Figure 15), thereby indicating a possible mechanism for changes in the depositional environment. The western edge of the trough has been postulated to be a basement fault or fault zone that may have created the stress fields that would open fractures in the shale necessary for production of natural gas (Martin and Nuckols, 1976).

GAS PRODUCTION

Drilling for shale gas in the Cottageville area began October 9, 1929, when the Federal Fuel Corporation drilled the first shale well. This well proved to be a meager beginning for the shale field as the well had a natural open gas flow of only 4.5 Mcf/d and a 213 Mcf/d final flow after stimulation by shooting. At that time, a well with such a small flow could not economically compete with shallower plays in the Berea and Injun sands that produced wells with natural flows of several million cubic feet of gas per day. However, as the field developed, wells with natural gas open flows up to 3.4 million cubic feet per day of gas (MMcf/d) were drilled, which encouraged additional developmental drilling.

The primary target for drilling has been the highly organic shale zones of the Lower Huron Member of the Ohio Shale Formation (known in Ohio as the Big and Little Cinnamon). A typical drilling program initially involves setting casing just below the Berea Sandstone. The Berea Sandstone and shallower Salt Sands (First, Second, and Third) of this area produce large volumes of saltwater and, therefore, must be cased off to insure a completion in the Devonian shale section. After the casing is set, the well is usually drilled to a point just below the lower organic shale zone in the Lower Huron Member (Zone II). At that depth the formation is normally tested for gas flow. A decision is made whether to produce the well naturally, if there is sufficient natural flow, or to stimulate the well if there is no flow of gas or a small subeconomical flow of up to

several hundred thousand cubic feet. Within the Cottageville field, 82 per cent of the wells have been stimulated by employing the shooting stimulation technique.

Shooting a well means that canisters of 80 per cent gelled nitroglycerine are lowered into the bore hole and then detonated. Some variation in shooting techniques, such as tamping the shot with pea gravel to contain the explosion (and thereby hopefully retain more energy to fracture the shale) has been tried. Until the late 1960s, drilling within the field was done exclusively by cable tool drilling rigs. This meant that wells stimulated by shooting open hole without tamping the shot ran the risk of being clogged by rubble from the shot. If the shot went smoothly, the hole would blow itself clean. This clean-up aspect of production stimulation was very critical; a shot that did not clean the bore hole risked losing a part or even all of its production potential. With the adoption of air rotary drilling, wells could either be shot tamped or untamped, and then careful reentry techniques could be applied to successfully clean out the remaining rubble.

After some 48 years of in-field drilling, approximately 110 shale wells have been drilled in the Cottageville field (Table 3, and Figure 2). Consolidated Gas Supply Corporation has drilled more wells than any other company (43); Columbia Gas Transmission Corporation, Cities Service, and Kaiser Exploration and Mining Company have drilled 17, 16 and 5, respectively (as of January 1, 1977)

<u>Year</u>	<u>No. of Wells Drilled</u>	<u>Per Cent of Total Wells Drilled</u>
1929	1	1
1930	1	1
1931	1	1
1947	4	3.5
1948	10	9
1949	9	8
1950	63	57
1951	6	5.5
1954	1	1
1957	1	1
1970	1	1
1974	2	2
1975	3	3
1976	7	6
TOTAL	110	110.0

Table 3. Summary of annual Devonian shale drilling activity.

The highest natural gas flow encountered while drilling was 3,480 Mcf/d, and the highest stimulated flow was 1,981 Mcf/d. This last well had a natural flow of only 36 Mcf/d. With the passage of time, rock pressures have generally decreased as the number of wells drilled to the reservoir increased (Figures 26 and 27). The highest initial rock pressure taken was 1,000 pounds per square inch early in the history of the field. Several wells have good production histories, but one in particular has produced over 953,500 Mcf in 26 years and is still producing (as of January 1, 1977).

Of the three organic-rich shale zones within the Devonian shale section, only those within the Lower Huron Member have been extensively drilled and stimulated. The primary gas reservoir in the Cottageville gas field is the lower organic shale zone (Zone II) of the Lower Huron Member (Martin and Nuckols, 1976). Stimulation of this organic shale zone by shooting has, for the most part, greatly increased the volume of gas produced from this field. However, the gas primarily comes from naturally occurring open fractures that were either penetrated by drilling or that were interconnected to the well bore by shooting.

In 1975, Consolidated Gas Supply Corporation and the United States Energy Research and Development Administration entered into an agreement to core and analyze the shale section for two wells in the Cottageville field. The first core was taken in a well near the Jackson-Mason County line. This first cored well, the E. L. Bailer Jackson - 1369, was located approximately five miles

Fig. 26. Initial well head pressure decline in the Cottageville field. Data points are either single well pressure values or several well pressures averaged together.

Fig. 27. Isopressure map of the Cottageville gas field.

southeast of the town of Cottageville, West Virginia (Figure 2). The second cored well, the W. L. Pinnell Jackson - 1371, was located three miles west of Cottageville, West Virginia (Figure 2). The two cored sections from the E. L. Bailer Jackson - 1369 well were examined and described in detail by Byrer, Trumbo and Rhoades (1976).

The top of the first cored section from the Jackson - 1369 well was 3,410 feet deep with the bottom of the core at 3,500 feet (Figure 13). The top of the second cored section was 3,600 feet deep with the bottom of the core at a depth of 3,797 feet. The total length of core obtained was 287 feet. Coring of the Lower Huron Member (Zone II) was interrupted when an initial gas flow of approximately 4,000 Mcf/d was encountered. This flow finally stabilized at 1,007 Mcf/d.

The analysis of the upper section of the core (3,410 to 3,500 feet) shows that the shale is medium to dark grey and dark brown in color with numerous pyrite nodules, silt stringers, spore casts, and carbonaceous fossil fragments. The lower section (3,600 to 3,797 feet) is a medium dark-grey to dark-brown color with silt stringers, pyrite nodules, spore casts, and carbonaceous fossil fragments. Mineral-filled fractures were found to be concentrated at a depth from 3,720 to 3,730 feet, and a few unmineralized fractures were found toward the bottom of the section. The gamma ray log from Figure 13 shows zones of high radioactivity between 3,426 to 3,470 feet and also between 3,676 and 3,784 feet, with the lower section containing the highly mineralized fractures.

A core from the W. L. Pinnell Jackson - 1371 well in the north-west portion of the field was also studied (Figure 14). The top of the cored section was at a depth of 3,220 feet, and the bottom of the core was at 3,690 feet. The total length of the core was 470 feet (Figure 14). Analysis of the core showed that the shale had few natural fractures (no mineralized fractures), and there were many silty zones and silty laminations throughout the shale zone. Most of the brown shale interval (as in Jackson - 1369) was medium to dark grey and dark brown with numerous zones of alternating thin laminations of medium to dark grey and dark brown shale. Distorted bedding indicating differential loading of the sediments is evident throughout the core, as was the smell of kerogen material. The gamma-ray log shows areas of high radioactivity at 3,275 feet, 3,380 feet, and a zone between 3,490 and 3,640 feet. The bulk density log and hardness test results are also shown on Figure 14.

Detailed laboratory analysis of the Jackson - 1369 core revealed low matrix porosities and permeabilities (Tables 4 and 5). From the detailed analysis of core data, a zonation characterization was attempted (Table 6). These data show that the average porosity for Zone II organic shales in the Lower Huron Member is much less than that for either the overlying grey shale interval or Zone III organic shales. In addition, this zone appears to have a higher average degree of residual oil saturation, lower water saturation, and lower grain density. By averaging (considering the high oil/water ratios and lower grain density of this one well), it appears that

Stratigraphic Interval		Sample Number	Depth (Feet)	Permeability (Millidarcys)	Porosity (Per Cent)	Residual Saturation (Per Cent Pore)		Grain Dens. (Grams/cc)
						Oil	Water	
Lower Huron Member of the Ohio Shale Formation		1	3412.0	<0.1	2.7	0.0	84.3	2.75
		2	3416.1	<0.1	3.4	5.0	73.8	2.72
		3	3421.9	<0.1	5.2	7.1	43.3	2.71
	Zone III	4	3426.5	<0.1	2.0	6.1	75.5	2.73
		5	3430.4	<0.1	1.9	4.3	51.1	2.77
		6	3437.5	<0.1	3.5	6.1	80.5	2.73
		7	3440.4	<0.1	4.0	9.1	52.5	2.65
		8	3446.5	<0.1	4.4	7.8	80.0	2.78
		9	3450.1	<0.1	2.7	6.1	83.3	2.72
		10	3455.5	<0.1	3.4	7.2	73.5	2.75
		11	3461.0	<0.1	2.9	5.7	54.3	2.74
		12	3467.1	<0.1	3.0	5.5	58.9	2.66
		13	3471.9	<0.1	4.0	5.2	81.3	2.71
		14	3475.6	<0.1	4.1	4.0	78.0	2.76
		15	3480.0	<0.1	3.4	0.0	71.4	2.73
		16	3485.0	<0.1	3.3	0.0	88.5	2.76
		17	3489.8	<0.1	3.0	0.0	69.9	2.76
		18	3494.6	<0.1	1.4	0.0	45.7	2.77
		19	3500.0	<0.1	0.8	0.0	57.9	2.71
		20	3600.7	<0.1	4.6	6.2	61.9	2.80
		21	3605.4	<0.1	1.7	0.0	63.4	2.80
		22	3609.3	<0.1	4.3	4.7	73.3	2.81
		23	3614.7	<0.1	3.3	0.0	68.4	2.76
		24	3620.5	<0.1	3.9	0.0	60.0	2.83
		25	3626.0	<0.1	3.0	0.0	90.3	2.85
		26	3630.4	<0.1	3.7	0.0	83.6	2.78
		27	3635.9	<0.1	3.6	0.0	87.0	2.75
		28	3641.0	<0.1	3.8	0.0	88.0	2.73
		29	3645.0	<0.1	1.6	0.0	60.0	2.74

Table 4. Dean-Stark plug core analysis results for well no. Jackson - 1369
(core analysis performed by Core Laboratories, Inc. of Dallas, Texas).

Stratigraphic Interval		Sample Number	Depth (Feet)	Permeability (Millidarcys)	Porosity (Per Cent)	Residual Saturation (Per Cent Pore)		Grain Dens. (Grams/cc)
						Oil	Water	
Lower Huron Member of the Ohio Shale Formation	Zone II	30	3649.0	<0.1	2.5	4.8	59.7	2.66
		31	3655.0	<0.1	3.4	9.6	54.2	2.62
		32	3660.6	<0.1	2.8	7.2	68.1	2.65
		33	3666.0	<0.1	2.0	8.2	71.4	2.57
		34	3671.0	<0.1	3.9	7.3	64.6	2.72
		35	3676.0	<0.1	2.4	6.9	63.8	2.64
		36	3681.0	<0.1	2.2	9.4	69.8	2.60
		37	3687.1	<0.1	3.0	8.3	48.6	2.62
		38	3696.5	<0.1	3.0	8.8	66.2	2.58
		39	3700.0	<0.1	1.9	4.3	85.1	2.56
		40	3705.5	<0.1	2.7	9.5	69.8	2.64
		41	3709.9	<0.1	3.5	9.5	54.8	2.62
		42	3714.0	<0.1	4.3	10.6	51.0	2.59
		43	3719.1	<0.1	3.9	0.0	75.3	2.74
		44	3727.0	<0.1	3.0	8.3	77.8	2.71
		45	3729.3	<0.1	2.7	6.1	81.8	2.75
		46	3735.0	<0.1	3.4	9.8	56.1	2.65
		47	3741.0	<0.1	3.1	9.2	53.9	2.58
		48	3745.8	<0.1	2.7	6.2	78.5	2.69
		49	3752.0	<0.1	2.7	7.7	67.7	2.59
		50	3755.0	<0.1	3.7	4.9	73.2	2.78
		51	3759.0	<0.1	3.0	11.3	63.4	2.63
		52	3765.0	<0.1	2.3	7.4	68.5	2.64
		53	3770.0	<0.1	2.6	6.3	82.5	2.69
		54	3775.0	<0.1	3.4	10.6	63.6	2.62
		55	3781.0	<0.1	2.1	7.8	78.4	2.59
		56	3784.5	<0.1	2.2	5.6	79.6	2.61
		57	3790.0	<0.1	3.4	2.4	69.5	2.67
		58	3795.0	<0.1	3.2	3.9	71.1	2.65

Table 4. Continued

Stratigraphic Interval	Sample Number	Depth (Feet)	Overburden Pressure, PSI	
			1650	3700
Zone II			<u>Air Permeability (Md.)</u>	
	1	3624.0	0.0013	0.00032
	2	3733.5	0.00034	0.00034
	3	3735.0	0.00045	0.00023
	4	3740.0	0.0019	0.0011
	5	3742.0	0.0012	0.00038
	6	3743.5	0.00023	0.00011
Zone II			<u>Porosity (Per Cent)</u>	
	1	3624.0	0.5	0.3
	2	3733.5	0.4	0.2
	3	3735.0	0.2	0.1
	4	3740.0	0.3	0.2
	5	3742.0	0.4	0.2
	6	3743.5	0.4	0.2

Table 5. Permeability and porosity as a function of overburden pressure for well no. Jackson - 1369 (core analysis performed by Core Laboratories Inc. of Dallas, Texas).

Stratigraphic Interval	Average Permeability (Millidarcys)	Average Porosity (Per Cent)	Average Residual Saturation (Per Cent Pore)		Average Grain Density (Grams/cc)
			Oil	Water	
Lower Huron Member of the Ohio Shale Formation	< 0.1	3.07	4.85	69.55	2.71
Zone III	< 0.1	3.18	6.31	69.09	2.72
Zone II	< 0.1	2.93	7.31	67.86	2.64
Internal Between Zones II & III	< 0.1	3.09	0.93	71.71	2.77

Table 6. Stratigraphic zonation analysis of Dean - Stark plug analysis data for well no. Jackson - 1369.

Zone II organic shales are the primary originator of natural gas (and some oil) in the Cottageville field.

APPLIED STIMULATION TECHNIQUES

It is characteristic that shale wells produce gas at relatively low rates for very long periods of time. Many wells producing gas from the Appalachian Devonian shale have been producing for several decades. Performance comparisons between stimulation techniques cannot then be based solely on flow rates measured immediately after stimulation (that is final open gas flow data), but one must consider the production decline curves for a number of years. For example, production comparisons drawn by Kentucky - West Virginia Gas Company for gas wells, shot and fractured in the southeastern Kentucky area, show that the major advantage of fracturing only becomes evident after comparing production decline curves of several years' duration.

Standard Shooting

The technique of explosive shooting for stimulation in Devonian shale gas wells has become so standard that it is called a well completion technique. The normal procedure is to fill the entire open hole shale interval with 80 per cent gelled nitroglycerine, (with a sand and/or water tamp) and to detonate it with a blasting cap. Most wells that have been stimulated this way, even if they had no gas show or a slight show, become on-line producers. This technique, with little change, goes back to the early history of the Devonian shale gas play. The disadvantages are that extensive cleanout is required, and the open flow rates obtained are lower than those that may be achieved with other techniques.

Hydraulic Fracturing

Hydraulic fracturing is a technique whereby the in-situ stress field is utilized to propagate a fracture using hydraulic pressure in a petroleum or natural gas reservoir; the in-situ stress field often determines the direction of propagation. The purpose is to open artificial flow channels from the reservoir into the well bore and thereby enhance hydrocarbon recovery. This is accomplished by pumping fluid under high pressure into the formation and then propping open the fracture once it is created with sand, glass beads, walnut hulls, or other such agents. The fluid utilized has to be designed for the specific reservoir rock and formation fluid properties so as not to damage the formation or inhibit production. The compatibility of hydraulic fluids is an extremely important aspect of shale stimulation since some fluids may cause some shales to expand, thereby cutting off potential gas production. Within the last few years, hydraulic fracturing has been attempted on the Devonian shales within the Cottageville field, principally by Kaiser Exploration and Mining Company. The somewhat expected meager success (since all wells had an initial open flow of zero) of some of these stimulation attempts is documented in Table 7.

Foam Fracturing

Foam fracturing is a process whereby nitrogen, water, and an emulsifying agent are combined and used as the fracturing fluid. One advantage of this system is the inhibition of leakoff in a permeable formation due to the strength of the gas bubbles and their

<u>W.V. State Permit No.</u>	<u>Organic Zone(s) Treated</u>	<u>Initial Open Gas Flow (Mcf/d)</u>	<u>Final Open Gas Flow (Mcf/d)</u>	<u>Shut In Pressure (Lbs. p.s.i.)</u>	<u>Treatment Description</u>
1374	Zone II	0	86	600	900 bbls of water and 50,000 lbs. of sand
1376	Zone II	0	?	850	1,090 bbls of water and 85,000 lbs. of sand
1378	Zone II and III	0	?	1025	372 bbls of water and 50,000 lbs. of sand
1380	Zone II	0	?*	1200	1,500 bbls of water and 87,000 lbs. of sand
1384	Zone II	0	100	680	971 bbls of water and 15,000 lbs. of sand

* Reported co-mingled production with the Devonian Oriskany Sandstone

Table 7 - Hydraulic fracturing stimulation results from five Devonian brown shale wells within the Cottageville gas field.

ability to block off pores and reorient the force along the plane of weakest stress. Laboratory tests run by Halliburton (private communication, 1978) to test leakoff characteristics of water versus foam indicate conclusively that because of the leakoff resistance with foam, three times the fracture surface area could be generated with foam.

Within the Cottageville field, only one large-scale foam fracturing operation has been attempted (Jackson - 1371). Here, the Energy Research and Development Administration in cooperation with Consolidated Gas Supply Corporation conducted a foam fracturing treatment using 973 barrels of water, 2,160 MSCF nitrogen, and 155 thousand pounds of sand proppant. The gross perforated formation interval was from 3,238 to 3,629 feet in the Lower Huron Member (Zones II and III). The fracture test was conducted to help evaluate the effectiveness of foam fracturing in the low-pressure water-sensitive Devonian shale of the Appalachian basin. The well had no natural flow of gas, but after being stimulated, it had an absolute open flow potential of 173 thousand cubic feet per day. An 804 hour pressure buildup test run on the well after the flow test indicated a static reservoir pressure of 564 psi, a well capacity of 3.42 millidarcy-feet, and an induced fracture half-length of 1,155 feet (private communication with Halliburton, 1978). Testing of this well was completed in early 1976 and it was not turned into production until the late spring of 1976. With the limited amount of production

data available, the well apparently will maintain a rather meager production of gas and, for all purposes, will be subeconomical.

Summary

The following summarizes the types of stimulation techniques employed within the gas field and the distribution of wells associated with gas flow ranges:

<u>Type of Stimulation</u>	<u>No. of Wells</u>	<u>Average Natural Gas Flow (Mcf/d)</u>	<u>Average Flow After Stimulation (Mcf/d)</u>
Shooting with 80% gelled nitro- glycerin	86	177.3	355.0
Normal hydraulic fracturing	5	0	93 (2 wells)
Foam fracturing	1	0	173

GAS PRODUCTION DECLINE AND ANALYSIS

After some 48 years of in-field drilling, approximately 110 Devonian shale wells have been drilled in the Cottageville field. Of these wells, only 62 production records could be obtained. The following is a company summary of this production:

	<u>No. of Wells</u>	<u>First Well Drilled</u>
Consolidated Gas Supply Corporation (formerly Hope Natural Gas Company)	41	1-17-49
Columbia Gas Transmission Corporation (formerly United Fuel Gas Company)	11	4-26-50
Cities Service Company (obtained wells from Federal Fuel Corporation and Columbia Carbon Company)	10	11-09-29

Production decline analysis was performed on 44 wells by using the Morgantown Energy Technology Center computer programs for production analysis. All production well data was utilized for wells that had been producing for 5 years or more. This cutoff point was deemed necessary, since fitting an exponential decline curve to the data required this much data to forecast total potential production. In addition, each well's first year of production was eliminated, since all wells studied had not been put on line until sometime after the first of each year.

The first step in production versus time analysis was to fit a curve to the individual well production data by using a least squares approach. This was done for every well with a resulting exponential decline curve fitted to all data points (Appendix A). In addition to

fitting a curve to the data points, the exponential curve was extrapolated out to forecast production for 2-1/2 times the actual production span. After this was accomplished, the wells were then grouped according to what their total natural open gas flows (Appendix B) or final open gas flows were (Appendix C). Test flows were grouped into 100 Mcf/d ranges. Annual production within each range was then grouped and an exponential decline curve fitted to the data. Therefore, each gas flow range (either for natural production or stimulated production) was modeled by an exponential decline of least squares best fit. Each curve was then extrapolated out to economic limits; total reserves were assigned to each range; and the time it took to produce that gas out to economic limits was determined. Exponential production decline analysis was then carried out to an annual production rate of 2.4 MMcf. This production averages out to 6.5 Mcf/d gas production, which most utilities within the Appalachian basin consider to be the lowest economical production limit (personal communication, Columbia Gas Transmission Corporation, 1978).

The most common analysis for the estimation of future gas reserves is the use of an exponential decline curve. To fit a mathematically derived curve to individual production values on a time-versus-production graph is often difficult. As can be seen in Appendix A, some production data can be fitted easily and smoothly with a decline curve. However, many wells have erratic production data, and an exponential decline curve cannot be fitted to the

data points; in such situations there is no possibility of predicting future reserves and the production potential for a particular area may be confused. This erratic behavior may be the result of one or more of the following:

- 1) The well may have been shut in during different years for periods of time, either due to mechanical failure of the well-head assembly or because the supply of gas in that area was more than the producer needed.
- 2) Transmission line pressures may fluctuate, thereby either reducing or increasing production of individual wells. Devonian shale reservoirs are typically under low pressure, and an increase or decrease in transmission line pressure would decrease or increase the flow of gas from the well.
- 3) Interference of other producing or newly drilled wells in the field could cause a well to erratically produce from year to year.

To try and evaluate natural and final gas flows in relation to their production potential and therefore potential reserves, Tables 8, 9, and 10 and Figures 28 and 29 were created. As can be seen from Table 8 and Figure 28, there is generally an increase in potential reserves as flow rates increase. However, this is not a linear relationship, and the gas flow ranges appear to be in two distinct clusters. What is unusual about these relationships is that group cluster number III (Table 8) seems to decline faster after 10 to 20 years of production than cluster number I (Figure 28). No definite reason for this difference in production rate can be sited at this time.

Group Number	Number of Wells	Gas Flow Ranges (Mcf/d)	Total Forecasted Reserves (MMcf)	Time to Economic Limit (years)	Exponential Curve Characteristics of Group
I	5	0 - 100 101 - 200 201 - 300	307	42.3	Low initial gas production (15-20 MMcf/y) with flat production decline out to economically forecasted limits.
II	1	401 - 500	312	12.2	High initial gas production with fast production decline characteristics for first 10 years. After first 10 years curve gradually flattens out.
III	37	501 - 600 601 - 700 701 - 800 801 - 900 >1000	664	41.1	Medium to high initial production (40-60 MMcf/y) with moderate production decline for first 15-20 years. After 15-20 years, production decline flattens out; flow ranges 701 - 800 and 801 - 900 have an appreciably faster decline than other ranges in cluster.

Table 8. Production decline summary analysis for initial open gas flows (see Figure 28)

Group Number	Number of Wells	Gas Flow Ranges (Mcf/d)	Total Forecasted Reserves (MMcf)	Time to Economic Limit (years)	Exponential Curve Characteristics of Group
I	12	0 - 100 201 - 300 501 - 600	68	13.4	Low initial production (5-10 MMcf/y) with a low to moderate production decline for first 5 years. After 5 years production decline flattens out. Flow range 501-600 has a faster production decline relative to other declines in the cluster.
II	8	101 - 200 801 - 900 ≥1000	207	16.4	Medium to high initial production (25-50 MMcf/y) with rapid production decline for first 10 years. After 10 years curve gradually flattens out to economic limit.
III	16	301 - 400 401 - 500 601 - 700 ≥1000	468	61.2	Medium initial production (15-20+ MMcf/y) with a shallow production decline slope (nearly flat) out to economic limit.
IV	1	901 - 1000	1,272	71.8	High initial production (45-60 MMcf/y) with a sharp production decline after first 10-15 years of production.

Table 9. Production decline summary analysis for final open gas flows (see Figure 29)

EXPONENTIAL PRODUCTION DECLINES						
Gas Flow Range in Mcf/d	NATURAL OPEN FLOW			FINAL OPEN FLOW AFTER STIMULATION		
	No. of Wells in Range	Total Reserves (MMcf)	Time to Economic Limit (2.4 MMcf/yr) (Years)	No. of Wells in Range	Total Reserves (MMcf)	Time to Economic Limit (2.4 MMcf/yr) (Years)
0 - 100	30	366	53.5	3	37	8.0
101 - 200	4	218	29.5	3	132	12.4
201 - 300	1	338	43.9	7	139	27.6
301 - 400		-----NO DATA-----		9	215	29.7
401 - 500	1	312	12.2	3	744	102.9
501 - 600	1	414	30.7	2	27	4.7
601 - 700	1	1272	71.8	2	555	65.5
701 - 800	1	278	18.3	2	357	46.6
801 - 900	2	572	32.7	2	234	20.8
901 - 1000		-----NO DATA-----		1	1,272	71.8
> 1000	2	784	52.2	3	256	16.1
	<u>43</u>			<u>37</u>		

Table 10. A summary of predicted total gas reserves and time needed to produce these reserves as a function of gas flow tests (either natural or stimulated).

Fig. 28. Summary: Exponential curves fitted for initial open gas flow ranges (100 Mcf/d increments - 43 wells).

Fig. 29. Summary: Exponential curves fitted for final open gas flow ranges (100 Mcf/d increments - 37 wells).

Unlike the natural gas flow summaries, the final gas flow summaries found in Table 9 and Figure 29 seem to be more erratic in their producing characteristics. There appears to be little correlation between final gas flow rates and total forecasted reserves. For example, wells with flow ranges of 301 to 400 Mcf/d (group cluster number III - Table 9) had better reserves than wells with flow ranges of 801 to 900 Mcf/d (group cluster number II - Table 9). Figure 29 shows general decline curves for final gas flow ranges. Within this graph, one cluster (number II - Table 9) appears to decline very rapidly after 5 to 10 years of production and actually does very poorly compared to group cluster number III (Table 9). An explanation for this erratic production may be that these wells, with their comparatively high flow rates (801 to 900 Mcf/d), depleted a limited but open fracture reservoir quickly. Another possible explanation is that the wells partially intersected a fracture system that was being drained by previously drilled wells.

