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A BOREHOLE GRAVITY SURVEY TO DETERMINE DENSITY VARIATIONS IN THE DEVONIAN SHALE SEQUENCE OF LINCOLN COUNTY, WEST VIRGINIA

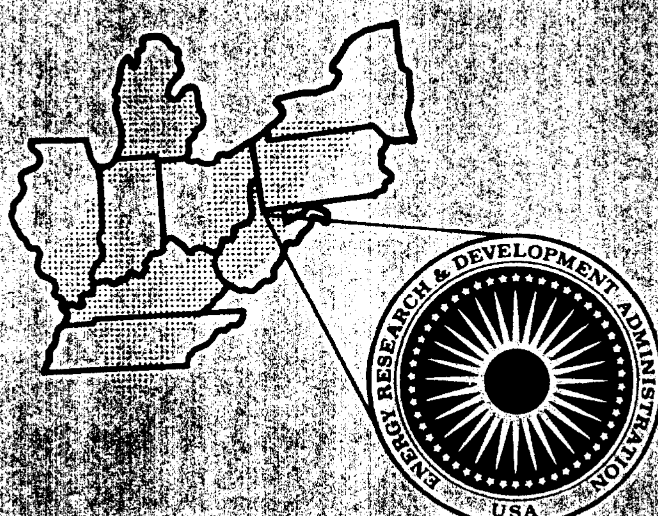
FOSSIL ENERGY

By

JAMES W. SCHMOKER

May 1977

EASTERN GAS SHALES PROJECT



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May 1977

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Prepared For
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Morgantown Energy Research Center
Morgantown, West Virginia

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A BOREHOLE GRAVITY SURVEY TO DETERMINE DENSITY VARIATIONS IN THE DEVONIAN SHALE SEQUENCE OF LINCOLN COUNTY, WEST VIRGINIA

by

James W. Schmoker[1/]

ABSTRACT

In situ bulk densities of the Devonian shale section penetrated by the Columbia Gas Transmission Corp. 20402 well, Lincoln County, West Virginia, were determined using the U.S. Geological Survey-LaCoste and Romberg[2/] borehole gravity meter. Densities from two gamma-gamma logs, run by different companies, were also available. A cumulative difference of .034 $g/cm^3/1000$ ft ($.112 g/cm^3/km$) exists between the two gamma-gamma logs. The two intervals of lowest density derived from the borehole gravity data show higher densities on both gamma-gamma logs, possibly indicative of the deeper investigation radius of the borehole gravity meter. In most intervals, higher gamma-ray intensity correlates with lower density, indicating that organic content is the primary variable affecting both bulk density and uranium concentration.

INTRODUCTION

The U.S. Geological Survey-LaCoste and Romberg borehole gravity meter (McCulloh and others, 1967a; McCulloh and others, 1967b) was used to determine the in situ bulk density of Devonian shale units penetrated by the Columbia Gas Transmission Corp. 20402 well, Lincoln County, West Virginia. The work was part of the Eastern Gas Shales Project sponsored by the U.S. Energy Research and Development Administration (ERDA) to evaluate the natural gas potential of the Devonian shales in the Appalachian Basin.

The borehole gravity meter can be regarded as a density logging device having a large radius of investigation compared to conventional density or porosity logging tools. Measurements are not significantly influenced by casing, borehole rugosity, or formation damage caused by drilling. For these reasons, the borehole gravity meter provides a unique and independent measurement of in situ bulk density which, integrated with data from conventional density logs, can provide a better understanding of formation properties.

Fundamentals of borehole gravity logging and data interpretation, considerations of the effective radius of investigation, and applications to geologic problems have been treated in the literature by Smith (1950), Goodell and Fay (1964), Howell, Heintz, and Barry (1966), McCulloh (1966), Healey (1970), Beyer (1971), Jageler (1976), and Hearst and McKague (1976).

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2/ Use of brand names in this report is for descriptive purposes only and in no way constitutes endorsement by the U.S. Geological Survey

In the absence of complicating factors, the relationship between in situ bulk density and measurements of gravity in a borehole is given by

$$\rho = (F - \Delta g/\Delta z)39.185, \qquad (1)$$

where ρ = the average formation density between two vertically separated points in the borehole (g/cm^3),

F = the free-air vertical gradient of gravity (mgal/ft),

Δg = the difference in gravity between the vertically separated points (mgal),

Δz = the vertical separation (ft).

ACKNOWLEDGMENTS

The cooperation of the Columbia Gas Transmission Corp. is gratefully acknowledged. This work was performed under the auspices of the U.S. Energy Research and Development Administration under Contract Number EX-76-C-01-2287. G. E. Claypool of the U.S. Geological Survey made available unpublished core data.

GEOLOGIC SETTING

The borehole gravity survey was conducted in the Columbia Gas Transmission Corp. 20402 well (State Permit No. Lin. - 1636-47-043), located at latitude 38°05°49" N. and longitude 82°14°25" W. in Lincoln County, West Virginia, about 25 air miles (40 km) southeast of Huntington, West Virginia. The site is in the Appalachian Plateaus physiographic province. Permian sandstones of the Dunkard Group are exposed at the surface. Wellhead elevation is 1,153 ft (351 m). Topography near the well is rugged, ranging in elevation from about 700 ft (213 m) to more than 1,300 ft (396 m). Landsat imagery indicates numerous linear features in the area which may reflect fracture and fault traces (W. M. Ryan, oral communication). The well is located close to, but not on, several major linears.

Gas Production

Natural gas is found locally throughout the Devonian shales in the Appalachians, but the principal areas of commercial production are southern Ohio, eastern Kentucky, and western West Virginia. Many wells are nonproductive prior to stimulation (Hunter and Young, 1953). Commercial production is from secondary reservoirs in joint and fracture systems, and bears no direct relation to the present structure (Thomas, 1951; Hunter and Young, 1953). Temperature and sibilation logs in the 20402 well indicated a number of gas shows in the Devonian shales, but prior to stimulation the well did not produce enough gas to gauge through a 1 in. (2.54 cm) choke.

Stratigraphic Relationships

The Devonian shale sequence in the 20402 well is 1,365 ft (416 m) thick. It is bounded on top by the Berea Sandstone of Mississippian age and at the base by the Onondaga Limestone (the "Corniferous" of the driller) of Middle Devonian age. The strata are nearly flat-lying. Identification and correlation of Devonian rock units in the Appalachian Basin is difficult as evidenced by the complexity of the correlation chart of Oliver and others (1969). The Devonian shale sequence in the study area can be subdivided into a dark, basal unit, the Marcellus shale of Middle Devonian age, overlain by gray shale and siltstone for which no surface name is completely appropriate. The black Ohio shale interfingers with this gray shale and siltstone. Locally, drillers have divided the Devonian shales into geologic units based on physical characteristics. Drillers call the interfingering tongues of Ohio shale, the upper and middle brown shales and the underlying Marcellus shale, the lower brown shale.

Figure 1 shows these formal and informal stratigraphic units for the shale sequence penetrated by the 20402 well and the corresponding gamma-ray and gamma-gamma