DELINEATION OF PRODUCTION TRENDS

Production characteristics of the gas field may indirectly indicate fracture trends in the reservoir. It would be expected that the trend of open fractures would be reflected by the linearity of many producing parameters. To test this assumption the following maps were used for comparison:

- 1) Isopressure map (Figure 27)
- 2) Initial open gas flow map (Figure 30)
- 3) Final open gas flow map (Figure 31)
- 4) Gas production maps (after de Wys and Shumaker, 1978), including: (A) highest annual production, (B) first five years cumulative production, (C) total cumulative production, and (D) mean annual production.

Isopressure Map (Figure 27)

An isopressure map (Figure 27) was constructed from well-head pressures taken after completion of each well but prior to the well's initial production. There are two important modifying factors that complicate interpretation of the data and resulting map. First, the well-head pressures were taken at various times after completion of the wells. Shut-in times ranged from a few hours to 14 days. Secondly, registration of true potential formation pressure probably did not occur since the well bore may have been altered by rubble from shooting or caving shortly after the withdrawal of drilling equipment. This rubble may possibly block off some production and, therefore, reduce the initial reservoir pressure test.

Fig. 30. Initial open gas flow isopach map of the Cottageville field.

Fig. 31. Final open gas flow isopach map of the Cottageville field.

A less important factor in analyzing initial reservoir pressure tests is the possibility that not all of the gas is being produced from the zone of interest. Production casing is not normally run in a shale well that has been left to produce naturally or has been stimulated by shooting. Thus, the gas could be coming from a shallower zone with less pressure.

From the isopressure map (Figure 27), an obvious linear trend of approximately N 40° E can be observed. This linear trough of low pressure trends through the axis of the field; however, it is interrupted by two areas of high pressure in the north-central portion of the field. Flanking this trough on either side are areas that are interpreted to be at or near their virgin rock pressures. The two high-pressure areas (in the north central portion of the field) were drilled early in the development of the field. These areas may have virgin rock pressures if pressure tests on the outer limits of the field are accurate. This brings up an important factor to consider. What effect does the time of completion have on reservoir pressure? A comparison between the drilling completion date map for shale wells (Figure 32) and the isopressure map (Figure 27) generally indicates a pressure decline for wells drilled later within the field. To better illustrate this point, a graph was constructed to show initial reservoir pressures plotted against date of drilling (Figure 26). It can readily be seen from this graph that wells drilled later in the field have encountered considerably lower reservoir pressures. This point can also be illustrated by observing a series of wells

drilled in 1974, 1975, and 1976 near the Jackson - Mason County Line. A final point to be made is that in order to have this linear drop in reservoir pressure (through time) the fractured reservoir must have been inner connected.

Initial Open Gas Flow Map (Figure 30)

An initial open gas flow map (Figure 30) was constructed from data taken just after the completion of drilling activities. The following shows the distribution of wells within the gas field in association with gas flow ranges:

<u>Initial Open Gas Flow Range (Mcf/d)</u>	<u>No. of Wells in Range</u>	<u>Per Cent of Total</u>
0 - 100	69	80
101 - 500	7	8
501 - 1000	7	8
> 1000	<u>3</u>	<u>4</u>
Total	86	100

As can be observed from the above, the bulk (80 per cent) of the wells fall into the 0 to 100-Mcf/d range with only 20 per cent of the wells having 101 Mcf/d flow or greater. From Figure 30 and Figure 33, several conclusions can be drawn:

- 1) The general trend of the gas flow data is approximately N 45° E to N 50° E.
- 2) The linearity of the gas flow trend is somewhat broken near the center of the field by a bend in the flow trend. This bend creates two shorter linear trends that are offset.

Fig. 33. Initial open gas flow isopach map with high contoured linear trends indicated for the Cottageville field.

- 3) The average initial open flow for 86 wells was 177.3 Mcf/d.
- 4) Normal to the general northeast linear trend are several areas of high initial open gas flows.
- 5) Exceptionally high (greater than 1,000 Mcf/d) gas flows are restricted to a linear trend in the southern portion of the gas field.
- 6) Since fractures are theoretically the main source of permeability within the organic shales, the northeast short linear trends offset by a dog-leg trend are most likely exceptional fracture trends that have enabled unusually high gas flow rates to occur. These trends are very similar to subsurface fracture trends found in well number Jackson - 1369 (Figure 24).

Final Open Gas Flow Map (Figure 31)

In conjunction with the initial open gas flow map, a final gas flow map was constructed (Figure 31). This map is composed of all stimulated wells and wells that had large enough gas flows which did not economically warrant stimulation. The rationale used to develop this map was that it may have been fortuitous that a well was drilled directly into a good fracture system, thereby not warranting stimulation. However, if the well had to be stimulated then it was hoped that a fracture system could be reached. The following is a distribution of wells found within the gas field:

<u>Final Gas Flow Range (Mcf/d)</u>	<u>No. of Wells in Range</u>	<u>Per Cent of Total</u>
0 - 200	34	38
201 - 400	18	20
401 - 600	15	16
601 - 800	9	10
801 - 1000	7	8
> 1000	7	8
Total	90	100

Within the Cottageville field, almost all wells have been stimulated except for the high initial open flow wells. Stimulation by well-bore shooting has dramatically affected gas flows with approximately a 50 per cent increase in flow rates. A comparison of the distribution of wells in the initial gas flow table (on page 90) and the final gas flow table (on page 93) illustrates the upward shift in gas flow measurements by stimulation. From Figures 30 and 31 and Figures 33 and 34, several conclusions can be drawn from the map data:

- 1) The linearity of the gas flow trend is broken by several splays to the north and a dog-leg of the main field trend.
- 2) The average final gas flow rate for 90 wells was 335 Mcf/d.
- 3) An exceptionally high gas flow area that was previously restricted to the southern end of the field (near the Jackson - Mason County Line) can now be extended further northward.

Fig. 34. Final open gas flow isopach map with high contoured linear trends indicated for the Cottageville field.

- 4) Since fracturing is apparently the main mechanism for permeability within the organic shales, the linear high gas flow trends are probably fracture trends.
- 5) Wells drilled in recent years within the field have encountered a somewhat depleted reservoir. A good example of this being Jackson - 1369 in the southern end of the field. This well was drilled in 1975 and is situated among wells that were drilled mostly in 1949 and 1950. As is evident from wells surrounding it, this well was drilled into a reservoir that was partially drained of gas for almost 24 years.

Gas Production Maps

The following gas production maps by de Wys and Shumaker (1978) were used in a comparison with gas flow trends:

- 1) Highest annual production
- 2) First five years cumulative production
- 3) Total cumulative production
- 4) Mean annual production

Within the Cottageville field, approximately 10.61 billion cubic feet of gas has been produced (as of 1-1-77) from 77 wells, with an average cumulative production per well of 137.7 MMcf. To see if an association exists between gauged gas flows producing naturally (Figure 33) and gas flows after stimulation (Figure 34), the two maps were compared to trends that were found on the above-mentioned gas-production maps. To facilitate this comparison, a

composite of the highest annual production, highest first 5-year cumulative production, highest total cumulative production, and highest mean annual production was constructed (Figure 35). From this composite map of well production (Figure 35), the following four major trends were observed:

- TREND NO. 1: A long linear northeast trend in the southern portion of the field that trends parallel to the production and structural strike of the field.
- TREND NO. 2: A somewhat shorter north-northwest trend that is almost normal to trend number 1.
- TREND NO. 3: A northeast linear trend paralleling the structural strike (but off structure) of the field in the northern portion of the field.
- TREND NO. 4: A somewhat shorter northeast linear trend just east of trend number 3.

Several visual comparisons between the initial open gas flow map (Figure 33) and the composite gas production map (Figure 35) can be made. Visual comparison of the maps finds a rough match of trend number 1 of each. However, there seems to be almost no correspondence between trend number 3 of the initial open flow map and trend number 2 of the composite gas production map. There appears to be a weak association between trend number 4 of the composite gas production map (Figure 35) and trend number 2 of the initial open gas flow map (Figure 33). A bulge north of the western

Fig. 35. Composite gas production map of the Cottageville field. This map was developed by superimposing the following four maps and their most prominent trends: (1) highest annual production, (2) first five years' cumulative production, (3) cumulative production, and (4) mean annual production (modified after deWys and Shumaker, 1978).

end of trend number 3 (the initial open flow map) may be the beginning of the northern extension of trend number 3 of the composite gas production map.

Trend associations between the composite gas production map (Figure 35) and the final gas flow map (Figure 34) tend to be better than those between the initial gas flow map (Figure 33) and the composite gas production map. There appears to be a good correspondence of both maps (Figures 34 and 35) between trend 1 (composite gas production map) and trends 1 and 1a (final open gas flow map). The norther portions of trends number 2 and number 3 of the composite gas production map appears similar with the north end of trends number 2 and number 4 of the final gas flow map. There also appears to be no overall association between trend numbers 3 and 4 of the composite gas production map and trend numbers 2 (southern end), 3, and 4 of the final gas flow map.

The significance of association between initial and final gas flow trends and gas production trends is the ability to predict successful wells. If major gas flow trends, such as those found on Figures 34 and 35, can be extended, then new successful wells can be located and drilled. This prediction factor is perhaps the most important key in the exploration for and the successful development of economical new gas wells.

OCCURRENCE OF OIL

Within the Cottageville gas field, there have been reports of oil shows and production from the Devonian organic shale section. The occurrence of oil has been detected mainly in the lowermost portion (lowest one hundred feet) of the Lower Huron Member of the Ohio Shale Formation. A total of 23 wells or 21 per cent of all shale wells within the field have reported encounters with oil. This occurrence has, for the most part, been restricted to just a show of oil except in two cases where oil has actually been produced. These oil occurrences appear to be localized in two distinct trends, with the southern trend containing the most wells with reported shows of oil (Figure 36). In Jackson - 760, oil was reported to be producing at a rate of 10 gallons in 20 hours, while in Jackson - 1294 oil was produced at a rate of 30 barrels per day. No production records were obtainable.

The location and occurrence of oil in this portion of the field is consistent with theories concerning hydrocarbon migration. Structurally, the oil occurrences are down dip and on the southeast side of a structural flexure found on the Lower Huron Member structure map (Figure 18). Just up dip (northwest) from these oil occurrences (trend 1, Figure 36) are the reported large natural and stimulated gas flows (Figures 30 and 31) and high gas production trends that were encountered in the Lower Huron Member.

Gas production has probably been affected by this occurrence of oil in the organic shale. After initially completing a shale well,

Fig. 36. Oil shows and oil production from the lower part of the Lower Huron Member of the Ohio Shale Formation (Zone II). Two apparent general trends occur within the Cottageville

the well was either left to produce naturally or was stimulated by shooting. If the well was shot, then the down-hole rubble (if the well did not clean itself) was not normally cleaned out, and the well was left to produce. During the drilling phase of the well, a show of oil may have been encountered; and if it did not amount to much, it was just noted and forgotten. After the well had been completed and put on-line to produce, this show of oil may have produced enough oil in the following months to start to fill the rubble-filled hole and slowly choke off production. This phase may take months (or years) and may not be noticeable in production records except for the gradual decrease in production rate. In this way alone, oil could be extremely detrimental to shale gas production.

CONCLUSIONS

The Cottageville gas field is a Devonian shale gas producing field in northwestern West Virginia. Gas production and gas show data indicate that primary production is from zones of organic shales in the Lower Huron Member of the Ohio Shale Formation. Due to the extremely low porosity (3 to 4 per cent) and permeability (less than 0.1 millidarcy) of these shales, production of gas is through natural fracture systems. Evidence of these fracture systems can be seen in linear trends that occur on the initial and final gas flow maps (Figures 33 and 34). By stimulation, the drainage ability of each well plus the fracture surface area of the shale was expanded, thereby allowing considerably larger gas flows to be realized.

Possibly, the single most important factor relating to gas production from this field is its proximity to the western edge of the Rome trough. The Cottageville field lies near the eastern limit of thick organic shales of the Lower Huron Member. This factor, combined with the possibility of basement faulting of the western side of the Rome trough, has produced the hydrocarbons and necessary fracturing mechanism for potential shale gas production. As was seen from structure maps constructed on the top of the Berea Sandstone and the bottom of the Lower Huron Member, a single monoclinial flexure structural feature trends southwest-northeast across the gas field. This feature may have been created by the dying out of a basement structure(s) that resulted in a more intense fracturing

across the gas field. Associated with this feature is the primary gas production from the Cottageville field (and also oil shows), with high gas flow rates on top of the structure and oil shows down dip off the structure. Therefore, a classical hydrocarbon migration model can be proposed for this field with the secondary migration of gas into the fractured shale reservoir.

Future exploration within and proximal to the Cottageville field must be based on subtle structural parameters that controlled the fracturing within the organic shales. Only detailed stratigraphic and structural studies will delineate possible potential gas production from these Devonian organic shales.

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APPENDIX A

FINAL OPEN FLOW 21 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 8.142 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 3.1 YEARS

FINAL OPEN FLOW 377 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 24.964 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 4.2 YEARS

FINAL OPEN FLOW 39.5 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 25.221 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 4.8 YEARS

FINAL OPEN FLOW 542 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 36.978 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 4.8 YEARS

FINAL OPEN FLOW 1483 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 43.816 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 4.9 YEARS

FINAL OPEN FLOW 574 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 19.662 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 5.3 YEARS

FINAL OPEN FLOW 103 MC/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 68.443 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 5.7 YEARS

FINAL OPEN FLOW 246 MC/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 23.038 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 8.0 YEARS

FINAL OPEN FLOW 371 MC/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 20.314 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 8.2 YEARS

FINAL OPEN FLOW 736 MC/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 66.867 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 8.6 YEARS

FINAL OPEN FLOW 350 MC/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 206.079 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 9.4 YEARS

FINAL OPEN FLOW 311 MC/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 148.162 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 11.3 YEARS

FINAL OPEN FLOW 341 MMCF/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 88.131 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 11.5 YEARS

FINAL OPEN FLOW 137 MMCF/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 136.429 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 11.5 YEARS

FINAL OPEN FLOW 403 MMCF/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 107.821 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 11.6 YEARS

FINAL OPEN FLOW 645 MMCF/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 312.298 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 12.2 YEARS

FINAL OPEN FLOW 1394 MMCF/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 189.325 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 12.5 YEARS

FINAL OPEN FLOW 1452 MMCF/D
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 368.122 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 13.3 YEARS

FINAL OPEN FLOW 264 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 102.214 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 19.6 YEARS

FINAL OPEN FLOW 422 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 306.898 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 21.2 YEARS

FINAL OPEN FLOW 247 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 119.255 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 24.1 YEARS

FINAL OPEN FLOW 316 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 164.007 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 24.7 YEARS

FINAL OPEN FLOW 541 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 414.266 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 30.7 YEARS

FINAL OPEN FLOW 640 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 265.002 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 31.3 YEARS

FINAL OPEN FLOW 165 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 167.816 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 31.6 YEARS

FINAL OPEN FLOW 243 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 213.283 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 35.3 YEARS

FINAL OPEN FLOW 729 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 366.759 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 39.4 YEARS

FINAL OPEN FLOW 111 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 192.812 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 41.2 YEARS

FINAL OPEN FLOW 3110 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 1131.184 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 42.4 YEARS

FINAL OPEN FLOW 381 Mcf/d
EXPONENTIAL CURVE FIT
TOTAL RESERVES = 338.385 MMCF
TIME TO ECONOMIC LIMIT (2.4 MMCF/YR) = 43.9 YEARS

APPENDIX B

APPENDIX C

APPENDIX D

DATA BASE FOR THE COTTAGEVILLE FIELD

KEY

- P West Virginia or Ohio State Permit Number
- S1 Structure: Subsea elevation on the top of the Mississippian Berea Sandstone.
- S2 Structure: Subsea elevation on the bottom of the Middle Devonian Lower Huron Member of the Ohio Shale Formation.
- S3 Structure: Subsea elevation on the top of the Middle Devonian Onondaga Limestone.
- I1 Isopach: Total Devonian shale.
- I2 Isopach: Organic Zone III of the Lower Huron Member of the Ohio Shale Formation
- I3 Isopach: Organic Zone II of the Lower Huron Member of the Ohio Shale Formation.
- I4 Isopach: Lower Huron Member of the Ohio Shale Formation.
- IOF Initial open gas flow.
- FOF Final open gas flow.
- RP Reservoir pressure.

MASON COUNTY, WEST VIRGINIA

P	S1	S2	S3	I1	I2	I3	I4	IOF	FOF	RP
1	-1349.	-2794.	-3218.	1869.	61.	116.	369.	5.	213.	860.
3	-1396.	0.	-3369.	1973.	0.	0.	0.	0.	350.	885.
29	-1491.	-2985.	-3512.	2021.	60.	174.	392.	0.	0.	0.
37	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
38	-1434.	-2969.	-3369.	2005.	91.	175.	395.	0.	103.	800.
39	-1433.	-2944.	0.	0.	78.	170.	399.	84.	84.	860.
40	-1439.	0.	0.	0.	0.	0.	0.	0.	40.	860.
41	-1324.	0.	0.	0.	59.	292.	512.	0.	0.	0.
42	-1382.	-2877.	0.	0.	0.	185.	395.	0.	30.	0.
43	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
44	-1381.	-2908.	0.	0.	70.	155.	410.	39.	21.	300.
45	-1086.	-2894.	0.	0.	45.	174.	405.	0.	0.	0.
46	-1397.	-2904.	0.	0.	65.	197.	412.	0.	0.	0.
47	-1462.	-2988.	0.	0.	74.	184.	414.	35.	60.	810.
48	-1438.	-2971.	0.	0.	0.	159.	408.	0.	0.	0.
49	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
50	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
51	-1359.	0.	0.	0.	42.	185.	413.	0.	666.	625.
52	-1497.	-3047.	0.	0.	65.	180.	430.	0.	18.	0.
53	-1507.	-3050.	0.	0.	70.	183.	415.	0.	25.	0.
54	-1539.	0.	0.	0.	60.	175.	415.	0.	2.	0.
55	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
56	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
60	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
61	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
63	-1208.	0.	-3012.	1804.	0.	0.	0.	0.	0.	0.
68	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
70	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
106	-1425.	0.	-3417.	1992.	0.	0.	0.	0.	0.	0.
125	-1463.	-3002.	-3487.	2024.	47.	184.	402.	0.	189.	0.
134	-1483.	-3028.	0.	0.	43.	187.	407.	0.	158.	360.
135	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
136	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
137	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
138	-1457.	-2989.	-3469.	2012.	48.	186.	404.	10.	72.	295.

JACKSON COUNTY, WEST VIRGINIA

P	S1	S2	S3	I1	I2	I3	I4	IOF	FOF	RP
10	-1407.	-2958.	-3425.	2018.	81.	194.	0.	0.	803.	875.
586	-1450.	-2975.	0.	0.	90.	182.	421.	445.	445.	875.
588	-1523.	0.	0.	0.	0.	0.	0.	0.	0.	0.
597	-1402.	-2929.	0.	0.	0.	0.	410.	0.	15.	0.
613	0.	-2981.	0.	0.	74.	175.	430.	52.	133.	800.
615	-1642.	-3288.	-3854.	2212.	0.	246.	0.	0.	0.	0.
621	-1421.	-2962.	0.	0.	0.	289.	0.	0.	133.	860.
653	-1549.	-3177.	-3729.	2178.	100.	235.	475.	0.	0.	0.
654	-1442.	-2982.	-3498.	2056.	85.	190.	430.	88.	1309.	790.
657	-1440.	-3006.	-3510.	2070.	0.	0.	441.	79.	736.	800.
660	-1463.	0.	0.	0.	0.	0.	0.	0.	0.	0.
676	-1460.	-3038.	0.	0.	85.	205.	450.	539.	539.	750.
682	-1404.	0.	0.	0.	90.	0.	0.	852.	852.	817.
687	0.	-3143.	0.	0.	32.	0.	469.	0.	582.	800.
691	0.	-2992.	0.	0.	80.	210.	420.	0.	231.	800.
693	-1478.	-3035.	0.	0.	53.	200.	433.	133.	381.	790.
694	-1462.	-3063.	0.	0.	85.	0.	0.	36.	1852.	775.
696	-1429.	-2999.	0.	0.	0.	200.	0.	0.	582.	760.
697	-1468.	0.	0.	0.	0.	0.	0.	0.	560.	805.
698	-1438.	-2978.	0.	0.	80.	190.	410.	5.	822.	765.
699	-1520.	-3159.	0.	0.	90.	214.	0.	0.	152.	0.
700	-1513.	-3078.	0.	0.	89.	175.	430.	0.	200.	780.
701	-1502.	-3059.	0.	0.	75.	186.	446.	0.	700.	735.
702	-1464.	0.	0.	0.	100.	0.	0.	0.	460.	780.
703	-1497.	-3086.	0.	0.	125.	195.	453.	1.	582.	650.
704	-1427.	-2985.	0.	0.	95.	200.	435.	0.	348.	775.
705	-1493.	0.	0.	0.	65.	0.	0.	900.	900.	715.
706	-1477.	-3080.	0.	0.	70.	193.	403.	36.	1981.	770.
707	-1407.	-2957.	0.	0.	66.	190.	419.	0.	50.	750.
709	-1475.	-3047.	0.	0.	83.	197.	436.	215.	381.	960.
715	-1435.	-2992.	0.	0.	69.	199.	417.	17.	267.	680.
716	0.	0.	0.	0.	0.	0.	0.	40.	283.	588.
717	-1504.	-3039.	0.	0.	60.	195.	430.	0.	1100.	740.
718	-1461.	0.	0.	0.	75.	211.	421.	0.	2.	0.
721	-1460.	-3030.	0.	0.	80.	203.	443.	9.	412.	675.
722	-1496.	-3100.	0.	0.	0.	194.	0.	15.	528.	740.
723	-1542.	-3134.	0.	0.	90.	210.	457.	0.	2.	0.
724	-1487.	-3057.	0.	0.	78.	0.	417.	25.	582.	740.
727	0.	-3168.	0.	0.	72.	208.	434.	0.	140.	1000.
728	-1426.	-2980.	0.	0.	23.	194.	381.	629.	959.	460.
729	-1443.	-3015.	0.	0.	84.	184.	440.	746.	746.	680.
731	-1544.	-3114.	-3637.	2093.	65.	195.	445.	14.	762.	865.
732	-1505.	-3125.	0.	0.	101.	0.	476.	0.	539.	680.
733	-1464.	-3041.	0.	0.	80.	188.	422.	5.	198.	685.
735	-1478.	-3022.	0.	0.	70.	175.	420.	35.	600.	675.
741	0.	0.	0.	0.	78.	0.	0.	0.	0.	0.
742	-1459.	-3022.	0.	0.	85.	198.	428.	1.	337.	690.
743	-1492.	-3060.	0.	0.	20.	207.	375.	163.	823.	660.
745	-1453.	-3020.	0.	0.	40.	199.	446.	0.	283.	350.

JACKSON COUNTY, WEST VIRGINIA

P	S1	S2	S3	I1	I2	I3	I4	IOF	FOF	RP
748	-1476.	0.	0.	0.	70.	0.	0.	823.	823.	520.
747	-1488.	-3071.	0.	0.	78.	197.	442.	23.	728.	755.
750	-1479.	-3060.	0.	0.	97.	202.	442.	49.	365.	565.
751	-1490.	0.	0.	0.	75.	0.	0.	0.	2.	0.
752	-1466.	-3027.	0.	0.	75.	190.	485.	0.	133.	0.
755	-1510.	-3088.	0.	0.	95.	183.	413.	0.	2.	0.
757	-1496.	-3087.	0.	0.	0.	206.	0.	61.	660.	625.
758	-1522.	-3118.	0.	0.	100.	0.	0.	18.	762.	685.
759	-1541.	-3099.	0.	0.	55.	0.	427.	0.	63.	0.
760	-1528.	0.	0.	0.	0.	0.	0.	15.	15.	0.
761	-1534.	-3128.	0.	0.	75.	216.	451.	21.	152.	0.
762	-1505.	-3075.	0.	0.	75.	195.	420.	28.	539.	645.
763	-1489.	0.	0.	0.	51.	0.	0.	3110.	3110.	640.
764	-1518.	-3066.	0.	0.	80.	178.	0.	33.	413.	500.
765	-1539.	-3117.	0.	0.	0.	185.	433.	4.	246.	610.
766	-1527.	-3137.	0.	0.	92.	215.	462.	5.	5.	0.
767	-1522.	-3132.	0.	0.	70.	0.	465.	0.	4.	0.
768	-1520.	-3095.	0.	0.	0.	0.	405.	4.	38.	0.
772	-1417.	-2981.	0.	0.	72.	185.	424.	2.	269.	465.
773	-1664.	0.	0.	0.	0.	0.	0.	0.	0.	0.
774	-1441.	-2992.	0.	0.	110.	186.	431.	12.	321.	375.
775	-1513.	-3095.	0.	0.	82.	200.	447.	2.	203.	375.
776	-1526.	-3099.	0.	0.	70.	190.	435.	0.	184.	380.
777	-1451.	-3003.	0.	0.	75.	202.	427.	38.	440.	667.
778	-1464.	0.	0.	0.	60.	0.	0.	3480.	3480.	405.
779	-1489.	-3067.	0.	0.	75.	202.	447.	30.	377.	505.
780	-1508.	-3064.	0.	0.	75.	190.	0.	0.	179.	385.
783	-1429.	-3000.	0.	0.	75.	185.	436.	140.	376.	430.
784	-1489.	-3075.	0.	0.	0.	196.	436.	4.	33.	0.
785	-1490.	-3094.	0.	0.	80.	209.	464.	0.	71.	430.
787	-1489.	0.	0.	0.	68.	0.	0.	728.	728.	435.
789	-1593.	-3201.	0.	0.	70.	200.	440.	15.	311.	0.
790	-1589.	-3193.	0.	0.	92.	200.	462.	6.	286.	0.
792	-1440.	-3011.	0.	0.	0.	188.	446.	2.	622.	615.
793	-1489.	-3077.	0.	0.	76.	200.	442.	158.	337.	665.
796	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
800	-1461.	-3027.	0.	0.	75.	200.	0.	112.	207.	480.
934	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
935	0.	-3026.	0.	0.	75.	198.	446.	0.	0.	0.
1008	-1689.	-3364.	-3985.	2296.	50.	215.	460.	0.	0.	0.
1036	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1038	-1662.	-3349.	-3923.	0.	47.	190.	475.	0.	0.	0.
1039	-1680.	0.	-4015.	2335.	0.	0.	0.	0.	0.	0.
1042	-1553.	-3231.	-3753.	2200.	80.	0.	0.	0.	0.	0.
1043	-1663.	-3442.	-3964.	2301.	85.	277.	555.	0.	0.	0.
1056	0.	-3389.	-3949.	0.	0.	268.	0.	0.	0.	0.
1082	-1721.	0.	-4004.	2283.	0.	0.	0.	0.	0.	0.
1123	-1663.	0.	-3971.	2308.	0.	0.	0.	0.	0.	0.
1128	-1653.	-3349.	-3957.	2304.	55.	257.	496.	0.	0.	0.

JACKSON COUNTY, WEST VIRGINIA

P	S1	S2	S3	I1	I2	I3	I4	IOF	FOF	RP
1130	0.	0.	-4008.	0.	0.	0.	0.	0.	0.	0.
1131	-1684.	-3379.	-3979.	2295.	58.	255.	494.	0.	0.	0.
1133	-1651.	-3360.	-3968.	2317.	58.	211.	502.	0.	0.	0.
1137	-1671.	0.	-3968.	2298.	0.	0.	0.	0.	0.	0.
1139	-1695.	0.	-4027.	2332.	0.	0.	0.	0.	0.	0.
1141	-1711.	0.	-4043.	2332.	0.	0.	0.	0.	0.	0.
1142	-1693.	0.	-3975.	2282.	0.	0.	0.	0.	0.	0.
1145	-1778.	0.	-4063.	2285.	0.	0.	0.	0.	0.	0.
1153	-1605.	0.	-3867.	2262.	0.	0.	0.	0.	0.	0.
1169	0.	0.	-3525.	0.	0.	0.	0.	0.	0.	0.
1170	-1443.	0.	-3643.	2200.	0.	0.	0.	0.	0.	0.
1180	-1408.	0.	-3563.	2155.	0.	0.	0.	0.	0.	0.
1184	0.	0.	-3555.	0.	0.	0.	0.	0.	0.	0.
1187	0.	0.	-3594.	0.	0.	0.	0.	0.	0.	0.
1202	-1523.	-3100.	0.	0.	140.	195.	435.	33.	100.	0.
1225	-1467.	0.	-3675.	2208.	0.	0.	0.	0.	0.	0.
1228	-1614.	0.	-3886.	2282.	0.	0.	0.	0.	0.	0.
1231	0.	0.	-3464.	0.	0.	0.	0.	0.	0.	0.
1233	-1477.	-3045.	-3559.	2082.	90.	160.	420.	0.	0.	0.
1239	0.	0.	0.	2210.	0.	0.	0.	0.	0.	0.
1240	0.	0.	-3898.	0.	0.	0.	0.	0.	0.	0.
1241	-1606.	-3299.	-3897.	2291.	55.	248.	496.	0.	0.	0.
1244	-1593.	-3266.	-3854.	2261.	63.	243.	495.	0.	0.	0.
1248	0.	0.	-3823.	0.	0.	0.	0.	0.	0.	0.
1249	-1539.	0.	-3746.	2207.	0.	0.	0.	0.	0.	0.
1251	-1438.	0.	-3639.	2201.	0.	0.	0.	0.	0.	0.
1252	-1468.	0.	-3669.	2201.	0.	0.	0.	0.	0.	0.
1253	0.	0.	-3751.	0.	0.	0.	0.	0.	0.	0.
1255	-1478.	0.	-3683.	2205.	0.	0.	0.	0.	0.	0.
1259	-1555.	0.	-3752.	2197.	0.	0.	0.	0.	0.	0.
1260	-1078.	-3215.	-3789.	0.	61.	239.	485.	0.	2.	0.
1262	0.	0.	-3738.	0.	0.	0.	0.	0.	0.	0.
1265	-1543.	0.	-3737.	2194.	0.	0.	0.	0.	0.	0.
1266	-1554.	-3184.	-3751.	2197.	60.	228.	474.	0.	0.	0.
1267	-1555.	-3143.	-3766.	2211.	60.	233.	475.	0.	0.	0.
1268	-1521.	-3147.	-3705.	2184.	58.	233.	466.	0.	0.	0.
1269	-1533.	-3169.	-3734.	2201.	55.	277.	473.	0.	0.	0.
1271	-1507.	0.	-3688.	0.	0.	0.	0.	0.	0.	0.
1272	-1491.	0.	-3643.	0.	0.	0.	0.	0.	0.	0.
1273	-1579.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1274	-1492.	0.	-3615.	2123.	0.	0.	0.	0.	0.	0.
1275	-1433.	-3001.	-3522.	2089.	52.	200.	430.	0.	0.	0.
1277	0.	0.	-3672.	0.	0.	0.	0.	0.	0.	0.
1279	-1581.	0.	0.	2145.	0.	0.	0.	0.	0.	0.
1280	-1487.	0.	-3680.	2193.	0.	0.	0.	0.	0.	0.
1282	0.	-3067.	-3613.	2146.	59.	215.	459.	0.	0.	0.
1283	-1455.	0.	-3678.	2223.	0.	0.	0.	0.	0.	0.
1284	0.	0.	-3758.	0.	0.	0.	0.	0.	0.	0.

NEIGS COUNTY, OHIO

P	S1	S2	S3	I1	I2	I3	I4	IOF	FOF	RP
1003	-1386.	-2975.	-3525.	2139.	0.	206.	0.	0.	0.	0.
1224	-1405.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1422	-1380.	-3359.	-3508.	2128.	0.	0.	387.	0.	0.	0.
1427	-1432.	0.	-3558.	2126.	0.	0.	0.	0.	0.	0.
1429	-1373.	0.	-3514.	2141.	0.	0.	0.	0.	0.	0.
1446	-1380.	-2985.	-3521.	2141.	0.	215.	0.	0.	0.	0.
1453	-1261.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1454	-1356.	-2949.	-3508.	0.	70.	297.	460.	0.	0.	0.
1456	-1314.	-2684.	0.	2075.	0.	225.	0.	0.	0.	0.
1457	-1446.	0.	-3588.	2142.	0.	0.	0.	0.	0.	0.
1458	-1377.	-2946.	-3500.	2123.	0.	198.	0.	0.	0.	0.
1459	-1325.	0.	-3366.	2341.	0.	0.	0.	0.	0.	0.
1483	-1390.	0.	-3540.	2150.	0.	0.	0.	0.	0.	0.
1465	0.	0.	-3517.	2118.	0.	0.	0.	0.	0.	0.
1471	-1302.	-2838.	-3306.	2004.	95.	169.	424.	0.	0.	0.
1478	-1563.	0.	-3641.	2008.	0.	0.	0.	0.	0.	0.

ABSTRACT

Exploration and development of Middle and Upper Devonian organic shales in the Cottageville gas field of western West Virginia began in the late 1920s. Continued development has lead to the drilling of over 110 shale wells with accumulative production of more than 10 billion cubic feet of natural gas. Data indicate primary production from zones of organic shales in the Lower Huron Member of the Ohio Shale Formation. Due to the extremely low porosity (3 to 4 per cent) and permeability (less than 0.1 millidarcy) of these shales, gas production is considered to be through natural fracture systems. These fracture systems have partially been delineated through the study of oriented cores.

Historically, production of gas has been through natural completion or by stimulation with gelled nitroglycerine. Varied success of this stimulation technique has recently led to more advanced types of stimulation (hydraulic and foam fracturing). Total production, natural gas flow trends, final gas flow trends, and structural breaks and trends have led to the delineation of the fractured shale reservoir. Careful examination of these parameters can lead to the exploration and development of successful shale wells within and near the gas field.

THE EASTERN KENTUCKY GAS FIELD

**A geological study of the relationships of Ohio Shale
gas occurrences to structure, stratigraphy, lithology,
and inorganic geochemical parameters.**

by

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FINAL REPORT

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ABSTRACT

The largest gas field in the Appalachian basin is examined in terms of: 1) structural elements described in existing literature, 2) stratigraphic relationships derived from gamma-ray logs, 3) lithologic sequences from well cutting studies, and 4) inorganic geochemistry of elements and minerals from well cuttings. Final open flow data from approximately 4750 wells producing from the Upper Devonian black shale are compared with the geological parameters.

The Eastern Kentucky Gas Field, a coalescence of many fields, is concluded to represent a highly complex structural-stratigraphic gas trap. Stratigraphic relationships dominate the origin and occurrence of the gas in the black shale facies, but structural constraints on basinal configuration and subsequent doming and uplift in the southeast probably resulted in gravity tectonics, decollement features, and compressional stresses, contributing to a widespread fracture facies concentrated in the Huron member of the Ohio Shale.

This fracture facies may be enhanced by the occurrence of complex intertonguing of organic black shale with silty gray shale in the center of the area of high gas production.

Radiating and circular fracture zones (interpreted from open flow patterns), related to the Paint Creek Uplift, probably provided conduits for the major pattern of gas accumulation off the nose of the uplift. High pressure zones in the shales are probably a result of the compressional and compaction relationships, coupled with the fracture conduits over the nose of the Paint Creek Uplift.

The mineralic ratios, determined by geochemical analysis, suggest an upper Devonian environment dominated by relatively fresh water, marginal, cratonic swamps, which were periodically destroyed, the organic debris from which contributed to the black shales accumulating at the toe of the prograding eastern deltas.

Inorganic elemental geochemistry shows promise as an exploration tool. The contoured data on the oxides of Si, Al, Mg, K, Fe, Ca, the ratio Si/Al, and S result in maps which show configurations similar to the density of high producing wells.

I. INTRODUCTION

A. Purpose

The purpose of the study presented here is to relate gas occurrence and production potential (as interpreted from open flow data) in the Upper Devonian black shales in eastern Kentucky to geological parameters, including regional structure, fracture frequency, stratigraphy, lithology, and inorganic geochemistry. Understanding of these relationships may provide better models for black shale gas production, a practical framework for field expansion, and may suggest constraints for technological advances in recovery methods.

The Big Sandy, as the original field is called, and the surrounding areas in eastern Kentucky account for about 90% of the total gas production in Kentucky; about 75% of this is produced from Devonian black shale; and about 92.2% of the black shale gas is produced from secondary reservoirs with vertical joints and fractures according to Hunter (1964). The source beds are the organic black shales and the primary reservoirs are the silt or sand layers. Coleman D. Hunter worked on this problem for nearly thirty years as chief geologist for Kentucky-West Virginia Gas.

B. Scope and Data Bases

Structural information and maps are primarily derived from existing, published and unpublished literature.

Stratigraphic relationships and structural-stratigraphic cross sections are based on gamma-ray logs selected from 300 well logs supplied by Kentucky-West Virginia Gas Company.

Lithology studies are conducted on about 600 samples of well cuttings from thirteen wells. All cuttings are from cable tool-drilled wells with one exception near the Pine Mountain Thrust. These samples are supplied by Kentucky-West Virginia Gas Company.

Inorganic geochemical analyses (x-ray fluorescence and x-ray diffraction) were performed on all samples used in the lithology study, plus an additional well, totalling approximately 700 samples.

Final open flow data from approximately 4750 wells are abstracted from Kentucky-West Virginia Gas Company maps.

C. Background

The Eastern Kentucky Gas Field may be considered a coalescence of many fields covering an area of about 3000 square miles and centering over a field better known as the Big Sandy (Figure 1). See Figure 1 for location of study area. This area has produced gas from the Upper Devonian black shales for nearly one hundred years; some wells are still economically productive after more than fifty years. The stratigraphic sequence of major interest in this study is the Ohio Shale, including the Cleveland, Three Lick, upper Huron, middle Huron, and lower Huron units. The Berea/Bedford sequence has been included where data permitted. See Table 1 for Stratigraphic relationship of Ohio Shale with the New Albany Shale and Chattanooga Shale, and Table 2 for stratigraphic units studied, with general gamma-ray log characteristics (Provo, 1977) and lithology. Figure 1 shows the formational terminology (after Swager, 1978).

The enigma of gas production from a tight shale with both low porosity and low permeability has plagued geologists in the area since the field's

inception (Hunter, 1935). Although some relationship was found with anticlinal structures, gas was also recovered from synclinal areas and troughs. As the field area developed, intricate and possibly inter-connected fracture geometry was suggested by the gas recovery pattern (Figures 2 and 3, after Hunter and Young, 1953).

As well cuttings were examined it became apparent that a relationship also existed between gas recovery and the occurrence of thin silty or sandy layers in the black shale. These siltier layers were related by several early workers to shore-line facies on the epicontinental shelf, as well as stringers related to deltaic progradation (Hunter, 1953; Thomas, 1951; Billingsley, 1934; Lafferty, 1935; and McFarlan, 1943).

With increased demand, accompanied by increased prices for fossil fuels, interest in more intensive and efficient recovery of gas from black shales spurred research on potential gas recovery from the Upper Devonian black shales in the Appalachian basin. This study is a part of the research funded by the Department of Energy in the Eastern Gas Shales Project, and represents an effort to bring together as much known data about the area as possible in combination with additional research on lithology, geochemistry, and analysis of open flow data.

This study presents the general field relationships and focuses the need for detailed studies in areas such as 1) fine structural features related to the Ohio Shale production in eastern Kentucky, 2) the role of lithological variation in gas production, and 3) the need to develop a technique to study fracture frequency and relationships of fractures to siltier layers. (See Suggested Future Problems for Study.)

II. DATA USED IN THIS STUDY

A. Summary of Previous Structure Maps

Various structural horizons have been studied in the field area at widely separated times. The maps existing in the previous literature are reviewed as a framework for the present study.

1. Accordant Summit Level

A study of accordant summit levels by McFarlan and Haag (1940) shows an area physiographically "not beyond early maturity, so that early upland levels are still represented in the accordant hilltops." (Figure 4, after McFarlan, 1943). There is a major east-west trend to the strike of the contours in the center of the field.

2. Structure on Top of the Fire Clay Coal (Pennsylvanian)

Structure on top of the Fire Clay coal is shown in Figure 5. A closed southern basin is observed on the 1000-foot contour. The shaded 900-1000-foot elevation interval shows an interference figure on the structural surface, with two crossing directions: northeast-southwest and north-south. The junction of these trends at this structural level is the point at which the north-south trending Paint Creek Uplift intersects the eastern Kentucky syncline.

Relationships of the Fire Clay coal attitude at present and at time of deposition are contrasted with the attitudes of the black shale under the section on Analysis of Data.

3. Coal Face Cleats

Coal face cleats measured by Long (1979) show a radiating pattern about a southeastern focus. See Figure 6. This pattern compared with Figure 5 shows a parallel relationship of face cleat directions to dip of structural contours on the Fire Clay coal. Long has suggested a directional constraint on the coal face cleats imposed by depositional basin configuration. It would appear that the face cleats may also be related to the uplift structure in the southeast, imposed on the coal after deposition. If coal cleats are related to this uplift and compression, the shale fractures or more intense fracture zones (described under 4. Density of High Open Flow Wells, page 379, and Figure 79) may also be related.

4. Structure on Top of the Berea

Structure on top of the Berea sandstone is shown in Figure 7 (after Thomas, 1951). Faults of the eastern Kentucky system are seen trending east-west across the upper left quadrant of the map. The Paint Creek Uplift dominates the structural configuration with a north-south trend entering the field from the north and changing to a broader southeastern slope.

5. Structure on Top of the Ohio Shale and Subcrop Structure (Hunton age)

Structure on the top of the Ohio Shale (Provo, 1977) is shown in Figure 8. Provo used about 250 data points, including drillers' logs and gamma-ray logs in the compilation of this map. Data points in the central area were sparse. Unfortunately, available gamma-ray logs for the present study also were lacking in the Floyd County area which is the center of highest production. However, some irregularities in contours suggesting smaller structure in Floyd County are apparent in Figure 8.

The 0-foot and 500-foot isopach lines for the Hunton age strata underlying the Ohio Shale are shown in Figure 1 (Weaver, 1973).

The erosional surface on the Hunton sloped to the east, northeast.

6. Evidence of Rome Trough Growth

The Rome trough, a basement structure buried under Middle and Upper Paleozoic sediments, probably originated in Late Precambrian time; however, major development of the asymmetrical graben occurred in Lower to Middle Cambrian time. Evidence for this dating is observed in the thickened sequences of siltstones, shale, and sand comprising the Rome formation (see Figure 9, after Dever, et al., 1977).

Associated with the Woodward Fault Zone, which trends northeastward and borders the study area on the north, (Figure 10, after Silberman, 1972) Cambro-Ordovician growth faults have been described trending east-west. Near the junction of two of these faults with the Woodward Fault Zone, a Permian igneous intrusive and surface dikes are described by Silberman (1972). The relationship to the northwestern corner of the study area is shown in the inset map.

7. Basement Structure

Basement structure has been interpreted by Ammerman and Keller (1979) from the Bouguer gravity map (Figure 11). The Floyd County Channel, extending northward into the center of the field, is suggested by these authors to be an aborted rift, entering the Rome Trough at the same structural elevation as the trough at that point. The Pike County Uplift and Perry County Uplift are shown well within the study area. The interpretation by Shumaker (1977) shown in Figure 12 (Negus-de Wys and Renton, 1979) suggests that

the Floyd County Channel is a saddle with the two flanking uplifts farther apart. The Rome Trough is shown as a complex graben with wedge-shaped blocks successively more down-thrown to the northeast. The trend of the trough changes rather abruptly to a more northerly direction after it enters West Virginia (Negus-de Wys and Renton, 1979).

8. Relationship of the Study Area to Precambrian Geological Provinces and Orogenic Trends

Figure 13 (after Muehlberger, et al., 1967) shows the study area to be located at the boundary between two provinces, the 1.35 billion year-old cratonic mass with north-east orogenic trend lines and the younger 1.0 billion year-old province with north-northeasterly orogenic trends. The Paleozoic, paleogeographic epicontinental shelf is suggested by Paul Price (Lafferty, 1941) to run directly through the center of the study area, covering most of the map area, with a slight easterly bulge in the center of the field (see Figure 14). The New York-Alabama lineament, based on aeromagnetic data (King and Zietz, 1978), trends northeast-southwest to the southeast of the field. This lineament has been interpreted by King and Zietz as a possible Precambrian plate suture.

9. Sequential Structural Development in the Study Area

The sequential development of the structural setting of the study area is shown in Figure 15 (Negus-de Wys, 1979), and suggests an active basement involvement from Precambrian to recent time. Detachment and gravity tectonics in late Paleozoic time will be

discussed under Data Analysis. The Precambrian New York-Alabama lineament is not shown (see Figure 14). Structures shown include: 1) Precambrian - Rome Trough, Floyd County Channel; 2) Cambro-Ordovician - major Rome Trough development, growth faults, and Waverly Arch trend; 3) Silurian-Devonian - Cincinnati Arch, initiation of the eastern Kentucky syncline; 4) Mississippian - Paint Creek Uplift, Waverly Arch (west), and the Pike County and Perry County uplifts; 5) Pennsylvanian - Pine Mountain Thrust movement initiated and major development of eastern Kentucky syncline; 6) Permian - intrusive igneous body and surface dikes associated with east-west growth faults intersecting the Woodward Fault Zone. Growth of selected basin faults in the Rome Trough area continues to recent time.

B. Stratigraphy from Gamma-Ray Logs

Stratigraphic units in the Ohio Shale, when interpreted from gamma-ray logs, are related to differing log signatures. These may or may not be identical with the outcrop lithologic units. The Three Lick bed which shows a unique log signature across the field area has also been found to be easily traced in outcrop. Other units are not always easily distinguished in outcrop. It was possible to obtain good samples from only one well which included a gamma-ray log. However, a nearby well which had a gamma-ray log was selected to study with samples in order to assess correlation problems.

1. Devonian Shale Stratigraphy

Emphasis in this study is on the Cleveland, Three Lick, and the Upper, Middle, and lower Huron units of the Ohio Shale. The Berea/Bedford

sandstone and shale is included where data permitted (see Table 1).

A comparison of nomenclature used for the Ohio Shale, the Chattanooga Shale, and the New Albany Shale is shown in Table 2. For areal delineation of nomenclature, see Figure 1.

Provo (1977) and Swager (1978) provide extensive reviews of the stratigraphic descriptions in the literature. Assistance in identification of unit tops was given by Ed Wilson and Z. Zagar of the Kentucky Geological Survey; W. de Witt, Jr., of the U.S.G.S; Doug Patchen of the West Virginia Geological and Economic Survey; and R. Hagar and E. Jenkins of Kentucky-West Virginia Gas.

2. Cross Sections

The locations of cross sections constructed from gamma-ray logs are shown in Figure 17. See Figures 18, 19, and 20 for the stratigraphic cross sections. The trace characteristics of each unit are apparent. High natural radioactivity is observed in the Cleveland which is a highly organic black shale in the northern and western portions of the field. The gray shading represents the highly organic black facies. The unshaded Cleveland is a silty gray shale which appears to inter-tongue from the east and southeast. It has a lower natural radioactivity, and less apparent organic material. The gray facies of the Cleveland appears from the logs to resemble more closely the typical gray Chagrin Shale (of the Ohio Shale in Ohio) to the northeast of the study area. The Cleveland thickens by a factor of 5 to 6 from southwest to northeast.

The Three Lick Bed characteristically shows three zones of low radioactivity that suggest three cycles of deposition. In outcrop the

Three Lick appears as green silty or mud-shale layers interbedded with dark organic layers. To the east in the Big Sandy Field this unit thickens slightly and shows a more complex radioactivity pattern suggestive of additional silty layers. This unit also becomes less distinctive in its radioactivity signature as it is traced on logs eastward to the edge of the field area and would suggest additional silty layers.

The upper, middle, and lower Huron units form a cyclic assemblage. The lower Huron shows the highest radioactivity, with the upper Huron second, and the middle Huron showing the lowest radioactivity. The lower Huron also shows the greatest log complexity, suggesting black organic layers thinly interbedded with silty layers. If the assumption is made that natural radioactivity may be equated with organic content, the middle Huron log signature suggests that the dominant lithology is a silty shale with less organic material. Evidence for the lack of correlation of natural radioactivity with gas content of the shales has been shown by Kalyoncu, et al. (1979). Thus, in these cross sections, it should be noted that stratigraphic units being correlated are radioactivity signatures and not necessarily continuous lithologies, lithofacies equivalents, or strict time unit equivalents. In Figures 21 and 22, cross sections are shown with the top of the Berea as the datum. Gas occurrence information was generated where temperature logs were available; however, temperature log data was not available for all wells. In wells where no gas is indicated, the omission may be because of the lack of data. Gas may occur at any level in the sequence and the general practice is to "shoot" the

entire section in completion procedures. In Perry County temperature logs are noted by Ray (1968) to confirm that most of the gas was coming from two zones: the upper Berea/Bedford and the lower "Hot Shale" unit in the upper Devonian (lower Huron). Figure 21 shows the interpreted intricate intertonguing of black and gray shales to be especially well developed in the heart of high production in Floyd County. Figure 22 shows the simpler gamma-ray log signature and relatively thin occurrence of the Cleveland at the southwestern edge of the field. In all cross sections the relatively uniform thickness of the Berea/Bedford may be noted. However, the signature changes across the field from a characteristic sand signature in the northeast to that of shale in the southwest.

The next seven Figures, 23-29 inclusive, are structural-stratigraphic cross sections with a 1:163 ratio of horizontal to vertical scale exaggeration. The steepest dip is approximately 50 feet to the mile. The open star symbols represent gas occurrence; the solid star symbols represent known oil occurrence. Again, lack of data may account for wells without hydrocarbons noted. The gas occurs throughout the sequence, on structural highs, lows, and flanks of the Paint Creek Uplift which dominates the structural configuration of the field. Figures 23 and 24 may extend into the Rome Trough; Figure 24 shows evidence of faults at the southwestern end of the section. See Frontispiece for 3-D model of structural-stratigraphic sections.

3. Isopach Maps

Figure 16 shows the isopach map of the Berea/Bedford sandstone (after Pepper, Demarest, Merrels, 2nd., and de Witt, Jr., 1946). The unit becomes almost one hundred percent shale in the west and southwest,

and from gamma-ray logs appears to be very uniform in thickness over the field. It is the lithology which changes and is perhaps what is reflected in Figure 16. Also see Figure 50.

Figure 30 shows isopach maps of the Cleveland, Three Lick, upper Huron, middle Huron, and lower Huron from Provo (1977). About 250 data points from drillers' logs and gamma-ray logs are utilized by Provo in the study area shown in these maps. No great improvement in coverage could be gained by the addition of logs available for this study. (See location of available logs under lithology studies.)

Figure 31 shows the isopach map of the total Ohio Shale sequence. The strike of isopachous lines changes with time; the total section shows a basic N-S trend in the strike of the isopach lines. All units thicken to the east, but with varying rates, with the exception of the Three Lick, which actually shows an isopach closure. These rate changes across the field will be further discussed under lithology studies in relation to bentonite occurrence.

4. The Berea/Bedford-Cleveland Boundary Problem

As consultations were held with various specialists in the field, concerning the best "pick" for the top of the Cleveland, it became abundantly clear that there is not total agreement on this subject, especially in areas where the Berea/Bedford loses its silty or sandy character and becomes shale, or in cases where the Cleveland shows a siltier nature. Such "top" problems are probably best decided on the basis of lithology and radioactivity studies, and where possible, with the addition of biostratigraphy.

Gamma-ray tops used in this study are in agreement with the Kentucky Survey (Wilson, 1979), U.S.G.S. (de Witt, Jr., 1978), and Kentucky-West Virginia Gas (Hager and Jenkins, 1977-79).

5. Fine Structure in Log Response of the Huron and Cleveland Units

Changes in the log signature of the Cleveland suggests complex inter-tonguing of black organic shales from the north and west with silty gray shales from the east and southeast. This reflects the delta toe sedimentation interrupted or interspersed with organic black muds, probably largely derived from the craton.

A similar, and in some cases more erratic, fine intertonguing is observed in log signature comparisons in the lower Huron. High radioactive zones are sometimes higher than in the Cleveland, but these spikes are not as easily correlated across the field. However, an illuminating study would be one in which the fine gamma-ray response for the lower Huron is studied and related to the other parameters, including lithology.

C. Lithology Studies from Well Cuttings

1. Well Locations

Cuttings from very few wells were available for study. Frequently in the center of the field cuttings are blown out of the wells when high pressure zones are encountered.

Figure 32 shows the locations of wells from which cuttings are studied. All samples were from cable tool-drilled wells except well #7289 which was drilled by rotary. Small dots are locations for wells from which gamma-ray logs are available. Not all, however, are usable for this study.

Samples representing drillers' runs varied from two and one-half-foot intervals to as much as 30-foot intervals. The majority of samples are from 10-foot intervals. Fourteen wells and a total of about 600 samples were examined wet using a binocular microscope with reflected light under 10X and 30X magnification.

2. Cross Sections

The mudrock terminology of Folk (1974) is used. See Table 3. Table 4 shows lithology symbols for cross sections. Early in the study it became apparent that the Ohio Shale sequence is predominantly very silty silt-shale in some wells, although this sequence is usually referred to as "brown shales."

In constructing cross sections it is deemed advisable to use the base of the Huron as the datum line because it is easily recognized and because of difficulties in correlation higher in the stratigraphic sequence.

Cross sections A-A', B-B', C-C', and D-D' are shown in Figures 33, 34, 35, and 36. Section A-A' (Figure 33), from southwest to northeast, shows the thickening section to the east. The Berea is 100% shale in the southwest grading into a siltstone with some sand grains in the east and northeast. Some dolomitic cementation is observed in the siltstone. In the Eastern Kentucky Field the Berea is of nearly uniform thickness over the entire area, but does show changing lithology. The Cleveland Formation is a black to dark brown, at times greasy looking, highly organic siltstone in the southwest. It grades into a browner silt-shale and then to brown mud-shale in the east, where it intertongues increasingly with gray clay-shale and mud-shale.

The Three Lick is designated as the "upper banded shale" by Swager (1978) at the outcrop. This banding of green and gray and brown shale is also apparent in the well cuttings. In some wells, silty zones are apparent.

The upper Huron is usually a brown, highly organic mud-shale, and is the "lower black shale unit" of Swager. The middle Huron is less organic, siltier, and frequently shows interbedding of gray or green with black shale. The lower Huron is very highly organic, black to dark mud-shale and may show some interbedding. It breaks into blocky rather than plate-like fragments. In the outcrop it also appears blockier and less fissile than the Cleveland or other Huron units.

For comparison with the lithological cross sections, similar sections using logs may be compared (Figures 18, 19, and 20) as well as the structural-stratigraphic sections (Figures 23-39 inclusive). These are not identical lines of section, because logs are not available for most of the wells from which well cuttings are used. Only one well from which cuttings were studied, could also be studied by gamma-ray log. Gamma-ray logs are only available for wells #7289 and #6869, neither of which could be considered key lithologic logs.

In cross section A-A' the center well appears to be lacking part of the lower Huron and shows a milky white chert and limestone unit. This is probably Huntersville Chert (Hager, 1978). The chert continues for approximately 75 feet with a tan-gray sandy, fossiliferous limestone and dark brown sucrosic dolomite. Stylolites occur in the limestone. This well, located more centrally in the field, shows indications of fractures at 29 different horizons. The lowest part of the Huron,

which is usually black shale, is not present in the well and could be a normal fault with 75-100 feet displacement in the Huron, eliminating the lowest part of the Huron and bringing the Huntersville Chert in higher in the section. Such a fault on the side of the Floyd County Channel would not be unreasonable. Other possibilities are 1) the collection of samples and 2) detachment tectonics related to the southeastern uplift. See section on Data Analysis.

The Boyle cherty limestone, observed to occur in some outcrops below the New Albany Shale, appears similar to the cherty well cuttings. The relationship of the Boyle and Huntersville is presently under study by Conklin (Wilson, 1979).

Cross section B-B' (Figure 34), north-south through the center of the field, shows the thickening of the section to the south. Redbeds occur in the northern two wells, but not in the southern where the sections show more silt. The most southeastern well appears to show repetition and, thus, may represent a faulted section. However, the increased slickensides which would be expected to accompany such an interpretation, are not apparent in the well cuttings.

Protosalvinia ravenna (a bifurcated form of the brown alga) occurs near the top (Cleveland Formation) of the southern-most Knott County well (Protosalvinia is not found such an horizon in other wells) and section repetition appears in the Knott County well, suggesting thrust faulting. A gamma-ray log from a well within 2 miles to the north does not show signature abnormalities, and thus, does not substantiate

such an interpretation at that distance in that direction. Proto-salvinia occurrence has usually been reported as restricted to the middle Huron just below the center of that unit. Provo (1977) and Swager (1978) do report occurrences from the Three Lick down through the lower Huron. Occurrence of forms suggestive of such a stratigraphic range are also found in these cuttings; publication of such results will await further study.

Tasmanites has been determined by Jux (1971) to be the spore of a green alga. This spore is very common throughout the sequence, both as a carbonaceous form as well as pyritized spheres. It would appear that the shales were a veritable algal soup!

Archaeopteris is a characteristic Upper Devonian plant represented by 15 or more species and recorded from numerous localities in New York, Pennsylvania, and eastern Canada, from Great Britain, Ireland, Belgium, and U.S.S.R. and from high latitudes in Ellsmere Island and Bear Island (Andrews, 1961). Lee and Tsai (1978) also report occurrence in China. Beck (1960) announced the important discovery of finding a pyritized stem with Callixylon wood structure bearing several fragments of Archaeopteris fronds. Thus, they are one and the same plant. Specimens of Callixylon exceeding five feet in diameter are reported in the Upper Devonian of Oklahoma. It is thus the largest known Devonian plant. Petrified wood of Callixylon is found in the Ohio Shale outcrop in Kentucky in several localities and is described by McFarlan (1943) in discussion of the Huron Member. This suggests swamp development with sizeable tree ferns existing not far from the study area.

Such swamp development could contribute the black muds from the craton area during periods of higher rainfall. See Figure 37 for a drawing of Archaeopteris. Woody, vitrinite fragments are common in the gray shales. The source plants were not identified.

Moore (1929) and Twenhofel (1939) postulated near-shore, shallow water environment and, in the absence of evidences of wave action, according to Rich (1951), are forced to postulate choking of the water by aquatic vegetation to such an extent as to damp out wave action. Because the Callixylon logs had not yet been associated with the Archeopteris fern-like fronds, and were thought, from the woody tissue, to be conifer-like, Rich (1951) argued that if the masses of vegetation were dense enough to damp out all wave action, it would seem that they would also have prevented the floating-in of the great logs of Callixylon which are so common in certain parts of the shales. Pelagic organisms such as cephalopods and pteropods are further offered by Rich as evidence of deeper water. However, the model of marginal swamps periodically inundated by marine fluctuations could satisfactorily explain the data. See Figure 37b for depositional model, after Twenhofel (1939).

To quote from Moore (1929) in discussing probable conditions of formation of Pennsylvanian age black shales: "perhaps the only difference between these and some of the so-called normal types may be restricted circulation due to abundant plant matter, or the presence of a large quantity of humous materials derived from drowned coal swamps."

3. Lithofacies Maps

Recognizing the scarcity of data points, which was caused by lack of available well cuttings, data were contoured. The resulting lithofacies

maps are presented with full awareness of the restricted data, but with a suggestion that the results are meaningful when compared with the other data.

In examining the well cuttings the rock types are noted and described, occurrence of plant and animal fragments are noted, as well as indications of fractures. Fracture indicators which were used include: slickensides, open fractures, filled fractures, fracture sides with attached spar, and separate spar crystals. Stylolites occur in the limestone unit in the bottom of the central well (Section B-B') with the Huntersville Chert.

Frequency of fractures was contoured (Figure 38). Because of the differences in sample intervals and the inherent problems in the fracture indicators (caving, slickensides from drilling, etc.) the author was extremely dubious about this aspect at the onset of the study. However, the resulting configuration appears reasonable, and did not require much alteration of contour lines when fractures from cored wells were added (Evans, 1979). Wells were examined in no logical sequence and not compared until all were completed. Nonetheless, a more objective and replicable method of obtaining fracture frequency data would be desirable.

Maps of relative percentages of gray, brown, and green shale in the total Ohio Shale sequence studied (Cleveland-Huron) are shown in Figures 39, 40, and 41. The isopach map of black shale is shown in Figure 42.

The configuration of the Devonian black shale isopach shown by Harris, de Witt, Jr., and Colton (1978) (Figure 43) should be compared with the combination of the brown shale and black shale of this study (Figure 40 and 42). In the compilation of the map by Harris, et al., de Witt included organic black and brown shales together (Figure 43), whereas the maps in this study separate the two.

Percent shale of total Ohio Shale sequence is shown in Figure 44 which may be compared to percent of silt and sand in Figure 45. Higher silt/sand areas occur in the northeastern section of the field and a patch southwest of field center. If the silt/sand percentage is contrasted, Figure 46 results, showing finer grained clastics to the southwest and coarser material to the northeast. Percent carbonate is shown in Figure 47. It shows a marked similarity to the isopach map of the "Corniferous" (McFarlan, 1943) seen in Figure 48. "Corniferous" includes limestones of Maysville (Upper Ordovician) to Hamilton (Devonian) formations. Hamilton underlies New Albany (Ohio Shale equivalent). Thus, the suggestion from the "Corniferous" isopach map that a northeastern basin in the Rome Trough complex was in existence during "Corniferous" deposition, leads to the conclusion that this northeastern basin, later known as part of the eastern Kentucky syncline, may have been defined as a deeper segment as early as Upper Ordovician (Maysville). Comparing sediment thicknesses suggests that in early Pennsylvanian time this northern basin was particularly well developed (McFarlan, 1943).

Percent redbeds of total sequence is shown in Figure 49. An area trending northeast-southwest across the study area shows occurrence of redbeds with the highest values to the northeast. This suggests a positive area during late Upper Devonian time, or preferential currents depositing detrital fragments from eastern deltaic origin.

The results of very scanty data on the Berea-Bedford show the unit to be 100% shale in the southwest, and, if the trend is extrapolated, the 50:50 shale:sandstone ratio line would run through the heart of the gas field. The isopach map of the Berea-Bedford (Pepper, et al., 1946) shows the sand in a highly complicated patchy thinning and thickening in the Floyd County area (Figure 16). (See Figure 50 for cross section.) From the gamma-ray logs the Berea-Bedford appears to be of nearly uniform thickness over the field. Thus, the lateral changes in lithology in the cross section may be regarded as facies changes. Other possibilities are erosional genesis and local structural anomalies. The small scale thins shown in the isopach map in the central area of the field may relate to growing structures.

Detailed structure maps on the Big Lime (Mississippian) in this area (Figure 51, after Miller and Withers, 1928, referenced in McFarlan, 1943) show several fine structures superimposed on the northwest regional dip.

4. Correlation of Gamma-Ray Logs with Sample Study

It would have been ideal to use samples from logged wells, but of the sampled wells only one gamma-ray log was useable of the two obtained. Nearby logs were used when available.

In the areas surrounding the center of the Eastern Kentucky Field area, the lithologic units as described from samples are easier to identify with gamma-ray logs of nearby wells. However, in the central part of the field, most of the production occurs in the area of maximum lithologic complexity. This probably is not fortuitous. The correlation of lithology to natural radioactivity in this area appears extremely difficult and questionable. The natural radioactivity need not relate directly to high organic content, so this lack of correlation is not surprising. Scale restrictions and the few number of wells studied dictate that the lithologic complexities be greatly simplified in the figures, but the isopach maps suggest complex depositional intertonguing of cratonic-derived, organic black muds with distal deltaic silts and clays. (Black organic muds also appear in the lower Huron from the east.)

D. Inorganic Geochemistry Studies from X-ray Fluorescence and X-ray Diffraction of Well Cuttings

The same cuttings included in lithology studies were utilized in geochemical analyses, with the addition of one well, #1660. From 1935 to 1964 Coleman Hunter studied the Eastern Kentucky Field and from well cutting examinations he published average values for quartz, pyrite, kerogen, and bituminous material (Hunter, 1964). Maps showing iso-value lines based on these data are shown in Figures 52, 53, 54, and 55. From the same study Hunter's estimated ultimate recovery per well is shown by county in Figure 56. The quartz map shows high values to the east; pyrite is high in Floyd County and may extend north; kerogen is high in Floyd County and on to the

northwest; bituminous material is higher to the northwest and low to the east-southeast; and the estimated recovery contours show an elongate oval configuration with a northeast-southwest axis.

1. Elements Analyzed

Elements analyzed include Mg, Al, Si, P, K, Ca, Ti, Mn, Fe, S, Cu, Zn, Sr, and Na. All elements except sulfur are analyzed as oxides. The ratio of the oxides Si/Al is also studied.

Table 5 shows the elements analyzed with minimum, maximum, and mean values, variance, and coefficient of variance. Variance is the average of the square of the deviations of the measurements about their mean; coefficient of variance is the standard deviation ($\sqrt{\text{Variance}}$) divided by its related mean, and is a relative measurement of deviation.

A comparison of Si and Al oxide graphs for the Berea/Bedford through Huron sequence is shown in Figure 57. The wells are arranged from west to east. Figure 58 shows the Si oxide graphs in the well positions. Field cross sections of the Si-Al oxide ratios are shown in Figures 59, 60, 61, and 62 with stratigraphic units noted. Legend preceeds figures.

Figure 58 shows great similarity among wells in the northeastern portion of the field (#5584, #5963, and #5903), some similarity in the southwest (#1678, #1380, #7272, and #7289), and practically none in the center (#965, #1486, and #5909). In the cross sections the 4 = a ratio of 4:1 in the Si/Al oxide ratio. Again, the center of the field shows more diverse relationships.

2. Computer-drawn Maps of Elemental Data

From these data, computer maps are run on the average values of individual stratigraphic units, for the total sequence, and for the Ohio Shale. The map for the Si oxide in the Three Lick unit is shown in Figure 63.

A comparison of computer-drawn map miniatures is shown in Figure 64 for all units for Si/Al, Al, Si, S, Mg, K, Fe, and Ca. The darkest shade is the highest value, the lightest shade represents the lowest value. All were run with six levels, not always representing equal increments, because of range differences in data.

The Si/Al map series for the stratigraphic units as well as total sequence and total Ohio Shale are shown in Figure 65. Average values used for total sequence may vary from an average of 25 samples to an average of 75 samples, depending on the thickness of the well sequence involved.

3. Minerals Analyzed and Mineralic Ratios Studied

The 13 minerals analyzed are shown in Table 6 with simple statistics for minerals and mineralic ratios. Chemical formulas are shown in Table 7 and Table 8 shows ratio definitions.

4. Computer-drawn Maps on Mineralic Ratios

Computer-drawn maps for the mineralic ratios, using average values for the total stratigraphic sequence are shown in Figures 66, 67, 68, 69, and 70. The darkest printout is the highest value area, the lightest printout being the lowest. Increments are not always equal because of constraints on computer mapping of closely spaced lines. Computer maps were run as a check on hand-contoured maps. (See Analysis of Data section.)

E. Production Studies from Final Open Flow Data from approximately 4750 wells.

The areas of Upper Devonian Ohio Shale gas production in eastern Kentucky are shown in Figure 71.

1. Distribution of Data Points

The locations of the approximately 4750 wells from which final open flow data were supplied by Kentucky-West Virginia Gas are shown in Figure 72. It is not intended that the well numbers be legible! Admittedly, there is some structure to the data distribution, but overall the density averages about 5 wells/square mile. Density of points may go as high as 20 wells/square mile. It was decided at the onset of the study, because of apparent complexities of the field, to use all data obtained. During the contouring procedures, by hand (Figure 73, using all 4750 points) and by computer (Figure 74, using 4138 points) data points were rejected because of faulty location on supplied base maps, double well numbers, missing open flow data, and illegible data.

2. Hand Contoured Map (Figure 73)

The data points were so densely spaced that little interpretation went into hand contouring the data. The resulting configurations are concluded to be fairly reliable, in terms of representing the data used.

Contouring was done on a base map at a scale of approximately 1:100,000. This was reduced to a scale of 1:250,000. A three-level version of final open flow contours was color-coded, from which the directional trends discussed later were measured.

3. Computer-drawn Map (Figure 74)

Data points were given coordinates by the computer data processing

section of the West Virginia Geological and Economic Survey under the direction of Mrs. Mary Behling. Sixteen computer-drawn map sections were run, the total compilation size of which was 8' x 16'. These map sections were reduced and compiled into a single map from which Figure 74 was hand-copied and coded at three levels like the hand drawn map. The resulting configurations tend to be rendered more orthogonally than the hand-contoured version (Figure 73). In the final computer mapping program used (ADMINMAP):

- 1) 2-3 points were averaged; 2) there was no overlapping of map strips;
- 3) areas were contoured rather than blocked; 4) paper was reversed to eliminate pattern; and 5) commencing with a value of 0.10 MMcf, increments used in mapping were 0.15, 0.25, 0.25, 0.25, 0.50, 0.50, 0.50, 0.25, 0.25, and 5.00 MMcf/day.

A histogram of the data (0.00 - 2.00) is shown in Figure 75. A break is represented between frequency of 800 and 2000 because of the total length that segment would have. The data are not graphed past 2.00 on this scale because of scanty data occurrence in the >2.00 MMcf/day section.

A second histogram of the data (0.00 - 0.225) is shown in Figure 76 to show the finer structure of the frequency represented in that interval of open flow values. Finally, Figures 77a and 77b show a large scale graph of all data used in computer mapping.

Two cross sections taken through the hand-contoured and computer-drawn maps are compared (See Figure 105, Data Analysis section). There is a general similarity between the two curves, but sufficient offset and smoothing occurs to suggest that exploration studies should use hand-contoured maps rather than computer-drawn maps, or use a combination of both types.

4. Density of High Open Flow Wells

A data set very similar to that provided to the author was provided to James Griffith of Mobile Oil (1976) for analysis. See Figure 78. In the data set given Griffith the author connected all wells with values $\geq .5$ MMcf/day where not contra indicated by lower open flow values. The resulting pattern is seen in Figure 79.

Griffith contoured the density of wells ≥ 0.5 MMcf/day per 25 square miles and ≥ 1.00 MMcf/day per 25 square miles. The contour values represent the general pattern of gas accumulation (Figure 80).

III. ANALYSES OF DATA

A. Open Flow

About 90% of eastern Kentucky gas wells are "shot", 9.9% are treated, and 0.1% are natural flow completions. Measurements on an 8 hour period following the shooting or well treatment are the basis of the open flow data used. It is not deemed necessary to separate data on the basis of the differences in well completion (Jenkins, 1977).

Three trend surface analysis programs were run first on the entire field and then on sections of the field. Figure 81 shows the first degree surface trends for these programs.

The fourth degree surface for the entire field, using a grid set of 417 equally spaced points, produces Figure 82. This may be compared with the plots of Griffith in Figure 80, which show the same basic NE-SW trend.

From the hand-contoured open flow map with 3 contour levels, Figure 83, trends of high production areas (Figure 84) and of low, or non-production areas (Figure 85) were traced. Although this is a subjective procedure, the close spacing of the data points used for the contouring suggests

severe restrictions on the resultant configurations. Trends represent long axes of patterns. The low open flow traces are more subjective because of the larger spaces involved.

Polar plots of trend lengths were plotted for the high (Figure 86) and low (Figure 87) trends. A change in direction is noted with change in length of trend. Cumulative plots of high and high plus low are shown in Figure 88. Three major directions are repeatedly apparent: NW-SE, NE-SW, and E-W. These configurations may be compared with the polar plot from Long (1979) of Devonian shale composite fractures from outcrop (Figure 89). This latter work shows the NE-SW and NW-SE directions to be dominant in fracture trends at the outcrop. The E-W direction is conspicuously absent.

Even in early writings (Hunter, 1935; Thomas, 1941; Lafferty, 1941; McFarlan, 1943; and Billingsley, 1934) the gas production was interpreted as being dependent upon fracture occurrence (See Introduction). Thus, the trend traces of high open flow configurations and possibly those of the low trends (See Figures 84 and 85) may be regarded as probable fracture patterns. This might further suggest that the Ohio Shale sequence is diversely fractured throughout the field, presenting a "fracture facies" as described by Shumaker (1977). In a series of studies of natural fractures in cores from Martin, Perry, and Johnson counties, Evans (1979) has observed great diversity in fracture orientation in the shale sequence.

Different lithologies may be expected to show a differing degree of fracturing, and therefore, percentages of silt and sand to organic black mud should affect the intensity of fractures or fracture frequency. Thus, the "fracture facies" concept may be even more restrictive in terms of a preferred lithologic unit which may or may not in turn relate to a

stratigraphic unit. Such a "fracture facies" could be independent of stratigraphy interpreted from natural radioactivity. We will return to this concept in considering the Analysis of Lithology Study results.

Table 9 shows a comparison of 1964 data and the present study in terms of total open flow, average open flow per well, and percent dry holes. Average per well has increased by 20 percent and dry holes have decreased by almost 10 percent. In 1964 Knott County shows the highest number of wells producing from the Devonian. See Table 10.

Based on 415 MMcf total recovery per well x 5000 wells the estimated recovery is approximately 2 trillion cubic feet of gas from the Devonian black shales in the field area for that number of wells.

B. Structure

Three main structural trends are apparent (Figure 14 and 15): north-south, east-west, and northeast-southwest. Table 11 shows the features, trends, and ages. North-south trends dominate from Precambrian through Mississippian time. East-west features are also prevalent from Precambrian through Mississippian with growth in the Rome Trough continuing to the Recent time. The northeast-southwest trend appears to become more dominant in Pennsylvanian time with domal structures (Pike County Uplift and Perry County Uplift) appearing probably in Mississippian and a known igneous intrusion in the Permian, with associated dikes.

The depth and continued displacement along and related to the Rome Trough basement feature is better brought into perspective with a three dimensional model based on Shumaker's (1977) interpretation of basement structure (Figure 90). The basement trough in the northern area is 14,000 feet or almost 3 miles deep (the northwest corner showing a depth of -2000

feet, deepening to -16,000 feet in the northwest). This is over four and one-half times the depth of the Grand Canyon at Toroweap, Arizona. By the Ammerman and Keller (1979) interpretation (Figure 11) the Floyd County Channel would intercept the Rome Trough at the same depth. These cratonic features and subsequent changes and developments of structural features may be expected to affect depositional characteristics and complexities. The black shale isopach values are greatest over the Floyd County Channel. This is also the area of complex intertonguing of the westward prograding deltaic facies with the organic muds. The geochemical data also suggests greater marine influence coming in from the southwest and slightly from the northeast; fresh water influence is suggested from the north, west, and east (See D. Geochemistry, page 45).

Fractures in black shale, like coal cleats, may relate to stress directions and basinal configuration. Although the Ohio Shale sequence shows an overall N-S strike in isopach contours, the present attitude of the black shales relative to the Fire Clay coal (Figure 91) suggests a northeast trending line of flexure along the eastern side of the eastern Kentucky syncline. The late Paleozoic uplift in the southeast hinged along this line. This hingeline also plunged slightly as it is followed northeastward and southwestward on each side of the Paint Creek Uplift, dividing the eastern Kentucky syncline into two basinal areas, one northeast and the other southwest of the Paint Creek Uplift. (Figure 5). Fracture zones and faults could be expected to relate to these movements and structures involved, and the fractures and faults could be expected to be reflected in production patterns (Figure 79), which do indeed show: 1) a northeast

trending cut off and several linear, east, southeast radiating high production bands from a central intricate pattern over the nose of the Paint Creek Uplift (Figure 92 and computer map, Figure 74). Note: A radiating pattern of lineaments in the area of radiating high production trends has been recognized from Landsat by three independent workers since the completion of this study (Donahue, 1979).

The pattern, when viewed in 3-D (Figures 93 and 94) shows the NE-SW trend, as well as some of the other possibly radiating directions.

A polar plot of structural features and trends of high open flow may be seen in Figure 95. The east-west and northeast-southwest directions appear to show the greatest correlation.

C. Stratigraphy-Lithology

During Devonian time the North American continental plate was probably situated south of the equator with the Appalachian black shales being deposited at about S 35 degree latitude. (Figure 96; after Heckel and Witze, 1978, with permission). This reconstruction is based on carbonates and lithic paleoclimatic indicators, and appears as the cover of the publication entitled "The Devonian System" which resulted from the International Symposium on the Devonian in 1978 in Bristol, England. It may be noted that in this interpretation South America is very nearly convergent upon the North American continental plate margin in close proximity to the study area. A model of island-arc collision is favored for Upper Devonian time.

Also from Heckel and Witze, (1978) see Figure 97 which shows Upper, Middle, and Lower Devonian paleogeography. The study area location is noted in these figures by a rectangle.

The role of plate interactions in sedimentation is discussed by Sloss and Speed (1974), related to miogeosynclinal and eugeosynclinal sedimentation by Rogers (1971), and suggested by Provo (1977) to relate to understanding the black shale sedimentation. Discussion of causal agents outside the study area is beyond the scope of this work other than to acknowledge the framework of present concepts into which this study may fit.

In such a framework it is interesting to note the change in rate of basinal subsidence deduced from unit isopach maps relative to two bentonite layers. (Figure 98). The lower bentonite is possibly the Tioga Bentonite (but 50 feet into the chert and limestone) and the upper is here designated as the "Big Sandy" Bentonite.

The changing strike of the isopach map contours (Figure 94) is also of interest, and appears to change from a northeasterly direction to north-south to northwesterly, suggesting changes in basinal configuration.

From the lithology studies, Figure 99 shows histograms of observed fractures versus lithotypes, stratigraphic units, structure on top of Ohio Shale, and thickness of total shale. The highest degree of correlation is seen in mud-shale lithology, the middle Huron unit, -1000 to -1250' (below sea level) on Ohio Shale structure, and a thickness of 500 to 600 feet in total sequence. If the areal values of the fracture occurrence, shale thickness, and structure on the Ohio Shale are superimposed, Figure 100 results. This suggests a high priority area (1) and second (2) and third (3) choices in terms of anticipated high open flow. The outlines of Griffith's contours of density of high producing wells are shown for comparison. From such a comparison, the mud-shale lithology is suggested

as the "fracture facies" lithotype and the middle Huron unit as the stratigraphic unit in which such a lithotype is more common in the field area. Fracture facies may be expected to relate to other units in other areas or specific locales.

From Thomas (1951) an isopach map of brown shale in the Prestonsburg Quadrangle, with the demarcation line between 0.1 MMcf and 0.1 MMcf open flow, is shown in Figure 100. The trend of the line is NNE across the quadrangle, diagonally across the 400-500-foot isopachs of "brown shale." This trend relates closely to the trend of contours of percent brown silty mud-shale in Figure 40, the 90% line being very close to the above mentioned demarcation line. However, the values for the percent brown silty shale in Figure 40 drop off to the southeast, whereas the open flow values increase. The highly organic black shale increases to the south of the figure in question and the silt and sand increase to the east-northeast.

The 10 fracture/well contour in Figure 38 closely parallels the demarcation line and could suggest a fracture frequency limit of 10 fractures per well for =0.1 MMcf open flow, other factors being suitable.

The isopach anomalies in Figure 101 show thickness anomalies of 20-30 feet imposed on a basically N-S strike. These may be a result of erosion at the top of the Ohio shale over structural features, or "ponding" of black shale deposition in depressions on the epicontinental shelf during sedimentation (Browning, 1935). There may have been some karst development in the underlying limestones. Because production has not appeared to show a 1:1 correlation with the individual closures in studies in the past (Thomas, 1951; Billingsley, 1934; Lafferty, 1941; Hunter, 1935 and 1964),

recovery may rather be more complexly related to compaction fractures which are related to shale thin and thicks, silt-sand layers, and fine structure, and thus, not show absolute constraint by fine structural anomalies. A present study of detailed structure and relationships to gas occurrence is in progress (Lee, 1979).

The role of structural development along with the lithological differences is discussed under structural development in this section and in Summary and Conclusions.

Using a stepwise regression procedure for dependent variables D1, which is density of high producing wells $> .5$ MMcf/day/25 square miles and D2, which is density of high producing wells > 1.0 MMcf/day/25 square miles and independent variables (fractures, structural depth on top of Ohio Shale, shale thickness, percent sandstone/siltstone in total sequence, carbonate percent, green shale percent, occurrence of redbeds, black shale thickness, brown shale percent, gray shale percent) the following relationships were observed:

1. D1 was best explained by fractures: $R^2 = 83\%$

Adding redbed occurrence: $R^2 = 92\%$ No other variables met the 5% significance level for entry into the model.

2. D2 was best explained by fractures: $R^2 = 64\%$

Adding brown shale % of total sequence: $R^2 = 92\%$

Adding structural position: $R^2 = 96\%$ No other variables met the 5% significance level for entry into the model.

3. Table 10 shows the correlation coefficients.

Significant relationships at the 5% level are boxed.

Thus, conclusions from the lithology studies may be summarized as follows:

1. The samples studied indicate a shaly Berea-Bedford sequence in the southwest of the field with increasing silt and some sand to the east. The thickness appears fairly uniform.

2. The Ohio Shale shows a high shale content in the southwest with increasing silt and sand to the northeast, with a high silt-sand value area to the southwest of the field center. The clastic grain size increases to the northeast.

3. A higher carbonate zone trends northeast-southwest. Red bed occurrence follows the same trend. This may represent a higher area during Upper Ohio Shale deposition time or a preferential current direction bringing in detrital red bed fragments and following the incipient development of the eastern Kentucky syncline. This area also correlates with the thickest area of the "Corniferous" limestone, which suggests early basinal development.

4. Fractures, as observed from well cuttings and core data, and related to frequency of indicated horizons, appear to be most strongly related to:

a) mud-shale lithology, b) middle Huron stratigraphic unit, c) 500-600 foot thickness of total shale, and d) -1000-foot to -1250-foot structural position on top of the Ohio Shale. Figure 101 shows the comparison outlines of areas using these correlations, and the configurations of Griffith's density of high producing wells ($\geq .5$ MMcf/day/25 square miles and ≥ 1.0 MMcf/day/25 square miles). A non-subjective method of fracture identification is desirable. However, results from this

study are promising in lieu of other means of fracture identification.

5. The more highly fractured well centrally located in Floyd County may penetrate a normal fault of approximately 75-150 feet on the west side of the Floyd County Channel. The Ohio Shale appears to be 75-150 feet short. The Huntersville Chert underlies the Ohio Shale section.

6. The Knott County well may have penetrated a shallow margin thrust fault.

7. Positive identification of all Ohio Shale members in cuttings is not feasible without other information. More studies using lithology, biostratigraphy, and radioactivity are needed in subsurface (similar to Swager's outcrop studies) to better interpret the intricacies of shale stratigraphy in the Eastern Kentucky Field.

D. Geochemistry

Configurations of elemental percentages are compared with density of high producing wells (Figures 64, 102, and 80). Those showing similar configurations (Figure 63 for example), whether from high central values or low, are related in Table 13 to stratigraphic units.

Elements showing great similarity in map configuration are Al, Si, S, Mg, K, Fe, Ca, and the ratio Si/Al.

The highest number of correlations is related to the lower Huron unit, followed closely by the upper Huron. The element showing the highest number of correlations is sulfur, followed closely by Mg, and then by both Al and the ratio Si/Al. Although Al and Si/Al showed these high correlations, Si alone, did not.

Mineralic ratios were interpreted in terms of paleoenvironment. The Kaolinite/Kaolinite + Illite Ratio #1 has been used in coal research

(Renton, 1979; Negus-deWys and Renton, 1979). Based on this work the ratio of kaolinite to illite changes, depending upon the inferred depositional environment. Kaolinite is an indication of fresh water environments while illite becomes increasingly dominant as the environment becomes more "marine" or alkaline. In the southern Appalachian basin coals or the western coals, interpreted as having fresh water origins (lacustrine, alluvial plain), kaolinite makes up 70% or more of the clays. In the northern Appalachian Basin, interpreted as being more "brackish," the ratio is about 50:50, while in the Illinois basin where coals accumulated in a more "marine" influence, the kaolinite represents about 30-40% of the clays. The terms "brackish" and "marine" are relative terms. The most marine conditions under which coal could be preserved would actually be brackish at best. Thus, the Kaolinite/Kaolinite + Illite ratio in this study is monitored as a possible indicator of marine influence, the shales being considered the product of a poorly preserved peat type of environment.

The Quartz/Quartz + Kaolinite + Chlorite + Illite Ratio #2 is basically a quartz-clay ratio. The relative abundance of quartz would be expected to increase as the clastic source is approached, i.e., greater proximity to land. This is the interpretation applied to the data.

The Siderite/Calcite + Dolomite + Siderite Ratio #3, again is based on coal studies. Siderite is correlative with a fresh water-dominated environment. This ratio parallels the Kaolinite/Kaolinite + Illite ratio, the siderite only appearing as a dominant carbonate phase when kaolinite represents 70% or more of the clays.

The role of diagenesis could be raised to complicate the picture, but at the present writing, it was decided to use the interpretation based on

coal studies unless conflict was shown with other map interpretations, or a good basis for changing interpretation of this ratio was revealed (Smosna, 1979).

The Calcite/Calcite + Dolomite Ratio #4 is the classic carbonate ratio with increased dolomite reflecting near-shore, evaporative environments.

The Chlorite/Chlorite + Kaolinite Ratio #5 is also interpreted on the basis of coal study results. Based on coal studied, chlorite is a marine indicator. There does seem to be a variation in the relative abundance of the chlorite and kaolinite depending upon the depositional geochemistry. This ratio monitors the chlorite portion of the clay suite.

Table 12 shows the basic interpretations used in the mineralic ratio maps. When the highest and lowest values of all ratios are compiled on a master map, Figure 103 results. Stage 2 of interpretation is shown in Figure 104. No major conflict is observed in the compiled interpretation map. The north central section of the study area (Paint Creek Uplift) is dominated by the highest fresh water indication, non-alkaline, and close to clastic source, with the closest to clastic source value situated at the central southern extreme of this area. Fresh water areas are indicated east and west in the vicinities of the Pike County and Perry County uplifts. An area of marine influence extends from the southwest into the study area, with a slightly marine area indicated in the northeast. This trend may be related to the eastern Kentucky syncline development (see Figure 2) and shows interruption of this marine trend, and perhaps central blockage of marine water; similarly, the syncline is interrupted by the N-S interruption by the Paint Creek Uplift from the north.

The marine, clastic source area just to the southwest of the center of

the field is an anomalous carbonate and clastic area, also shown in the lithology studies to show the largest number of fractures. Fracture filling probably contributes to the anomaly. The center of the field has been shown also in the lithology studies to be an area of intertonguing complexity of different shale types. The green shale appears to be emanating from the northeast, which coupled with the geochemistry would suggest fresh water transport. The brown shales appear to originate largely in the northwest, related through geochemistry to fresh water transport and clastic source. The indication of near-shore evaporative environment for the entire northwestern three-quarters of the area is suggestive of very shallow water deposition.

The southeast direction, from which later thrust and uplift occur, appears not to be strongly marine, but also not strongly fresh. Lack of data hampers further interpretation.

Marginal trends of computer-maps are computer-related distortion and the central area is thus more reliable. It should be mentioned that this is an ongoing study, in which 162 maps and 160 graphs have been produced to date. A proposal has been funded for further definitive interpretation and regional relationships.

Conclusions based on the geochemistry study to date include the following:

- 1) elemental inorganic geochemistry shows promise as an exploration tool for field development,
- 2) the Si/Al ratio of oxides, Al oxide, S and Mg oxide maps show the highest number of correlations with contoured densities of high producing wells,

3) the lower Huron shows the highest number of correlations of elemental data with production; the upper Huron is a close second; the Three Lick shows the least correlation, and

4) mineralic ratios are best used for paleoenvironmental interpretation, at the present stage of data analysis.

Stratigraphic unit tops need refinement from lithology studies and ratio interpretation should be further researched for more specific paleoenvironmental implications.

E. Speculation

It is always tempting after an intensive study to speculate on possibilities with the fragmentary evidence at hand. When the structure, stratigraphy-lithology, geochemistry, and open flow data are all compared, gravity tectonics, driven by the uplift in the southeast and abutting against the Paint Creek Uplift, may explain an area following closely the basement Floyd County Channel, having 1) shorter and more intense fractures, 2) early gas migration to the area off the nose of the Paint Creek Uplift, 3) disruption of lithology patterns, 4) geochemical anomalies, 5) patchy sands in the Berea/Bedford, 6) high pressure in the center of the field, 7) a ghost thrust pattern on accordant summit levels, and 8) fracture facies more intense in the Huron where detachment is known to occur. The N-S trend in open flow trends occurs only in the low or non-productive areas outside the high open flow area.

Eastern flowing rivers from the central area off the Paint Creek Uplift are mentioned in older literature (Billingsley, 1934) as occurring in Berea/Bedford time. This may also account for "meandering" patterns of high open flow off the nose of the Paint Creek Uplift.

The contemporary residual in situ compressional stress is oriented E-W in eastern Kentucky and is suggested by Sybar and Sykes (1973) to be related to the driving mechanism of plate tectonics. This in situ stress could be expected to affect both the existing fracture patterns of the black shale, and induced patterns of fracture after "shooting" a well.

IV. SUMMARY AND CONCLUSIONS

Trends in the structural setting of the Eastern Kentucky Gas Field originate in the Precambrian with N-S, E-W, and NE-SW directions.

Basement tectonics, whatever the cause, appear to continue to play a role in basinal configuration, thin-skinned tectonics, and interaction of structural development throughout the Paleozoic history of the field. Sedimentation, facies relationships, and fracture development in turn are affected by one or more of these factors. The pattern was established early with the formation of the northeast trending Rome Trough in the area of the present-day eastern Kentucky syncline.

Basinal subsidence, during deposition of the Ohio Shale sequence, was preceeded by volcanic ashfalls (bentonite) during several intervals. Thicker shales, suggesting more rapid basinal subsidence, occurred in lower Huron time shortly after these ashfalls and again in Cleveland time following another period of volcanic ashfalls ("Big Sandy" bentonite). These thicker sequences are also blacker as a result of higher organic content. An obvious correlative question would be the possibility of volcanic activity preceeding the upper Huron blacker shales.

The source material for the organic black shales appears to originate largely from cratonic marginal areas to the north and west of the field area where it may be presumed, large swamp forests of Archaeopteris

(Callixylon) existed. These tree-ferns, placed in the special class of Progymnospermopsida, reached a diameter of more than five feet.

How far into the inland sea these early giants of the Devonian swamps ventured is open to conjecture, but they probably did not grow in water deeper than 1-2 feet. The shallow, anoxic, inland seawater was teeming with green algae (Tasmanites) and brown algal forms, i.e., Protosalvinia, and the black shales show evidence of at least six other plants. Prevailing winds during the upper Devonian were from the east; related to present-day geography the prevailing wind direction would be from the northeast of the study area concentrating floating vegetation in the southwestern part of the basin against the cratonic margin. A similar condition presently exists in Lake Erie.

Detrital clays and silts, from the prograding deltas to the east and north, were deposited in complex intertonguing relationships with brown organic silts from the north and northwest and black muds from the northern and western cratonic swamplands. There may also have been contributions from the south. Ashfalls may have actually increased plant productivity after temporary damage or destruction. Organic soils were washed off the cratonic margin in fresh water along with fine clays. Erosion of such soils would also have taken place as the lower Huron seas transgressed the low-lying craton.

The Paint Creek Uplift emerged in a north-south trend in the northwestern part of the study area, doming the Ohio Shale, and interrupting the earlier established synclinal structure (ancestral Rome Trough) of the northeast trending eastern Kentucky syncline. This uplift divided the syncline into a northern "basin" and a southern "basin". Fracturing of the

Ohio Shale in radiating bands to the east and southeast probably accompanied this structural development.

Uplift and compression originating in the southeast in post-Devonian time, was hinged along the eastern Kentucky syncline, and elevated the southeastern two-thirds of the area to form the southeastern slope flank of the syncline. This tectonic movement raised the Ohio Shale sequence slightly in that area and was probably accompanied by a second series of fractures related to these stresses emanating from southeast of the study area. The lowest portion of the sequence (lower Huron) might be expected to show the greatest effect of tensional fractures from this movement.

This uplift imparted a gravity gradient toward the northwest so that decollement features related to gravity tectonics could be anticipated. The lower Huron Shale, the base of which is the zone of detachment in the southeast, could be expected to be the site of greatest disruption.

The most complex intertonguing of lithofacies occurs over the center of high gas production, which has long been known to be associated with fracture occurrence and siltier lithology.

Cross sections through open flow data compared with structure show a close correlation of high gas accumulation to general doming of the Paint Creek Uplift. (Figure 105).

On a more localized scale, the high open flow trends appear related to radially oriented bands of higher production, focussed on the nose of the Paint Creek Uplift, but also showing smaller subtrends, possibly resulting from interaction of the southeastern uplift and later southeastern and eastern compressional forces with the Paint Creek Uplift (Figure 92). The postulated radiating permeable fracture zones related to the Paint

Creek Uplift probably provided conduits for the major pattern of gas accumulation off the nose of the uplift. Circular trends are also apparent around this nose. High pressure zones in the shales are probably a result of the compressional and compactional relationships, coupled with the fracture conduits over the nose of the Paint Creek Uplift.

The eastern flank of the eastern Kentucky syncline demarcates the major area of higher open flow from the area of little economic production to the northwest. Gas may have escaped in this latter area because of fractures extending to the surface and probably related to growth of the Rome Trough.

Thus, the Eastern Kentucky Gas Field, a coalescence of many fields, appears to represent overall a highly complex structural-stratigraphic gas trap.

Certain inorganic geochemical elements appear to delineate gas accumulation and/or structure, and thus provide a tool for field development and exploration. (Figure 106). Mineral ratios present a basis for interpretation of paleoenvironmental conditions, which in turn may prove useful in development and exploration.

The shale reservoir of the Eastern Kentucky Field area appears to have been deposited in an area which was dominated by relatively fresh water, marginal, cratonic swamps. These swamps were periodically destroyed and the organic debris contributed to the black shales accumulating at the toe of the prograding delta from the east. Cyclic development of gray and black shales on a detailed scale (within members) as well as on a larger scale (stratigraphic members) in the Upper Devonian Ohio Shale sequence is especially apparent in the northeastern part of the field. It is evidenced in wireline logs, lithology, and geochemical graphs. This recognizable

cyclical sedimentation continued through most of the Upper Paleozoic reaching a climax in the Pennsylvanian time when the swamp development phase of a cycle is preserved as coal.

Possibly future field development could benefit from exploring trends relating to the two interacting structural patterns resulting from the intersection of the Paint Creek Uplift trend and the southeastern uplift trend. Blocks within the Rome Trough could individually be productive because of more intense fracturing along their margins (Schaefer, 1979). Production might also be sought from smaller structures off the nose of the Paint Creek Uplift, but of sufficient size to cause compactional fractures or fractures originating from tectonic stress associated with the development of the structure. The contemporary in situ compressional stress is oriented east-west, which is also the trend of the 1st degree surface from trend surface analysis based on open flow data. A statistical advantage in offset wells from older high producing wells could be based on this evidence. Clearly, fracing (hydrofrac, etc.) results should be expected to have such a preferential direction and such information plus lithology and fracture frequency trends could be of use in bifurcating (trifurcating, etc.) in drilling wells.

The silt-clay ratios appear to play an important role in defining the best production in the field, and where possible, following these ratios may enhance drilling success. The 90% line for "percent clay of total sequence" runs approximately through the center of high density of high open flow values. The 50:50 silt:sand ratio passes N-S through the center of high production. These lines should be utilized in exploration.

The 10/well fracture frequency contour, parallels the greater than

0.1 MMcf open flow demarcation on the northwestern margin of the field.

This is probably not fortuitous that such a minimum frequency of fracture horizons within a well relates to higher open flow. The fracture frequency pattern alone would also suggest extending exploration to the southwest. However, thickness of organic black shale diminishes rapidly in that direction so that will be a limiting factor to exploration in that direction.

The stratigraphic nomenclature of the Ohio Shale places the black bituminous Cleveland Member above the gray Chagrin Member, which in turn overlies the black Huron Member, which is very similar in lithology to the Cleveland. The upper portion of the Ohio Shale is a complex intertonguing of shales from primarily different source areas: grays and greens representing for the most part, uplift and distal deltaic sedimentation from the east and northeast, and black and brown resulting from encroachment and destruction of cratonic swamp margins by the sea primarily from the west and northwest with some addition from the southeast. As such, the Cleveland and Huron Members are part of the same black lithofacies as are the gray and green lithofacies of the, again, Cleveland, Three Lick, and Huron units. Gray silty tongues in the Cleveland can be traced eastward toward the source area where they increase in thickness, as can black tongues usually be traced toward the craton to the north and west.

A revamping of the nomenclature is thus suggested, based on lithofacies, source relationship, as well as biostratigraphic basis. The true depositional relationships of this time--transgressive sequence are not represented in the present nomenclature. A suitable and acceptable solution represents a major endeavor by itself.

V. SUGGESTED FUTURE PROBLEMS FOR STUDY

Other problems besides that of stratigraphic nomenclature raised by the present study include:

1. Study of black shale-coal as a continuum in paleoenvironments in terms of sedimentation, geochemistry, and energy dynamics (proposal in preparation),
2. Analysis of structure using 4200 + wells above and below the Ohio Shale sequence, and relationships to open flow data (study in progress),
3. Lithotypes in the Eastern Kentucky Field area and relationships to adjacent areas (pilot study on 700 thin sections funded and in progress),
4. Detailed production decline studies on segments of the field, and relationships to other parameters,
5. Detailed geochemical analysis of stratigraphic units and relationships to natural radioactivity and lithofacies (proposal funded for first year of a 2-year study),
6. Relationships of geological development of the Eastern Kentucky Gas Field to continental plate collisions and subduction,
7. Relationships of bentonite occurrence to basinal configuration and sedimentation; is there another bentonite zone beneath the upper Huron black shale; what effects did bentonite have on plants on land and sea,
8. What Devonian plants contributed to gas formation, their habitat, evolution, etc.,
9. Into what depth(s) of water did the Upper Devonian black shales settle and what was their transport history,
10. How does the uranium content change across the field; what is the relationship to organics; what amount of gold exists in the shales,

11. Could elemental geochemistry on a finer scale be useful in exploration; could it be used in a mobile unit (under study),

12. Assuming gas is produced from fractures, what other methods could be used for detection: gas 'snoopers' (U.S. Army equipment), infra-red, plant changes, low altitude air surveys, shallow seismic (under study); would lichens be subject to gas emanations and, thus be natural fracture indicators,

13. Instead of cryogenicies, why not "hot" wells, where a heat source (or differential) is used to encourage gas release from shales,

14. A more regional tie-in of present study with surrounding areas (study initiated),

15. Study the true range vertically and horizontally of Protosalvinia, and possible significance of its restricted zones,

16. Where are the "zillions" of spores (homosporous and heterosporous) that are large tree-fern, Archaeopteris, must have produced,

17. Are fish found in Ohio black shale in the state of Kentucky as they are in Ohio black shale in the state of Ohio; if not, why not,

18. What is the stratigraphic relationship of the Boyle to the Huntersville,

19. Are there other bentonities in the Ohio Shale sequence and where are the source volcanoes; what kind of emissions,

20. Are there unrecognized erosional horizons within the shales,

21. What are the current directions for gray, green, black, and brown shales; what are the differences in each member of the Ohio Shale sequence,

22. Could the black shale be primarily eroded soil from the craton (as suggested as one possibility in this paper),

23. How extensive is channelling in the black shales; what are the directions and locations of channels,

24. A complete mica study along with other mineral contaminants in the lithology; possibility of igneous intrusions in the field area,

25. Is there a recognizable porosity difference (which may be the result of the silt or sand content) related to the demarcation of greater than 0.1 MMcf per day open flow, and that can be determined from wireline logs in combination (density logs, radioactivity, etc.),

26. Investigate Devonian cyclic sedimentation as a precursor to Carboniferous coal swamps (as suggested in this paper); causes common to both,

27. Tidal differences in the Upper Devonian and possible effects on sedimentation, including deltas, and

28. Could gravity tectonics driven by the southeastern uplift be the basic cause, in an area following the Floyd County Channel, for: 1) increased and shorter fractures, 2) early gas migration to the area off the Paint Creek Uplift nose, 3) disruption of lithology patterns, 4) geochemical anomalies, problems in log correlation, 5) patchy sands in the Berea/Bedford, 6) high pressure in the center of the field, 7) "thrust" pattern on accordant summit levels, and 8) fracture facies more intense in the Huron where detachment is known to occur.

TABLE 1 **STRATIGRAPHIC UNITS IN STUDY AND RELATIONSHIPS**
TO NEW ALBANY SHALE AND CHATTANOOGA SHALE
(after Swager, 1978, Provo, 1977, Lineback, 1968, Miller, 1965, McFarlan, 1943)

System	Series	Units of New Albany Shale in S.IN.-W.KY.	Units of Ohio Shale in OH.-E.Ky.	Units of Chattanooga Shale in W.VA.-E.TENN.
DEVONIAN	Miss. Lower Miss.	Rockford Limestone	Sunbury Shale	Big Stone Gap Member
		Jacob's Chapel Bed Henryville Bed Underwood Bed Falling Run Bed	Bedford Berea Sequence	
	UPPER DEVONIAN	Clegg Creek Member	Cleveland Shale	Middle Gray Siltstone Member
		Camp Run Member	Three Lick Bed	
		Morgan Trail Member	Upper Member	Lower Black Shale Member
		Selmier Member	Middle Member	
		Boyle ls./ch.	Lower Member	
	Mid. Dev.	Blocher Member	Olentangy Shale	Absent
			Marcellus Shale	
			Onondaga Limestone/ Huntersville Chert/ Needmore Shale	

Bedford-Berea Sequence			O H I O S H A L E
Cleveland Shale 200 API units Brownish-black, organic-rich shale with phosphate nodules near top.		Partial Chagrin Shale Equivalent	
Three Lick Bed 3-4 closely spaced negative deviations (less than 200 API units) on gamma ray curve Interbedded brownish-black and greenish gray shales or mudstones (Provo, 1977). Limestone with cone-in-cone may be present.			
Upper Member 100-200 API units; massive brownish-black shale		H U R O N S H A L E	
Middle Member	Brownish-black and gray shales interbedded in lower half; <i>Protosalvinia</i> found in outcrop and core. Slightly less radioactive than Upper Huron Shale.		
Lower Member	Brownish black, organic-rich shale with 1-4 thin zones of greenish gray to gray. 200 API units; 1-4 thin zones of lesser radioactivity.		

Table 2. Stratigraphic Units Studied with General Gamma Ray Log Characteristics (Provo 1977) and Lithology.

PETROLOGY OF MUDROCKS (Folk, 1974)

"Mudrock (word coined by Ingram) is a general term used herein to cover those Terrigenous rocks that contain more than 50 percent silt and/or clay. The most obvious division of mudrocks is on the basis of texture and structure:" (Folk, 1974)

<u>Grain size of mud fraction</u>	<u>Soft</u>	<u>Indurated, non-fissile</u>	<u>Indurated, fissile</u>
Over 2/3 silt	silt	siltstone	silt-shale
subequal silt and clay	mud	mudstone	mud-shale
over 2/3 clay	clay	claystone	clay-shale

Table 3. Mudrock Terminology of Folk (1974).

LITHOLOGY SYMBOLS

	Sandstone	Y	Plant Fragments
	Siltstone	P	<u>Protosalvinia?</u>
	Redbeds	T	<u>Tasmanites</u>
	Limestone	→	Slickensides
	Dolomite	f	Fractures
	Pyrite	S	Spar
	Spicules?	g	Gouge
	Pseudo-oolites	μ	Microspores
	Bedding
	Missing Sample
	Shales		
	B- Black BR- Brown		
	G- Gray GR- Green		

Table 4. Lithology Symbols for Cross Sections.

SIMPLE STATISTICS FOR CHEMICAL ELEMENTS

Variable	Weight Percent oxide (except Sulfur)			Variance	Coefficient of Variance
	Minimum	Maximum	Mean		
MN	0.016	0.500	0.051	0.001	66.789
FE	3.590	20.150	8.519	2.679	19.214
S	0.051	8.258	2.364	0.907	40.272
ZN	0.001	0.106	0.013	0.000	72.342
SR	0.000	0.064	0.004	0.000	109.953
NA	0.149	0.730	0.661	0.004	9.660
MG	0.733	4.157	1.428	0.171	29.007
AL	6.000	18.120	14.206	3.333	12.851
SI	48.000	78.300	55.103	7.912	5.105
P	0.102	0.962	0.138	0.009	70.618
K	0.401	8.460	3.354	0.438	19.720
CA	0.155	32.985	1.252	12.565	283.140
TI	0.230	1.160	0.931	0.020	15.043
SI/Al RATIO	2.829	12.102	3.982	0.776	22.113
Coefficient of Variance: Highest Least					

Table 5. Simple Statistics for Chemical Elements.

SIMPLE STATISTICS FOR MINERAL DATA

VARIABLE	Percent Total Integrated Intensity*			Variance	Coefficient of Variance
	Minimum	Maximum	Mean		
ILLITE	0.0	91.4	52.3	189.2	26.308
CHLORITE	0.0	1.9	0.7	0.1	50.586
QUARTZ	4.0	83.3	33.7	119.6	31.085
KAOLINITE	0.0	13.0	0.5	3.2	374.000
SZOMOLNOKITE	0.0	2.2	0.0	0.1	664.617
CALCITE	0.0	68.9	1.3	42.9	522.579
ORTHOCLASE	0.0	2.0	0.0	0.0	469.630
ANHYDRITE	0.0	1.1	0.1	0.1	277.298
PLAGIOCLASE	0.0	2.7	0.9	0.2	42.371
BASSANITE	0.0	4.0	1.9	0.5	36.698
DOLOMITE	0.0	70.5	1.7	67.1	475.066
SIDERITE	0.0	17.5	2.2	2.6	72.945
PYRITE	0.0	13.1	4.8	15.6	49.622
RATIO 1	0.0	100.0	1.3	42.8	515.179
RATIO 2	4.4	100.0	39.3	160.1	32.197
RATIO 3	0.0	100.0	78.7	717.6	34045
RATIO 4	0.0	100.0	9.1	586.3	267249
RATIO 5	0.0	5.5	1.2	0.3	46639

*May be considered numerically equivalent to weight percent

Table 6. Simple Statistics for Minerals and Mineralic Ratios.

CHEMICAL FORMULAS FOR MINERALS

ILLITE	$(\text{H}_3\text{O}, \text{K})_y (\text{Al}_4 \cdot \text{Fe}_4 \cdot \text{Mg}_6) (\text{Si}_8 - \text{Al}_y) \text{O}_{20}(\text{OH})_4$ where $y < 2$, usually $y = 1-1.5$
CHLORITE	$(\text{Mg}, \text{Fe}^{+2}, \text{Fe}^{+3})_6 \text{AlSi}_3\text{O}_{10}(\text{OH})_8$
QUARTZ	SiO_2
KAOLINITE	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$
SZOMOLNOKITE	$\text{FeSO}_4 \cdot \text{H}_2\text{O}$
CALCITE	CaCO_3
ORTHOCLASE	KAlSi_3O_8
ANHYDRITE	CaSO_4
PLAGIOCLASE	$(\text{Na}, \text{Ca})\text{Al}(\text{Si}, \text{Al})\text{Si}_2\text{O}_8$
BASSANITE	$\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$
DOLOMITE	$\text{CaMg}(\text{CO}_3)_2$
SIDERITE	FeCO_3
PYRITE	FeS_2

Table 7. Chemical Formulas for Minerals.

RATIO DEFINITIONS

RATIO 1	$\frac{\text{KAOLINITE}}{\text{KAOLINITE} + \text{ILLITE}}$
RATIO 2	$\frac{\text{QUARTZ}}{\text{QUARTZ} + \text{KAOLINITE} + \text{ILLITE} + \text{CHLORITE}}$
RATIO 3	$\frac{\text{SIDERITE}}{\text{CALCITE} + \text{DOLOMITE} + \text{SIDERITE}}$
RATIO 4	$\frac{\text{CALCITE}}{\text{CALCITE} + \text{DOLOMITE}}$
RATIO 5	$\frac{\text{CHLORITE}}{\text{CHLORITE} + \text{KAOLINITE}}$

Table 8. Ratio Definitions.

DATA	TOTAL OPEN FLOW	AVERAGE PER WELL	PERCENT DRY HOLES (.06 MMcf/DAY)	AVERAGE TOTAL RECOVERY PER WELL
1964 (Hunter) 4205 wells	1,450 MMcf	.342 MMcf	13	405 MMcf
1978 (de Wys) 4143 wells	1,711 MMcf	.413 MMcf	11.8	415 MMcf

Table 9. Comparison of 1964 (Hunter) Open Flow and this Study.

COUNTY	PERCENT OF TOTAL GAS WELLS PRODUCING FROM DEVONIAN	% DRY HOLES (<.06 MMcf/DAY)
Knott	78.3 (highest %)	9.2
Magoffin	6.3	32.5 (highest %)

Table 10. Counties with Highest and Lowest Open Flow Based on
4205 Wells (Hunter 1964)

Symbol Summary	Age	Feature	Trend			Dome
			N-S	E-W	NE-SW	
	Precambrian	Rome Trough Floyd County Channel New York-Alabama lineament	x	x	x	
	Cambrian- Ordovician	Waverly Arch (east) Rome Trough Growth Faults	x	x	?	
	Silurian- Devonian	Cincinnati Arch Eastern Kentucky Syncline	x		x	
	Mississippian	Paint Creek Uplift Waverly Arch (west) Pike County Uplift Perry County Uplift	x x			x x
	Pennsylvania	Eastern Ky. Syncline Pine Mountain Thrust			x	
	Permian	Igneous Intrusion (Woodward Fault Zone) Surface Dikes (Woodward Fault Zone)				x

⊗ = greatest movement or development

associated
with E-W

Table 11. Trends and Ages of Structural Features in the Eastern Kentucky Gas Field Area.

STATISTICAL ANALYSIS SYSTEM

CORRELATION COEFFICIENTS / PROB !R! UNDER HO:RHO=0 / NUMBER OF OBSERVATIONS

	D1	D2	F	STRU	THICK	SS,SLT	CO ₂	GREEN	SH	R	BLK	BR	GRN
D1	1.00000 0.0000 7	0.94827 0.0019 6	0.91249 0.0041 7	0.37341 0.4044 7	-0.03424 0.9340 7	-0.09627 0.8340 7	0.09781 0.4144 7	0.04554 0.8340 7	0.09467 0.8400 7	0.14470 0.6757 7	0.47123 0.2858 7	-0.28190 0.5401 7	0.02922 0.9504 7
D2	1.00000 0.0000 6	0.79768 0.0573 6	-0.12742 0.8994 6	0.21758 0.6744 6	-0.19347 0.7134 6	0.00000 1.0000 6	0.32441 0.5232 6	0.14324 0.7282 6	0.10227 0.8471 6	0.50728 0.3044 6	-0.51729 0.2933 6	-0.08869 0.8673 6	
F	1.00000 0.0000 7	-0.02674 0.1364 7	0.01532 0.9734 7	-0.02653 0.9510 7	0.17562 0.7001 7	-0.04941 0.9162 7	0.03114 0.9471 7	0.48867 0.2658 7	0.27429 0.5517 7	-0.04281 0.9274 7	0.04818 0.9183 7		
STRU	1.00000 0.0000 7	0.01537 0.4722 7	-0.02144 0.9029 7	-0.08652 0.8537 7	0.03065 0.9480 7	0.01057 0.4421 7	-0.41219 0.3581 7	-0.20766 0.6550 7	-0.14755 0.6711 7	-0.21692 0.6090 7			
THICK	1.00000 0.0000 7	-0.08601 0.8512 7	-0.07024 0.8410 7	0.80387 0.0293 7	0.08133 0.8624 7	0.36356 0.4228 7	0.00703 0.9881 7	-0.60940 0.1463 7	-0.28995 0.5282 7				
SS,SLT	1.00000 0.0000 7	0.97501 0.0002 7	-0.46922 0.5505 7	0.99882 0.0001 7	0.02919 0.9505 7	-0.72244 0.0607 7	-0.15200 0.7649 7	0.79581 0.0323 7					
CO ₂	D1	Density of High Producing Wells 0.5 MMct/Day/25sq.mi.	1.00000 0.0000 7	-0.28345 0.5371 7	0.97481 0.0002 7	0.15248 0.7441 7	-0.68439 0.0899 7	-0.16235 0.7280 7	0.75147 0.0515 7				
	D2	Density of High Producing Wells 1.0 MMct/Day/25 sq.mi.	1.00000 0.0000 7	0.25832 0.5759 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
GREEN	F	Fractures	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
	Stru	Structure on Ohio Shale	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
SH	Thick	Thickness of Total Shale Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
	SS,SLT	Percentage of Sandstone and Silt in Total Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
R	CO ₂	Percentage of Carbonate in Total Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
BLK	Green	Percentage of Green Shale in Total Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
	Blk	Percentage of Black Shale in Total Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
BR	Sh	Percentage of Shale in Total Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
	Br	Percentage of Brown Shale in Total Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
GRN	R	Percentage of Redbeds in Total Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					
	Grn	Percentage of Green Shale in Total Sequence	1.00000 0.0000 7	0.5759 0.8806 7	-0.07048 0.8806 7	0.45626 0.3035 7	0.82426 0.0226 7	-0.24988 0.5809 7					

Table 12. Correlation Coefficients for Lithology Study. Highest Degrees of Correlation are Boxed. Others are not Significant at 95% Level.

CORRELATION OF COMPUTER MAPS WITH CONTOURED DENSITY OF HIGH PRODUCING WELLS									
Units	Oxides of Si/Al Ratio	Elements (all oxides except Sulfur)							Totals
		Al	Si	S	Mg	K	Fe	Ca	
Berea-Bedford	+	+		+	+	+			5
Cleveland	0	+		+	+	+			5
Three Lick		0	+	+					3
Upper Huron	+	0	+	+	0	0			6
Middle Huron		+		0+	+			+	4
Lower Huron	+	0		+ -	+	0	0	+	7
Total Sequence	+			+ -	+		0	+	5
Ohio Shale	+			+ -	+		0	+	5
Totals	6	6	2	8	7	4	3	4	

Table 13. Correlation of Computer Maps with Contoured Density of High Producing Wells.

+ Means a High Map Value Correlation

0 Means a Low Map Value Correlation

+ - is Correlation with the Second Highest Map Value

Blank is no Correlation with Highest and Lowest Map Values

RATIO

$$1. \frac{Ka}{Ka + Ill}$$

$$2. \frac{Q}{Q + Ka + Ill + Chl}$$

$$3. \frac{Sid}{Cal + Dol + Sid}$$

$$4. \frac{Cal}{Cal + Dol}$$

$$5. \frac{Chl}{Chl + Ka}$$

ENVIRONMENT

>Ka = fresh water
>Ill = marine or alkaline influence

>Q = clastic source

>Sid = fresh water

>Dol = near shore evaporative environment

Chl = marine indicator

RATIO MEANING

>Ratio—fresher water
<Ratio marine alkaline

>Q >Ratio
>Ratio—closer to clastics

>Ratio—fresher water

<Ratio—near shore evaporative environment

>Ratio—more marine

Table 14. Environmental Interpretations of Mineralic Ratios.

Figure 1. Location of study area and U.S.G.S. formational terminology (after Swager, 1978). Isopach lines (after Weaver and McGuire, 1973)

Figure 2. Pattern of gas recovery in a portion of Floyd County, suggesting recovery from fractures (after Hunter and Young, 1953).

Figure 3. Rock shale pressure decline of 200# contour from 1935-1951 (after Hunter and Young, 1953).

Figure 4. Accordant summit levels (after McFarlan, 1943).
Shaded area shows E-W central trend of contours.

Figure 5. Structure on top of the Fire Clay coal (after McFarlan, 1943). Note: Northeast-southwest trend of syncline interrupted by the N-S trend of the Paint Creek Uplift; the northeast basin is deeper than the southwest basin; this is the area (NE) where the "Corniferous" limestone isopach suggests an early basin; and this northeastern area is suggested by geochemistry to be an area of marine tidal influence. See Figures 48 and 104. Age of structural development is indicated in parentheses.

Figure 6. Coal face cleats (Long, 1979).

Figure 7. Structure on top of the Berea (after Thomas, 1951).

Figure 8. Structure on top of the Ohio Shale (after Provo, 1977).

Figure 9. Evidence of major development of the Rome Trough in Cambrian time (after Dever, et al., 1977).

Figure 10. Location of Cambro-Ordovician growth faults trending east-to-west, Permian igneous intrusive, and Permian dikes at the surface, related to the Woodward Fault Zone. Position of map area is shown in relationship to study area in inset map (after Silberman, 1972).

Figure 11. Bouguer gravity map with interpreted basement structures as named (after Ammerman and Keller, 1979). Surface faults and southern boundary of Rome Trough are indicated by solid line and heavy dashed line respectively.

Figure 12. Basement structure (after Shumaker, 1977). Interpretation is based on gravity data.

Figure 13. Geological provinces and orogenic trend lines (after Muehlberger, *et al.* 1967). The location of study area is shown by rectangle. Province ages are in billions of years.

Figure 14. Field location relative to the epicontinental shelf (after Price in Lafferty, 1941), the New York-Alabama Lineament (King and Zietz, 1978), Grenville metamorphic front (Bass, 1960), Cincinnati Arch, and oil and gas occurrence. Contours are of thickness of early Paleozoic clastics.

Figure 15. Sequential structural development.

Figure 16. Isopach map of Berea-Bedford Sandstone (after Pepper, Demarest, Merrels, 2nd., and de Witt, Jr., 1946). At 0-isopach the unit becomes all shale. The >100-foot contour area runs almost N-S adjacent to the eastern side of the highest production area in Floyd County.

Figure 17. The locations of cross sections constructed from formation density logs. Basement structure (after Shumaker, 1978) is shown in dashed lines.

Figure 18. Stratigraphic cross section B-B', southwest to north-east through the field center, showing log traces of natural radioactivity from the formation density logs. Intertonguing of the black and gray shales in the Cleveland are usually related to the changes in natural radioactivity. The black shale in the Cleveland is shaded gray.

Figure 19. Stratigraphic cross section E'-E, north to south through the southern end of the field, showing log traces of natural radioactivity from the gamma ray logs. The black shale in the Cleveland is shaded gray.

Figure 20. Stratigraphic cross section K'-K, north to south through the northern end of the field, showing traces of natural radioactivity from the gamma ray logs. The Protosalvinia zone is where the brown algae occur most commonly. It has been reported at horizons in the Three Lick down through the Lower Huron (Provo, 1977; Swager, 1978).

Figure 21. Stratigraphic cross section B-B'; datum: top of Berea. The intertonguing black and gray shales in the Cleveland, especially over the center of the field, are apparent in this cross section. Where temperature logs are available, gas occurrence is noted.

Figure 22. Stratigraphic cross section E'-E; datum: top of Berea. Slight structure at the base of the section is apparent. Gas occurrence from temperature logs is noted, where temperature logs are available.

Figure 23. Structural-stratigraphic cross section A-A'. Oil and gas occurrence from temperature logs and drilling records is noted.

Figure 24. Structural-stratigraphic cross section B-B'. Gas occurrence is noted where temperature logs or drilling records are available.

Figure 25. Structural-stratigraphic cross section C-C'. Gas occurrence is noted where temperature logs are available.

Figure 26. Structural-stratigraphic cross section E-E'. Gas occurrence is noted where temperature logs are available.

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Figure 27. Structural-stratigraphic cross section F'-H. Gas occurrence is noted where temperature logs are available.

Figure 28. Structural-stratigraphic cross section H'-J. Gas occurrences are noted where temperature logs are available.

Figure 29. Structural-stratigraphic cross section K'-K. Gas occurrence is noted where temperature logs are available.

CLEVELAND SHALE

THREE LICK BED

ISOPACHS of Ohio Shale Units Eastern Kentucky Gas Field(s) after Provo, 1977

J. Negus deWys

February, 1979

UPPER HURON SHALE

MIDDLE HURON SHALE

LOWER HURON SHALE

Figure 30. Isopach maps of the Cleveland, Three Lick, Upper Huron, Middle Huron, and Lower Huron units (after Provo, 1977). About 250 wireline logs and drillers' logs were used in the preparation of these maps. Note changing strike of isopachs with progression up the section. The thickness of units W-E also changes up the section, suggesting changes in the rate of basinal subsidence.

Isopachs of Total Ohio Shale

deWys, 1979

Figure 31. Isopach map of total Ohio Shale.

Figure 32. Location of wells from which cuttings are studied (large dots). Well #1660 is studied by geochemistry only. Small numbers are locations from which gamma ray logs are available, but not always usable for this study.

Figure 33. Lithology cross section A-A'.

Figure 34. Lithology cross section B-B'.

Figure 35. Lithology cross section C-C'.

Figure 36. Lithology cross section D-D'.

Figure 37a. Drawing of Archaeopteris from Gillespie, et al., 1978, with permission from the West Virginia Geological and Economic Survey. This fern-like tree was placed in a new class Progymnospermopsida in 1971 after the fronds of Callixylon were found attached to the stem of Archaeopteris which is reported from several locales in the Ohio Shale, and is known to exceed a diameter of five feet.

Figure 37b. Deposition of black muds in shallow tideless waters (after Twenhofel, 1939). "A peneplaned surface, or any level surface of any origin, is gradually submerged with plants adjusted to depths. The marginal areas are covered with aquatic plants bathed by fresh waters. Seaward the aquatic plants are bathed by brackish and salt waters. Between the salt-water and fresh-water plants is a zone of variable waters. It is postulated that the plants would hinder and largely prevent circulation, thus insuring deposition of black muds. An advancing sea would leave a deposit of black mud over the area of advance and this would become covered by other deposits as the waters become too deep for the plants to thrive. A receding sea would leave a deposit of black mud over the areas deserted." (Twenhofel, 1939).

Figure 37b. (Caption on preceding page.)

(after Twenhofel, 1939)

Figure 38. Map of observed frequency of fracture horizons in wells studied.

Figure 39. Map showing iso-value lines of percent gray clay- to mud-
shale of total sequence.

Figure 40. Map showing iso-value lines of percent organic brown silty mud-shale of total shale sequence.

Figure 41. Map showing iso-value lines of percent green clay-shale of total shale sequence.

Figure 42. Isopach map of highly organic black mud-shale (in feet).

Figure 43. Upper Devonian black shale isopach map (after Harris, de Witt, Jr., and Colton, 1978). Contours in feet.

Figure 44. Map showing iso-value lines of percent shale in total shale sequence.

Figure 45. Map showing lines of percent silt plus sand in total shale sequence.

Figure 46. Silt to sand ratio map.

Figure 47. Map showing iso-value lines of percent carbonate in total sequence.

Figure 48. Isopach map of "Corniferous" limestone (McFarlan, 1943).
Contours in feet.

Figure 49. Map showing occurrence of redbeds and bentonites. Contours in feet.

DIAGRAMATIC CROSS-SECTION SHOWING FACIES CHANGES
IN BEREA-BEDFORD SEQUENCE IN EASTERN KENTUCKY
(after Pepper, Demarest, Merrels, and deWitt, 1946)

J. Negus deWys, 1979

Figure 50. Diagrammatic cross section showing facies changes in the Berea/Bedford sequence in eastern Kentucky (after Pepper et al., 1946). The cause of these changes is not completely understood.

Figure 51. Structure on the Big Lime (after Miller and Withers, 1928).

Figure 52. Isolines drawn on quartz data from Hunter (1935). Data values are based on published county averages in percent.

Figure 53. Isolines drawn on pyrite data from Hunter (1935). Data values are based on published county averages in percent.

Figure 54. Isolines drawn on kerogen data from Hunter (1935). Data values are based on published county averages in percent.

Figure 55. Isolines drawn on bituminous material data from Hunter (1935). Data values are based on published county averages in percent.

Figure 56. Isolines drawn on estimated ultimate recovery well data (Hunter, 1935). Data values are based on published county averages.

Figure 57. Comparison of Si and Al oxide graphs for the Berea-Bedford through Huron sequence. Wells are arranged west to east from left to right.

Figure 58. Si oxide graphs in well positions.

LEGEND for Si/Al RATIO CROSS SECTIONS

↓	WELL LOCATION on CROSS SECTION
B/B	TOP of BEREА/BEDFORD
O/C	OHIO SHALE/TOP of CLEVELAND
3 L	TOP of THREE LICK
UH	TOP of UPPER HURON
MH	TOP of MIDDLE HURON
LH	TOP of LOWER HURON
HB	BOTTOM of HURON
	>4.0 Si/Al OXIDE RATIO
•	STUDY WELLS
○	CORED WELLS

EASTERN KENTUCKY GAS FIELD **SOUTHWEST-NORTHEAST CROSS SECTION A-A' OF** **Si/Al RATIO**

J. Negus de Wys June, 1979

Figure 59. Si/Al oxide ratio cross section A-A'.

EASTERN KENTUCKY GAS FIELD
SOUTHWEST-NORTHEAST CROSS SECTION B-B' OF
Si/Al RATIO

J. Negus de Wys June, 1979

Figure 60. Si/Al oxide ratio cross section B-B'.

CROSS SECTION C-C' OF Si/Al RATIO

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Figure 61. Si/Al oxide ratio cross section C-C'.

CROSS SECTION **D-D'** OF Si/Al RATIO

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June, 1979

Figure 62. Si/Al oxide ratio cross section D-D'.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	53.20	54.34	54.91	56.06	56.63
MAXIMUM	53.20	54.34	54.91	56.06	56.63	57.20

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

	93.00	2.00	1.00	2.00	1.00	1.00
--	-------	------	------	------	------	------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
	=====	=====	=====	=====	=====	=====
	.....	+++++	XXXXXXXX	00000000	0000000000	0000000000
	.....	+++++	XXXXXXXX	0000000000	0000000000	0000000000
SYMBOLS	1.....	+++2+++	XXX3XXX	000040000	0000000000	0000000000
	.....	+++++	XXXXXXXX	0000000000	0000000000	0000000000
	.....	+++++	XXXXXXXX	0000000000	0000000000	0000000000
	=====	=====	=====	=====	=====	=====
FREQ.	4	2	1	3	1	3
1	I..1..I	I++2++I	IXX3XXI	100400I	100500I	100600I
2	I..1..I	I++2++I		100400I		100600I
3	I..1..I			100400I		100600I
4	I..1..I					100600I

Key to Figure 63.

PERCENTAGE OF Si OXIDE FOR THE THREE LICK UNIT

Figure 63. Computer-generated map of average Si oxide values in the Three Lick unit. Darkest print out area represents the highest level. Intervals in mapping are not necessarily equal value increments because of computer mapping constraints. See key on preceding page.

*All elements in oxides except Sulfur

Chart of
COMPUTER DRAWN MAPS
Eastern Kentucky Gas Field
J.Negus deWys July, 1979

Figure 64. Comparison of computer drawn map miniatures for all units for Si/Al, Al, Si, S, Mg, K, Fe, and Ca.

Figure 65. Computer-drawn maps for Si/Al oxide ratio for stratigraphic units. B/B = Berea/Bedford; C = Cleveland; 3L = Three Lick; UH = Upper Huron; MH = Middle Huron; and LH = Lower Huron; TS = Total Shale Sequence; OS = Ohio Shale.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	0.17	0.40	0.62	0.85	4.58
MAXIMUM	0.17	0.40	0.62	0.85	4.58	4.98

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

3.50	4.50	4.50	4.50	75.00	8.00
------	------	------	------	-------	------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
SYMBOLS	1.....	++++++ ++++++ ++12++ ++++++ ++++++	AA AA 3 AA AA	----- ----- ----- ----- -----	XXXXXX XXXXXX XX XXXXXX XXXXXX	XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX
FREQ.	2 1 1 1 4	1 2 1 1 1	2 3 3 3 3	4 4 4 4 4	4 5 5 5 5	1 2 6 6 6

TIME = 0.0

Key to Figure 66.

Figure 66. Computer-drawn map of Ratio 1 for total stratigraphic sequence studied.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL ONLY
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	33.32	35.21	37.09	38.98	40.87	42.75
MAXIMUM	35.21	37.09	38.98	40.87	42.75	44.64

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

16.67 16.67 16.67 16.67 16.67 16.67

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
SYMBOLS	1	2	3	4	5	6
FREQ.	1	5	0	2	3	2

TIME = 0.0

Key to Figure 67.

Figure 67. Computer-drawn map of Ratio 2 for total stratigraphic sequence studied.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

	9.10	17.58	60.00	76.97	82.91	88.85
MINIMUM	9.10	17.58	60.00	76.97	82.91	88.85
MAXIMUM	17.58	60.00	76.97	82.91	88.85	93.94

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

	10.00	50.00	20.00	7.00	7.00	6.00
	10.00	50.00	20.00	7.00	7.00	6.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
SYMBOLS	..... ..... ..... ..... ..... .....	+++++ +++++ +++++ +++++ +++++ +++++	..... ..... ..... ..... ..... .....	----- ----- ----- ----- ----- -----	..... ..... ..... ..... ..... .....	..... ..... ..... ..... ..... .....
FREQ.	1 1 1 1 1 1	2 2 2 2 2 2	2 3 3 3 3 3	1 4 4 4 4 4	4 5 5 5 5 5	4 6 6 6 6 6

TIME = 0.0

Key to Figure 68.

Figure 68. Computer-drawn map of Ratio 3 for total stratigraphic sequence studied.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	0.32	1.60	6.38	19.15	28.73
MAXIMUM	0.32	1.60	6.38	19.15	28.73	31.92

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

1.00 4.00 15.00 40.00 30.00 10.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

SYMBOLS

FREQ.

TIME = 0.0

Key to Figure 69.

Figure 69. Computer-drawn map of Ratio 4 for total stratigraphic sequence studied.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	77.82	82.26	90.02	91.57	93.12	95.56
MAXIMUM	82.26	90.02	91.57	93.12	95.56	100.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

20.00	35.00	7.00	7.00	11.00	20.00
-------	-------	------	------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

[illegible]

TIME = 0.0

Key to Figure 70.

Figure 70. Computer-drawn map of Ratio 5 for total stratigraphic sequence studied.

Figure 71. Areas of Upper Devonian Ohio Shale gas production.

Figure 72. Locations of 4750 wells for which final open flow data was supplied by Kentucky-West Virginia Gas.

Figure 73. Hand-contoured map of final open flow data from 4750 wells. Complexity of the coalesced fields is apparent.

Figure 74. Computer-drawn map of open flow data.

Figure 75. Histogram of open flow data (0.00 $\geq$ 2.00 MMcf/day open flow). Vertical scale is number of wells. Total wells = 4750; total wells used = 4138. Note vertical break in scale.

Figure 76. Histogram of open flow data (0.00-0.225 MMcf/day) vertical scale is number of wells.

Figure 77a. Histogram of all wells used in computer-mapping (4138). Figure 77b shows tail of histogram representing only 19 wells.

Figure 77b. Histogram tail of 77a, showing highest value 19 wells. Note histogram must be broken twice on the horizontal scale.

Figure 78. Data points used by Griffith (1976). Points $> .5$ MMcf/day are connected where not contra indicated.

Figure 79. Pattern resulting from connecting all wells with $\geq .5$ MMcf/day where not contra indicated. This should be compared with Figure 76 in order to recognize the density of data and constraints of such density imposed on this pattern.

Contours of High Volume Wells
Based on ~4750 Wells
(after Griffith, 1976)

J. Negus deWys
March, 1979

Figure 80.

Contours of density of high producing wells (after Griffith, 1976). Contours represent number of wells $\geq .5$ MMcf/day/25 square miles (left) and ≥ 1 MMcf/day/25 square miles (right). These figures may be interpreted as the area of gas accumulation with recovery details smoothed out. Note pattern irregularities suggesting linear peripheral extensions. Compare with Figures 77a and 77b.

Figure 81.

First degree trends from three trend surface analysis programs. Total map study area is represented by quadrangle in 1, 11, and 111. Areas with arrows are the map segments on which trend surface analysis programs were run. Arrows indicate 1st degree surface, or major trend of data. R^2 values are very low, suggesting a low predictive value in the designated direction.

Figure 82. Trend surface analysis (4°) using a grid of 417 points of open flow data.

Figure 83. Hand-contoured map of open flow data with three contour levels, using 4750 wells. The highest value areas are shaded to enhance the pattern of higher open flow. Circled dots are locations of wells used in lithology and geochemistry studies.

Figure 84. Trends of high open flow data taken from Figure 83.

Figure 85. Trends of low open flow data taken from Figure 83.

Polar Plot of High Open Flow Trends

Figure 86. Polar plots of high open flow data trends. The length of trends are measured from a 1:250,000 scale map. Radial scale = number of trends. X = trends.

Polar Plot of Low Open Flow Trends

Figure 87. Polar plots of low open flow data trends.
 Radial scale = number of trends.
 Trends measured on a 1:250,000 scale map.
 X = trends.

Polar Plots of A) Cumulative Length of Total High, and B) Total High and Low Open Flow Trends

Figure 88. Cumulative plots of trend lengths of high and low open flow data. Radial scale = number of trends. Trends measured on a 1:250,000 scale map.

Figure 89. Polar plot of composite of Devonian Shale fracture orientations at outcrop (after Long, 1979).

Figure 90. Three dimensional interpretation of basement structure after Shumaker (1977). Breaks are shown on contours. Actual structure would probably be smoothed out between contours except in the Rome Trough area. Note 14,000-foot difference in depth of trough in the northeast corner, when compared with 2,000-foot depth of trough margin.

Figure 91. Cartoon comparison of depositional and present attitudes of Fire Clay coal and black shales. No scale is intended. Upper diagram after McFarlan, 1943.

Figure 92. Pattern of open flow basic fracture band trends from Figure 79. Compare with Figures, 73, 74, 80, 81, and 83.

Figure 93. Three dimensional computer plot of open flow data in center of the field. Z-plane is set at 0.25 MMcf/day open flow.

Figure 94. Three dimensional computer plot of open flow data in center of the field with z-axis rotated 90° counter-clockwise from Figure 91.

Figure 95. Polar plot comparing open flow trends (*italics*) with structural trends.

Figure 96. Position of continental plates in Devonian time (from Heckel and Witze, 1978, with permission). Note position of study area.

(with permission from Heckel and Witze, 1978)

Figure 97. Lower, Middle, and Upper Devonian paleogeography (from Heckel and Witze, 1978, with permission).

Figure 98. Changes in unit isopach thicknesses across the study area (west to east) related to two bentonite occurrences. Rate of basinal subsidence, interpreted from isopach thicknesses, appears to change with units, and is greatest after the pre-Huron and pre-Cleveland bentonite layers.

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and thickness of total shale. Highest fracture frequency
shows greatest correlation with 1) mud-shale, 2) Middle
Huron, 3) -1000 to -1250 feet on Ohio Shale structure, and
4) 500-600-foot thickness of total Ohio Shale sequence.

Figure 100. Using fracture relationships shown in Figure 99 priority areas 1, 2, and 3 are presented as predictive of high gas recovery. For comparison, contours of density of high producing wells from Griffith's (1976) two maps are shown.

Figure 101. Isopach map of brown shale in Prestonsburg quadrangle, with demarcation line of <0.1 MMcf/day open flow and >0.1 MMcf/day open flow (after Thomas, 1951).

Contours of Elemental Data

deWys, 1979

Figure 102. Hand-contoured maps of elemental data representing averages of values for the entire shale sequence. These are some of the maps which showed similarity to the contours of density of high producing wells.

Figure 103. Map showing first stage of geochemical interpretation based on five ratio maps (Figures 66, 67, 68, 69, and 70).

Figure 104. Maps showing second stage of geochemical interpretation based on five ratio maps. See Figure 103.

Figure 105. Comparison of similar cross sections. For details see figures noted.

Figure 106. Comparison of Si/Al oxide ratio map (average for total shale sequence) with density of high producing wells 0.5 MMcf/day/25 square miles (the latter map after Griffith, 1976).

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UNSPONSORED RESEARCH

A STATISTICAL ANALYSIS OF GEOCHEMICAL DATA
FOR THE EASTERN KENTUCKY GAS FIELD *

by

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December 1979

* Written by a graduate student in the Statistics and Computer Science Department of West Virginia University; the report was an outgrowth of the data generated under DOE contract number DE-AC21-76MC05194.

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Summary *

It can be seen from the results of the multiple comparisons that some elements are closely correlated with one another within a single well or among the wells for given stratigraphic unit. Thus, it is natural to inquire if they are really alike or dissimilar, whether the data are univariate or multivariate.

As each single observation consists of numbers specifying percentages of the concentrations of 14 elements, we may be interested in multivariate methods to study interrelationships among these 14 dependent variables. Studies (Koch & Link, 1970) show that some of the measured chemical properties are so closely related to others that they would not have to be determined by actual analysis; they could be predicted instead from those already analyzed.

The reason the data are treated as univariate data here is that until some preliminary understanding has been achieved the problem should not be compounded with multivariate methods, because of uncertainties about the number of variables actually present and the difficulties of specifying an exact objective. However, it is worthwhile doing multivariate examination in the future time.

* Since this paper does not have an abstract, the Summary appears here at the beginning for the reader's convenience as well as at the end.

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1. Introduction

A study of about 3,000 square miles including 4,750 wells in the Eastern Kentucky Gas Field has been undertaken in the Devonian Shales Program under the auspices of the Geology and Geography Department, West Virginia University.

The 'Devonian Shale' or 'Brown Shale' comprise one of the older, but least studied or understood reservoirs in eastern Kentucky and have produced most of the natural gas of that state. The purpose of the above mentioned program is to identify and describe geological parameters of the Devonian Shales and relate these to gas occurrence and potential production. These geological parameters include stratigraphy, structure, and geochemistry and are estimated from the following data:

- 1) approximately 300 formation density logs
- 2) approximately 75 temperature logs
- 3) final open flow data on 4,750 wells
- 4) well cuttings from 14 wells in 10 counties
- 5) core data on three wells
- 6) fracture study data from 3 cores and field surface studies

All data from the stratigraphic, petrologic and geochemical phases of the project will be synthesized and analyzed with the aid of the computer through various statistical and mapping programs. The computer-generated information will then be combined with geological interpretation in order to arrive at the best interpretation of the Devonian Shales prognosis for gas occurrence and production.

Preliminary results on final open flow data which were compared with structure, stratigraphy (including lithology and thicknesses) of producing

units in Devonian Ohio Shales have been reported (Negus-de Wys and Shumaker, 1978; Negus-de Wys, 1979).

This problem report considers the geochemical phase of the study, and it will analyze the geochemical data on 14 elements, related to the five stratigraphic units within the Upper Devonian Ohio 'Brown Shales':

Cleveland Shale, Three-Lick unit of Chagrin, and the Upper, Middle, and Lower Huron Shales units. The primary objective is to determine whether there are differences among the stratigraphic units with respect to the concentrations of the chemical elements. A second objective will be to see if geochemical differences exist among all the wells.

Most previous work on geochemical exploration methods involve the application of geochemical methods to search for valuable metals, petroleum, and other substances based on systematic measurement of one or more chemical properties of a naturally occurring material. However, it is also of importance to relate geochemistry to stratigraphy and this was accomplished with the 'Brown Shales' in the Devonian System to see if their geochemical properties are in any way controlling factors in gas occurrence and production. Such studies are not found in the literature.

2. Description Of The Data

2.1 How Data Were Obtained

The data used in the overall study consist of final open flow data from 4,700 wells scattered over 10 counties of eastern Kentucky. For the geochemical study 14 of these wells were selected with one or two wells being chosen from each county. The fourteen wells are shown on the map of the Eastern Kentucky Gas Field given in Figure 1. Rock samples (chips) from

Figure 1. Location of Sample Wells

each well were collected by drilling down through the strata. Rock samples were continuously flushed out of the hole in the returning drilling mud and samples were collected at random from specified depth intervals. Half of each sample was kept for lithologic examination. The other half was crushed and prepared for analysis by x-ray spectroscopy to determine the concentrations of the 14 elements.

2.2 Detailed Description of the Data Set

Within a well the Devonian Ohio Shale lies directly below the Berea/Bedford formation. The shale consists of the five stratigraphic layers: Cleveland Shale, Three-Lick Shale, Upper Huron, Middle Huron, and Lower Huron. For each well the driller's log, supplemented by a formation density log, the gamma-gamma neutron log, were used to define the top and bottom elevations of Berea/Bedford formation and the five stratigraphic units of Devonian 'Brown Shales'. The resulting data on concentrations of the 14 elements were accordingly classified into six groups corresponding to the stratigraphic units selected for each well.

From the 14 wells a total of 466 rock samples were obtained and analyzed. Table 1 gives the numbers of samples taken from each of the 14 wells. In doing classification, however, it was necessary to delete the results for some samples because the interval sampled overlapped two stratigraphic units. The rule was to classify an observation into the unit in which more than 75% of the interval lies. Otherwise it would be deleted from the data set. There are 397 observations having a distinct classification, and these were kept in the data set. Table 2 gives the number of samples for the stratigraphic units within each well after the classification.

Table 1. Distribution of the Samples Among 14 Wells Showing County, Depth Interval and Sample Size

Well #	County	Depth Interval (ft.)	Thickness (ft.)	Sample Size
1	Magoffin	2010 - 2512	502	35
2	Lawrence	1211 - 1986	775	54
3	Perry	3206 - 3620	414	27
4	Floyd	2240 - 3016	776	65
5	Knott	2300 - 2775	475	10
6	Leslie	2430 - 2770	340	12
7	Johnson	1605 - 2105	500	21
8	Floyd	3305 - 3950	645	35
9	Pike	3257 - 3955	698	57
10	Martin	2350 - 2980	630	58
11	Knott	2812 - 3260	448	27
12	Letcher	3320 - 3945	625	34
13	Perry	3290 - 3710	420	14
14	Letcher	3365 - 3935	570	<u>17</u>
				466

Table 2. Number of Observations Classified by Well and Unit

Well #	Berea/ Bedford	Cleveland Shale	Three Lick Shale	Upper Huron	Middle Huron	Lower Huron	Total
1	1	7	2	4	8	8	30
2	1	10	4	5	11	10	41
3	1	4	2	2	8	6	23
4	5	11	2	5	9	11	43
5	1	1	0	1	2	2	7
6	1	1	1	0	2	2	7
7	0	5	1	1	6	5	18
8	0	2	2	8	7	11	30
9	0	8	3	6	15	21	53
10	0	15	6	7	18	12	58
11	1	2	3	2	6	8	26
12	2	7	4	4	15	9	41
13	2	0	1	1	4	2	10
14	2	1	0	1	4	2	10
Total	17	78	31	47	115	109	397

Examination of Table 2 reveals that for the stratigraphic unit of Berea/Bedford, four wells had no observations while the others had very few compared with the other stratigraphic units. This being so, together with the fact that it was not of primary interest, we decided not to include the Berea/Bedford unit in this study. Also because so few samples were obtained for wells #5, #6, #13, #14 it was decided to omit them to obtain better balance with respect to the numbers of observations.

The data set finally used includes ten wells, five stratigraphic units, and 352 observations. Each observation consists of measurements of concentration for the 14 elements - Al, Ca, Cu, Fe, K, Mg, Na, P, S, Si, Sr, Ti, and Zn. Figure 2 gives a bar-chart representation of the data finally selected for the use in the analysis.

2.3 Conclusions from Preliminary Investigation of the Data

Table 3 gives the overall view of whole data set. Almost all the elements have means closer to the left end (minimum values). To examine the distribution further 140 bar-charts showing the frequency distribution of data point values for each element in each well have been made. These charts reveal the skewedness of the distribution of an element - most of the values are small but a few are very large. Figures 3 and 4 are typical ones.

Tables 4-17 are two-way tables of means and variances by well and units. The tables of means give a preliminary idea of how units within one well, and the wells using one unit are different from each other. From the tables of variances the heterogeneity of cell variances is obvious. Also, for most of the elements the cell variances have a tendency to be positively or negatively related to their means.

Symbol: 2 = Cleveland Shale
 3 = Three Lick Shale
 4 = Upper Huron
 5 = Middle Huron
 6 = Lower Huron

Figure 2. Distribution of The Data Used Among Well & Unit

Table 3. Simple Statistics of 14 Chemical Elements

<u>Element</u>	<u>Mean (%)</u>	<u>Standard Deviation</u>	<u>Coefficient of Variance</u>	<u>Minimum Value (%)</u>	<u>Maximum Value (%)</u>
Al	14.18	1.85	13.03	6.0	17.85
Ca	1.26	3.76	299.13	0.155	32.985
Cu	0.004	0.0002	4.26	0.003	0.004
Fe	8.64	1.63	18.90	3.59	20.15
K	3.35	0.66	19.80	1.23	8.46
Mg	1.42	0.40	28.26	0.73	4.16
Mn	0.05	0.025	49.66	0.016	0.169
Na	0.66	0.066	9.884	0.149	0.730
P	0.135	0.101	74.90	0.102	0.962
S	2.37	0.92	38.95	0.077	8.258
Si	54.93	2.62	4.78	48.00	63.30
Sr	0.004	0.005	117.14	0.00	0.064
Ti	0.929	0.145	15.65	0.23	1.13
Zn	0.012	0.008	65.43	0.001	0.059

Figure 3. Histogram of Manganese in 352 Observations from Ten Wells

Figure 4. Histogram of Magnesium in 352 Observations from Ten Wells

Table 4. Mean and Variance of Element Al by Well & Unit
(concentration measurement: %)

Well		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	13.53	13.09	14.63	14.33	13.27
	Variance	6.05	0.16	0.65	0.07	1.18
#2	Mean	13.10	13.87	14.87	14.32	14.67
	Variance	0.80	0.60	0.06	0.59	0.91
#3	Mean	13.77	14.07	14.56	14.61	14.78
	Variance	1.34	0.00	1.25	1.12	0.49
#4	Mean	15.18	12.26	12.37	16.08	7.67
	Variance	0.89	0.00	0.02	0.06	2.30
#7	Mean	13.43	14.27	12.87	14.61	13.38
	Variance	2.02	-	-	0.71	0.55
#8	Mean	12.56	15.18	14.69	15.00	13.78
	Variance	0.02	0.05	0.56	0.29	0.24
#9	Mean	12.13	13.88	14.44	14.51	16.03
	Variance	0.62	0.88	2.39	1.94	1.30
#10	Mean	13.41	17.13	14.23	14.46	12.95
	Variance	2.58	0.05	0.69	1.77	0.55
#11	Mean	13.59	14.33	14.55	14.26	14.30
	Variance	0.63	0.12	0.01	0.05	1.01
#12	Mean	13.99	15.94	14.62	15.97	15.10
	Variance	2.04	1.30	0.28	1.79	0.45

Table 5. Mean and Variance of Element Ca by Well & Unit
(concentration measurement: 0.1%)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	7.97	5.73	8.20	5.98	5.95
	Variance	30.62	2.14	0.18	0.21	0.26
#2	Mean	6.02	5.29	5.89	5.03	10.53
	Variance	2.75	2.30	3.43	0.93	10.25
#3	Mean	9.84	12.33	6.42	7.21	6.97
	Variance	3.21	0.07	1.34	0.91	4.80
#4	Mean	4.84	6.25	6.01	10.80	208.41
	Variance	2.66	0.05	0.17	7.27	5687.08
#7	Mean	10.68	4.63	4.61	5.18	7.60
	Variance	177.64	-	-	3.15	9.46
#8	Mean	4.17	5.09	4.60	5.29	6.97
	Variance	0.07	1.23	0.72	0.46	1.58
#9	Mean	4.81	6.77	9.79	5.35	5.19
	Variance	0.93	14.23	64.64	7.27	3.35
#10	Mean	5.66	3.81	5.77	4.67	6.38
	Variance	8.88	0.24	2.30	0.88	2.86
#11	Mean	5.92	7.04	6.18	7.04	8.21
	Variance	0.47	0.24	0.47	0.26	7.84
#12	Mean	5.27	6.29	5.65	3.56	6.86
	Variance	3.36	2.94	0.18	1.41	5.69

Table 6. Mean and Variance of Element Cu by Well & Unit
(concentration measurement: 0.001%)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	3.66	3.60	3.80	3.80	3.74
	Variance	0.05	0.08	0.03	0.02	0.02
#2	Mean	3.79	3.65	3.74	3.73	3.65
	Variance	0.03	0.003	0.008	0.002	0.03
#3	Mean	3.70	3.85	3.75	3.80	3.77
	Variance	0.03	0.05	0.005	0.020	0.02
#4	Mean	3.64	3.80	3.72	3.71	3.82
	Variance	0.02	0.02	0.02	0.07	0.03
#7	Mean	3.82	3.60	3.70	3.60	3.70
	Variance	0.007	-	-	0.008	0.015
#8	Mean	4.00	3.70	3.84	3.83	3.75
	Variance	0.02	0.02	0.05	0.009	0.01
#9	Mean	3.69	3.63	3.73	3.67	3.72
	Variance	0.01	0.05	0.04	0.022	0.026
#10	Mean	3.69	3.70	3.79	3.73	3.67
	Variance	0.03	0.044	0.025	0.023	0.012
#11	Mean	3.77	3.77	3.60	3.70	3.70
	Variance	0.003	0.003	0.02	0.02	0.057
#12	Mean	3.64	3.80	3.70	3.75	3.72
	Variance	0.02	0.05	0.007	0.024	0.014

Table 7. Mean and Variance of Element Fe by Well & Unit
(concentration measurement: %)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	9.41	8.02	10.09	8.97	8.67
	Variance	24.33	1.50	10.05	0.53	0.89
#2	Mean	7.18	7.27	7.36	7.93	8.91
	Variance	0.55	0.63	0.34	0.62	0.37
#3	Mean	7.38	6.81	7.88	8.55	8.80
	Variance	0.23	0.01	0.08	2.58	2.02
#4	Mean	8.48	9.28	8.34	8.58	5.25
	Variance	0.13	0.16	0.67	0.21	1.80
#7	Mean	8.23	10.74	8.78	8.91	8.75
	Variance	3.21	-	-	0.12	0.10
#8	Mean	10.58	9.02	9.74	10.22	9.75
	Variance	0.48	0.05	2.85	0.55	1.49
#9	Mean	8.24	9.09	10.53	9.54	10.13
	Variance	2.94	4.92	2.58	1.34	1.27
#10	Mean	9.22	8.95	9.39	9.45	8.93
	Variance	2.35	0.23	0.83	0.87	1.61
#11	Mean	7.53	8.93	8.55	8.70	8.48
	Variance	0.06	0.48	0.03	0.29	0.67
#12	Mean	6.77	7.76	6.88	7.52	7.22
	Variance	1.18	0.26	0.37	0.37	0.11

Table 8. Mean and Variance of Element K by Well & Unit
(concentration measurement: %)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	2.97	2.79	3.51	4.12	3.40
	Variance	0.70	0.01	0.03	3.08	0.12
#2	Mean	2.40	3.14	3.38	3.27	3.69
	Variance	0.24	0.06	0.002	0.07	0.10
#3	Mean	3.30	3.32	3.54	3.74	3.97
	Variance	0.12	0.001	0.15	0.11	0.04
#4	Mean	3.77	2.88	2.94	4.39	2.01
	Variance	0.09	0.002	0.001	0.01	0.30
#7	Mean	2.81	3.13	2.82	3.57	3.41
	Variance	0.14	-	-	0.12	0.08
#8	Mean	2.80	3.68	3.51	3.87	3.50
	Variance	0.003	0.08	0.14	0.01	0.04
#9	Mean	2.21	2.92	3.16	3.18	3.93
	Variance	0.05	0.19	0.25	0.23	0.10
#10	Mean	2.82	3.84	3.15	3.39	3.12
	Variance	0.28	0.003	0.07	0.17	0.08
#11	Mean	2.92	3.27	3.32	3.28	3.48
	Variance	0.11	0.01	0.002	0.002	0.14
#12	Mean	2.82	3.58	3.12	3.92	3.80
	Variance	0.08	0.19	0.03	0.17	0.06

Table 9. Mean and Variance of Element Mg by Well & Unit
(concentration measurement: %)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	1.13	0.92	1.44	1.33	1.25
	Variance	0.029	0.003	0.005	0.003	0.025
#2	Mean	1.03	1.22	1.29	1.26	1.65
	Variance	0.027	0.010	0.010	0.016	0.036
#3	Mean	1.22	1.34	1.23	1.40	1.47
	Variance	0.005	0.005	0.023	0.016	0.009
#4	Mean	1.40	1.17	1.16	1.97	3.02
	Variance	0.010	0.018	0.001	0.009	0.716
#7	Mean	1.37	1.25	1.07	1.48	1.41
	Variance	0.345	-	-	0.009	0.035
#8	Mean	1.07	1.52	1.36	1.46	1.48
	Variance	0.001	0.017	0.023	0.007	0.011
#9	Mean	0.93	1.15	1.47	1.32	1.61
	Variance	0.030	0.003	0.012	0.021	0.007
#10	Mean	1.16	1.26	1.30	1.39	1.31
	Variance	0.020	0.004	0.016	0.017	0.024
#11	Mean	1.15	1.29	1.30	1.34	1.51
	Variance	0.029	0.005	0.006	0.003	0.127
#12	Mean	1.17	1.48	1.31	1.58	1.68
	Variance	0.014	0.029	0.003	0.010	0.047

Table 10. Mean and Variance of Element Mn by Well & Unit
(concentration measurement: 0.01%)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	6.14	3.35	10.90	4.56	4.19
	Variance	25.86	0.85	32.04	0.33	0.19
#2	Mean	6.40	2.80	3.02	3.61	7.06
	Variance	6.94	0.30	1.08	0.46	7.45
#3	Mean	3.56	3.75	4.25	3.96	3.98
	Variance	0.69	0.24	1.13	0.39	1.86
#4	Mean	4.08	3.40	3.44	7.82	2.41
	Variance	0.16	0.18	0.13	1.48	0.43
#7	Mean	5.72	6.30	3.60	4.47	4.06
	Variance	39.10	-	-	0.53	1.09
#8	Mean	4.05	7.35	5.49	4.80	4.94
	Variance	0.41	6.84	4.77	0.27	0.72
#9	Mean	4.64	5.37	11.02	6.17	6.49
	Variance	2.51	12.24	15.04	12.38	5.32
#10	Mean	4.83	7.85	4.17	4.96	4.22
	Variance	1.16	0.26	0.33	2.37	2.59
#11	Mean	3.05	4.43	4.35	4.67	4.51
	Variance	0.22	0.12	0.13	0.29	1.17
#12	Mean	3.67	7.63	4.30	4.31	4.00
	Variance	3.89	10.52	1.65	3.06	1.03

Table 11. Mean and Variance of Element Na by Well & Unit
(concentration measurement: 0.01%)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	69.26	66.25	68.73	67.95	68.85
	Variance	1.79	0.41	0.85	1.03	0.78
#2	Mean	66.39	66.35	66.82	68.04	68.21
	Variance	1.79	0.54	2.40	0.64	0.92
#3	Mean	68.15	66.60	68.60	69.87	68.97
	Variance	2.44	0.72	0.32	2.17	0.67
#4	Mean	68.74	67.45	67.20	70.54	38.66
	Variance	0.93	0.05	0.07	0.88	259.22
#7	Mean	66.98	67.20	70.80	70.17	69.20
	Variance	11.69	-	-	3.47	0.63
#8	Mean	67.60	68.50	69.12	69.33	68.00
	Variance	0.72	0.08	3.33	1.15	0.59
#9	Mean	64.48	65.73	67.05	67.45	69.25
	Variance	2.37	9.85	4.49	2.00	1.36
#10	Mean	67.07	71.88	68.09	69.32	69.58
	Variance	5.13	0.52	0.37	2.10	0.87
#11	Mean	66.22	67.60	67.85	67.82	68.39
	Variance	1.97	0.07	8.41	1.41	2.06
#12	Mean	59.81	56.98	59.43	60.37	59.52
	Variance	1.32	29.00	0.04	0.68	0.07

Table 12. Mean and Variance of Element P by Well & Unit
(concentration measurement: 0.01%)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	12.48	11.50	12.50	11.59	11.69
	Variance	2.50	0.32	0.03	0.08	0.05
#2	Mean	11.76	11.30	11.64	11.25	13.14
	Variance	0.40	0.31	0.52	0.12	1.58
#3	Mean	13.57	13.95	11.75	12.05	12.10
	Variance	1.65	0.01	0.13	0.26	0.36
#4	Mean	11.11	11.75	11.78	13.24	66.91
	Variance	0.38	0.01	0.04	0.69	328.23
#7	Mean	13.24	10.90	11.30	11.28	12.22
	Variance	17.58	-	-	0.35	0.77
#8	Mean	11.60	11.35	11.19	11.77	12.05
	Variance	0.00	0.05	0.15	0.14	0.20
#9	Mean	11.48	12.00	13.07	11.43	11.60
	Variance	0.14	1.29	6.31	0.71	0.47
#10	Mean	11.53	10.97	11.56	11.20	11.88
	Variance	0.93	0.13	0.33	0.07	0.65
#11	Mean	12.08	11.87	11.50	11.92	12.40
	Variance	0.33	0.06	0.02	0.06	0.87
#12	Mean	11.68	11.88	11.55	10.97	12.03
	Variance	0.34	0.36	0.02	0.15	0.59

Table 13. Mean and Variance of Element S by Well & Unit
(concentration measurement: %)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	1.427	2.324	1.845	2.892	3.372
	Variance	0.869	0.000	0.158	0.014	0.218
#2	Mean	0.695	1.936	2.060	2.483	3.111
	Variance	0.748	0.050	0.051	0.007	0.144
#3	Mean	2.355	2.211	2.655	3.012	3.070
	Variance	0.177	0.061	0.026	0.328	0.266
#4	Mean	2.793	4.175	3.616	1.486	2.334
	Variance	0.260	1.012	0.393	0.099	0.771
#7	Mean	1.755	2.285	2.628	2.755	3.241
	Variance	1.141	-	-	0.191	0.158
#8	Mean	2.077	2.263	2.760	3.402	3.739
	Variance	0.013	0.351	0.233	0.135	2.480
#9	Mean	0.888	1.648	0.682	2.018	2.605
	Variance	0.090	0.372	0.272	0.653	0.408
#10	Mean	1.905	0.878	2.535	2.536	2.792
	Variance	0.188	0.006	0.020	0.301	0.087
#11	Mean	1.956	2.414	2.574	2.427	2.875
	Variance	0.069	0.004	0.040	0.009	0.765
#12	Mean	1.457	1.534	2.261	2.376	2.730
	Variance	0.367	0.548	0.039	0.108	0.225

Table 14. Mean and Variance of Element Si by Well & Unit
(concentration measurement: %)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	54.81	55.80	53.32	53.69	55.40
	Variance	4.93	2.00	4.60	0.67	3.10
#2	Mean	59.22	56.27	64.84	55.03	54.44
	Variance	4.48	2.48	2.23	3.47	3.54
#3	Mean	55.92	57.15	54.75	54.99	54.00
	Variance	3.12	0.05	1.13	2.72	0.53
#4	Mean	54.26	56.65	56.96	54.43	54.43
	Variance	1.20	0.85	1.17	0.80	9.57
#7	Mean	56.82	53.10	56.20	54.63	55.54
	Variance	10.47	-	-	1.07	1.10
#8	Mean	53.70	54.45	52.71	51.27	54.39
	Variance	0.32	0.05	2.41	1.12	2.75
#9	Mean	60.07	55.97	54.60	54.19	51.70
	Variance	5.38	23.96	1.63	5.41	6.29
#10	Mean	55.54	50.83	53.89	53.94	55.46
	Variance	7.67	0.15	1.42	4.69	8.77
#11	Mean	57.40	54.33	54.25	55.48	56.45
	Variance	0.36	0.30	1.13	0.96	0.88
#12	Mean	58.46	55.07	56.92	55.33	56.80
	Variance	12.02	2.97	2.25	3.65	1.23

Table 15. Mean and Variance of Element Sr by Well & Unit
(concentration measurement: 0.001%)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	5.14	3.50	5.25	4.00	4.00
	Variance	2.81	24.50	10.92	8.29	5.71
#2	Mean	6.00	4.25	5.60	5.27	5.20
	Variance	4.00	8.25	0.80	3.02	2.18
#3	Mean	1.25	1.50	2.00	5.75	5.33
	Variance	2.25	0.50	8.00	11.93	4.67
#4	Mean	1.91	0.50	1.00	5.22	8.55
	Variance	2.29	0.50	1.00	5.69	348.87
#7	Mean	1.80	2.00	1.00	2.50	4.40
	Variance	4.20	-	-	2.70	8.30
#8	Mean	3.00	5.00	3.38	4.29	2.91
	Variance	18.00	50.00	5.70	2.57	2.49
#9	Mean	3.38	2.00	2.17	3.33	3.14
	Variance	15.98	4.00	2.17	28.81	6.43
#10	Mean	2.47	2.50	0.86	2.50	2.92
	Variance	2.41	0.70	1.14	5.68	4.99
#11	Mean	2.17	1.33	23.00	4.50	5.00
	Variance	2.57	1.33	882.00	4.30	2.86
#12	Mean	4.71	3.25	5.75	7.67	7.22
	Variance	4.24	0.92	1.58	3.24	0.69

Table 16. Mean and Variance of Element Ti by Well & Unit
(concentration measurement: 0.01%)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	95.00	103.50	98.00	94.88	80.25
	Variance	190.67	4.50	2.00	1.27	10.50
#2	Mean	96.50	97.75	101.40	94.09	85.40
	Variance	28.72	6.92	0.80	19.69	19.60
#3	Mean	94.75	100.50	100.50	91.63	91.83
	Variance	61.58	0.50	4.50	54.55	5.77
#4	Mean	93.64	75.00	75.40	99.33	28.09
	Variance	35.45	2.00	2.30	2.50	35.29
#7	Mean	94.00	98.00	96.00	87.67	82.20
	Variance	141.50	-	-	50.27	6.20
#8	Mean	93.50	95.50	98.00	93.86	90.82
	Variance	4.50	60.50	34.00	7.81	4.36
#9	Mean	97.25	102.33	105.00	104.33	97.57
	Variance	11.64	2.33	66.80	5.10	36.36
#10	Mean	97.07	109.67	100.29	91.06	79.33
	Variance	66.35	1.07	1.57	107.35	8.42
#11	Mean	98.17	102.00	101.50	100.83	91.63
	Variance	10.17	0.00	4.50	2.97	44.55
#12	Mean	102.86	105.25	105.75	99.00	92.44
	Variance	20.81	16.92	4.25	24.71	11.53

Table 17. Mean and Variance of Element Zn by Well & Unit
(concentration measurement: 0.01%)

<u>Well</u>		<u>Cleveland</u>	<u>Three L</u>	<u>Upper H</u>	<u>Middle H</u>	<u>Lower H</u>
#1	Mean	2.23	1.36	1.02	0.92	1.44
	Variance	3.41	0.03	0.13	0.46	0.43
#2	Mean	1.12	3.10	1.62	1.15	1.00
	Variance	1.30	4.02	0.12	0.11	0.03
#3	Mean	2.69	2.26	1.00	0.77	1.54
	Variance	3.10	0.08	0.30	0.09	0.62
#4	Mean	1.12	0.62	0.73	1.10	0.88
	Variance	0.29	0.01	0.02	1.47	0.84
#7	Mean	1.39	0.77	1.16	0.90	0.84
	Variance	0.82	-	-	0.27	0.04
#8	Mean	3.19	1.17	1.45	1.28	1.08
	Variance	0.004	0.001	0.54	0.41	0.16
#9	Mean	1.73	1.03	0.96	1.10	0.85
	Variance	2.06	0.06	0.10	0.45	0.14
#10	Mean	1.40	0.49	1.21	0.96	0.91
	Variance	0.38	0.01	0.20	0.30	0.26
#11	Mean	2.02	1.03	1.36	1.10	1.35
	Variance	0.31	0.03	0.04	0.05	0.54
#12	Mean	1.87	1.07	1.68	1.05	1.25
	Variance	0.38	0.14	0.11	0.12	0.18

3. Statistical Analysis

For analyzing the data it was considered appropriate to use the technique of analysis of variance with wells and stratigraphic units as the two variables of classification. The technique of Analysis of Variance has been extensively used in analyzing geological data previously.

J. C. R. Li in his book of Statistical Inference, 1964, discussed the use of a Randomized Complete Block Design to analyze pH readings from the top, middle, and bottom of six core samples of soil. His problem was to determine if the average readings vary with soil depths. Several other examples are also presented in the article 'Design of Experiment for Statistical Analysis of Geological Data,' W. C. Krumbein and Robert I. Miller (1953).

In one of the examples, sand samples were collected from Lake Michigan beach at Wilmette, Illinois, on a grid to investigate the variation of sand moisture content along and across the beach. In another example, students at Northwestern University, under the supervision of W. C. Krumbein and E. C. Dapples, collected samples along and across a beach and determined a number of beach-sand attributes, such as geometric mean diameter (mm.), average roundness, percent heavy minerals, porosity, etc. Also, A. L. Howland, Northwestern University used data on quadruplicate analysis of magnetite in two samples by three operators to see whether there was laboratory error, i.e., interaction of operator and sample.

As we have two factors with arbitrarily selected levels we decided to use the two-way analysis of variance model with fixed effects:

$$X_{ijk} = u + A_i + B_j + (AB)_{ij} + (e)_{ijk}$$

where X_{ijk} is the measurement of the concentration of a particular chemical element in one observation.

A_i is the main effect from i th stratigraphic unit

B_j is the main effect from j th well.

$(AB)_{ij}$ is the effect of interaction between i th unit and j th well.

$(e)_{ijk}$ is the error term corresponding to X_{ijk} .

Several remarks concerning the selection of this model are perhaps in order. Although it might be preferable to have a random component in the model to represent the well effect, the validity of doing so would be questionable due to the manner in which the wells were selected. Rather than being obtained randomly the wells apparently were chosen for convenience in obtaining the necessary data, and thus they do not represent a sample from a population of wells. It is also felt appropriate to include an interaction term in the model because geological theory (such as facies changes horizontally because of the changes of basin configuration, land elevation, temperature . . . , etc.) suggests that the stratigraphic unit effects might be different from location to location.

3.1 How Do The Data Meet The Assumptions Underlying The Analysis of Variance

As the initial step in the analysis an investigation was made of the assumptions underlying the use of analysis of variance with particular attention to normality and homogeneity of variance.

Those underlying assumptions, made in deriving statistical methods, are sometimes apt to be violated in applications. In particular, many

distributions of geological observations are non-normal. In fact, one of the more common distributions in geological problems is the log-normal distribution. This distribution is followed more or less closely by trace elements and is characterized by the fact that compared with the mean value, most of the observations are small while a few are very large. In geochemistry, the large values represent the geochemical anomalies. Thus, it is more likely that our data will come closer to having a log-normal distribution than being normally distributed (see Figures 2 and 3).

The standard test - Bartlett's test for homogeneity of variance was used to test whether all cell variances are equal. The test statistic for this test is:

$$S = \frac{(N_g \times \log S_g) - N \times \log((N_g/N) \times S_g)}{1 + (1/3 \times (G-1)) \left((1/N_g) - (1/N) \right)}$$

and its distribution is approximately a Chi-Square distribution with $G-1$ degree of freedom. Where N_g and S_g are the number of observations and the sample variance in the g th group respectively; N is the total number of observations and G is the number of groups.

The result found in application of the test was that there exists heteroscedasticity. Bartlett, in his 'The Use of Transformations', 1947, summarized all types of heterogeneity of variances and the corresponding proper methods of transformation. Most of those methods were considered here to try to stabilize the variance, but none were completely successful. Finally, we decided to use a log-transformation on the data because not only does it improve on the heteroscedasticity, but it also tends to normalize the distribution. Presumably this will increase the power of detecting true differences between population means.

3.2 Other Alternative Methods of Statistical Analysis

Since, as stated above, we have reason to doubt that our data would meet the assumptions underlying the basic parametric statistical method, we considered the alternative of nonparametric methods in which the type of distribution of the population need not be specified. However, no appropriate nonparametric method has been developed for data arranged in a two-way classification with unequal numbers of observations per cell. The Friedman test gives a two-way analysis of variance by ranks when there is a single entry per cell. An extension of the Friedman test for an equal number of replicates per cell is given by Wilcoxon.

As another alternative one might consider a nonparametric one-way analysis of variance and treat each well individually because the likelihood of interaction between the wells and stratigraphic units will prevent the making of conclusions that hold across the ten wells in any event. The Kruskal-Wallis test is available for a one-way classification of data no matter whether the group sizes are equal or not. Because of inadequacies of follow-up multiple comparison procedures, however, it was considered better to use the parametric method of analysis after transforming the data. In order to see how different the parametric and nonparametric procedures would be, however, the Kruskal-Wallis test was run in addition to the parametric analysis of variance. The results were strikingly conformable with each other. This again gives us more confidence in the validity of using the parametric statistical method.

3.3 Consequence of Violation of Assumptions Underlying the Parametric Analysis of Variance

Statistical methods have been called robust if the inferences are not seriously invalidated by the violation of the assumptions underlying the

parametric methods. Many empirical results, simulations and mathematical proofs (Bartlett, Pearson, Donaldson, Box, Bradley, Stalof, etc.) conclude that the F-test is quite insensitive to the assumption of normality unless the underlying distribution is extremely skewed.

Those studies cited above also obtained the conclusion that the validity of the F-test for all treatments (the overall F-test) is the least affected by heterogeneity of variance, although there will be a loss of efficiency in the estimate of treatment effects. Scheffe in his 'Analysis of Variance' has done some empirical experiments and mathematic models to show the effect of heterogeneity of variance on Type-I error (α - level) was slight if the population distribution was normal. In addition, if the population was not normally distributed but sample sizes are equal, a quite reliable F-test still could be obtained.

Unfortunately, because of the method of sample collection and the heterogeneous nature of the thickness of the stratigraphic units within a well it is not convenient for us to have an equal number of entries per cell. That is, besides a non-normally distributed population we also have a variable number of observations per cell ranging from 1 to 21. One might alternatively analyze the data by averaging the observations in each cell and using the average as a single-cell entry so as to solve the problem of unequal sample sizes. We prefer not to do so because this raises the question of efficiency since the means have different variances. Besides, the two-way classification form with replication not only provides more power in detecting the true difference between the means by increasing the error degree of freedom but also automatically provides a technique for evaluating interaction which obviously exists in our data set as mentioned previously.

3.4 Details of the Analysis of Variance Procedure

For data classified in two ways, application of the analysis of variance procedure leads to a table of the following form:

<u>Source</u>	<u>Degree of Freedom</u>	<u>Sum of Square</u>	<u>Mean of Square</u>	<u>F-Value</u>
Wells	9	SSw	MSw	MSw/MSe
Units	4	SSu	MSu	MSu/MSe
Interaction	36	SSi	MSi	MSi/MSe
Error	302	SSe	MSe	
Corrected total	351			

The ANOVA table gives four meaningful partitions of the total variation. One for the variation among sample means of stratigraphic units; the second for the variation among the sample means of wells; the third for the variation among the combinations of units and wells; the last, the residual variance, is the random, uncontrolled variation within the population.

The degrees of freedom are found by taking one less than the number of units, one less than the number of wells for unit and well effects respectively, and multiplying these two to get the d.f. for the interaction effect.

Because of the unequal number of entries per cell, the main effect and the interaction effect are not orthogonal. In order to obtain a meaningful test, the unit sum of squares adjusted for well effects, the well sum of squares adjusted for unit effects, and the interaction sum of squares adjusted for the main effects will be used. Thus the four sums of squares will not add to the total corrected sum of squares.

The mean squares are the sum of squares divided by the corresponding degrees of freedom. The F-value is the ratio of the mean square for the effect to be tested and the mean square for the error. If a significance level of 5% is set, we will conclude an effect is significant if its computed F-value exceeds the tabulated F-value, i.e., $F_{0.05}(9,302) = 1.88$ for testing well effects, and $F_{0.05}(36,302) = 1.43$ for testing interaction effects.

3.5 Further Analysis

If the overall F-test is significant in the two-way ANOVA, it is of interest to inspect the individual sample means more closely. We are particularly interested in knowing which stratigraphic units are significantly different from the others within a particular well (i.e., vertical comparison). Of interest also would be comparisons among the wells for a given stratigraphic unit (i.e., horizontal comparison). The method of multiple comparisons is appropriate. The outstanding attribute of this method is that the Type-I error is set at a constant level regardless of the number of paired comparisons to be made. With multiple comparison method, we can simultaneously compare all possible pairs of means with the error rate controlled for the experiment as a whole. The primary interest is in simple differences.

Although Tukey's multiple comparison (T-method) is more powerful in testing simple differences and extremely easy to apply, its validity for unequal sample sizes has not been verified. Consequently we choose to use the more general method, which is appropriate for either equal or unequal sample sizes, i.e., Scheffe's multiple comparison method (S-method). The S-method corresponds to the F-test while the T-method is based on the Studentized range of the test statistic.

The most important advantage of the S-method is the robustness against non-normality and inequality of variance, concerning Type-I errors of F-tests about means extending to the corresponding S-method of multiple comparison. This is not evident for the T-method. We may imagine that the S-method, in offering statements about all the contrasts, somehow averages out the variation in probability encountered with individual contrasts.

3.6 The S-method, Mathematical Formula

To test $H_0: C = 0$ vs $H_a: C \neq 0$, a confidence interval for the $\hat{C}$ with the probability $1 - \alpha$ that simultaneously for all $C \in L$ is,

$$\hat{C} - s\hat{\sigma}_C^2 = \hat{C} = C + s\hat{\sigma}_C^2$$

Where the constant s is $s = (qF_{0.05}^{1:q,n-r})$

L is the set of all estimable functions.

C is the contrast in which we are interested.

$\hat{C}$ is the estimate of C .

$\hat{\sigma}_C^2$ is the estimate of variance of $\hat{C}$.

q is the number of linearly independent estimable functions.

$n-r$ is the degrees of freedom for error mean square.

In this study we are only interested in the simple contrast

$C = U_{ij} - U_{ij'}$ or $C = U_{ij} - U_{i'j}$. U_{ij} represents the mean in the i th well, j th stratigraphic unit. The best unbiased estimator for U_{ij} is $\hat{U}_{ij} = \bar{X}_{ij}$. Thus, $\hat{C} = \bar{X}_{ij} - \bar{X}_{ij'}$ for vertical comparison, or $\hat{C} = \bar{X}_{ij} - \bar{X}_{i'j}$ for horizontal comparison.

$$\hat{\sigma}_C^2 = \text{Var}(\bar{X}_{ij} - \bar{X}_{ij'}) = S/N_{ij} + S/N_{ij'} = \text{MSe}(1/N_{ij} + 1/N_{ij'}).$$

For vertical comparison we have 4 linearly independent estimable functions in each well. There are ten wells, so $q = 4 \times 10 = 40$. Likewise, for horizontal comparison, $q = 9 \times 5 = 45$.

$n - r$, the degrees of freedom within well and unit, is $352 - 50 = 302$.

If the above confidence interval does not cover $\hat{C} = 0$, i.e., if $|\hat{C}| > s_{\hat{C}}$, we will say the contrast C is significantly different from zero. This is equivalent to saying U_{ij} and $U_{ij'}$ are significantly different from each other.

4. Results

In this section the results of statistical analysis are presented and discussed for each of the 14 chemical elements. First, an ANOVA table is given to show the overall tests. Then follows the findings of multiple comparisons provided that the overall tests in the ANOVA table are significant.

4.1 ANOVA Tables

1) Aluminum

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	0.66	11.03**
Unit	4	0.596	22.39**
Interaction	36	4.388	18.33**
Error	302	2.009	
Corrected Total	351	8.2011	

2) Calcium

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	19.696	17.83**
Unit	4	16.227	33.06**
Interaction	36	82.654	18.71**
Error	302	37.058	
Corrected Total	351	191.920	

3) Copper

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	0.022	1.36 (ns)
Unit	4	0.001	0.20 (ns)
Interaction	36	0.070	1.09 (ns)
Error	302	0.534	
Corrected			
Total	351	0.630	

4) Iron

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	2.483	14.88**
Unit	4	0.258	3.48**
Interaction	36	2.967	4.45**
Error	302	5.598	
Corrected			
Total	351	12.683	

5) Potassium

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	0.599	3.75**
Unit	4	2.195	30.89**
Interaction	36	6.899	10.78**
Error	302	5.366	
Corrected			
Total	351	15.622	

6) Magnesium

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	1.566	11.74**
Unit	4	4.039	68.12**
Interaction	36	4.279	8.02**
Error	302	4.477	
Corrected Total	351	18.123	

7) Manganese

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	4.798	4.91**
Unit	4	0.976	2.25 (ns)
Interaction	36	20.861	5.34**
Error	302	32.781	
Corrected Total	351	60.799	

8) Sodium

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	0.812	11.69**
Unit	4	0.233	7.54**
Interaction	36	3.319	11.95**
Error	302	2.331	
Corrected Total	351	7.519	

9) Phosphorus

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	2.982	45.99**
Unit	4	2.356	81.76**
Interaction	36	19.623	75.65**
Error	302	2.176	
Corrected Total	351	33.917	

10) Sulphur

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	15.781	9.83**
Unit	4	20.535	28.79**
Interaction	36	43.814	6.83**
Error	302	53.846	
Corrected Total	351	142.727	

11) Silicon

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	0.075	6.31**
Unit	4	0.061	11.48**
Interaction	36	0.204	4.30**
Error	302	0.399	
Corrected Total	351	0.797	

12) Strontium

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	0.0006	3.35**
Unit	4	0.0002	2.34*
Interaction	36	0.0011	1.64**
Error	302	0.0058	
Corrected Total	351	0.0077	

13) Titanium

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	3.035	70.13**
Unit	4	2.690	139.85**
Interaction	36	8.898	51.40**
Error	302	1.452	
Corrected Total	351	19.649	

14) Zinc

<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>F-value</u>
Well	9	13.600	5.02**
Unit	4	9.287	7.71**
Interaction	36	19.866	1.83**
Error	302	90.994	
Corrected Total	351	132.746	

Thirteen out of the fourteen elements have highly significant effects of interaction. The only element with non-significant effects of interaction effects is copper, for which both the well and the unit effects are not significant either. This confirms the assumption we made before that the main effects are non-additive. Therefore, instead of making conclusions holding across the ten wells or across the five stratigraphic units we will investigate well by well the nature of unit means and unit by unit the nature of well means.

For the element copper none of the three types of effects is significant. We fail to reject the null hypothesis that there are no differences among the units or among the wells in terms of the concentration of Cu. Thus, the follow-up step, the multiple comparison, is not necessary for this element. For the element of manganese the well effect is highly significant while the unit effect is not significant. The multiple comparison techniques are used to find the horizontal differences only, i.e., the differences among wells for a given stratigraphic unit. For the other elements the effects of well and unit are highly significant. Thus, the hypothesis of no differences among units, among wells are rejected. To explore the nature of these effects requires the vertical and horizontal multiple comparisons. Likewise, these multiple comparisons would be based on the means computed from the log-transformed data.

4.2 Vertical Comparison

S-method was used to make vertical comparison within each well for the elements having significant unit effect in the overall F-test. The results are summarized in the following figure. Any two means not underscored by the same line are significantly different from each other. Otherwise, they are not significantly different.

Figure 11. Results of Vertical Comparison

Figure 11. Results of Vertical Comparison (con't)

Well #2, Well #4, Well #9, and Well #10 are the only wells within which significant differences are found among the stratigraphic units. It is interesting that except well #4 all the other three wells are located in the northeastern section of the Kentucky Gas Field (see Figure 1), where occur the higher percent silt and sand (Figure 5), the high sand to silt ratio (Figure 6), and the highest value of occurrence of redbeds (Figure 7).

Figure 5. Iso-Value Lines of Percentage of Silt Plus Sand in Total Shale Sequence

Figure 6

MAP SHOWING OCCURENCE OF
REDBEDS AND BENTONITE

Figure 7

As one can see from the above charts, the Lower Huron is always involved when significant differences among the stratigraphic units within one well exist for an element. Cleveland Shale unit is also involved in quite a few significant comparisons. Obviously, significant differences between the Cleveland Shale and Lower Huron are the most common. However, the other three stratigraphic units - Three Lick Shale, Upper Huron, and Middle Huron are not significantly different from one another in any case.

Also, when arranging the means of the five stratigraphic units within a single well in ascending or descending order, all significant elements in that well have the same pattern, though some might be in reverse direction. This type of pattern may be in accordance to the natural sequence of the stratigraphic units, say in the order of Cleveland Shale, Three Lick Shale, Upper Huron, Middle Huron, and Lower Huron, like the pattern in wells #2, #4, #9, and #10. Or, it may mix up, like the pattern in well #4. Figure 8 is an illustration of this pattern, showing cyclic concentration of elements and may be reflecting depositional cycles or changes.

Figure 8. Plot of the Mean Value vs. the Stratigraphic Units in Well #4

4.3 Horizontal Comparison

The following lists the pairs of wells and the elements which are significantly different between the two wells. The symbol within the bracket indicates how the first well is different from the second well.

Cleveland Shale

<u>Wells</u>	<u>Elements</u>
#4 & #9	K (>), Mg (>), Si (<)
#4 & #2	K (>), S (>)
#2 & #3	S (<)
#2 & #10	S (<)
#2 & #11	S (<)

Three Lick Shale

<u>Wells</u>	<u>Elements</u>
#4 & #10	S (>), Ti (<)

Upper Huron

<u>Wells</u>	<u>Elements</u>
#4 & #2	Ti (<)
#4 & #9	S (>), Ti (<)
#4 & #10	Ti (<)
#4 & #12	Ti (<)
#8 & #9	S (>)

Figure 12. Results of Horizontal Comparison

Middle Huron

<u>Wells</u>	<u>Elements</u>
#4 & #12	Ca (>), P (>)
#4 & #2	Mg (>)
#4 & #9	Mg (>)
#4 & #10	Mg (>)

Lower Huron

<u>Wells</u>	<u>Elements</u>
#4 & any of the others	Al (<), Ca (>), Fe (<) K (<), Mg (>), Na (<), P (>), Ti (<)
#4 & #2	Mn (<)
#4 & #9	Mn (<)
#4 & #1	Zn (<)
#4 & #3	Zn (<)
#4 & #11	Zn (<)
#4 & #12	Zn (<)
#9 & #10	Al (>), Ti (>)
#9 & #11	Si (<)
#9 & #12	Si (<)

Figure 12. Results of Horizontal Comparison (continued)

It is noticed that given any stratigraphic unit well #4, which is located in the central area of Kentucky Gas Field which happens to be the area of high density of high producing wells (Figure 9) and high fracture frequency (Figure 10), is found significantly different from

Contours of High Volume Wells
Based on ~5000 Wells
(after Griffith, 1976)

J. Negus deWys
March, 1979

Figure 9

some or all other outlying wells for each element with significant results. Well #2 and well #9 are also involved in a few significant results with the direction (> or <) opposite that of well #4. No significant differences are found involving the rest of the wells.

5. Summary

It can be seen from the results of the multiple comparisons that some elements are closely correlated with one another within a single well or among the wells for given stratigraphic unit. Thus, it is natural to inquire if they are really alike or dissimilar, whether the data are univariate or multivariate.

As each single observation consists of numbers specifying percentages of the concentrations of 14 elements, we may be interested in multivariate methods to study interrelationships among these 14 dependent variables. Studies (Koch & Link, 1970) show that some of the measured chemical properties are so closely related to others that they would not have to be determined by actual analysis; they could be predicted instead from those already analyzed.

The reason the data are treated as univariate data here is that until some preliminary understanding has been achieved the problem should not be compounded with multivariate methods, because of uncertainties about the number of variables actually present and the difficulties of specifying an exact objective. However, it is worthwhile doing multivariate examination in the future time.

Figure 10

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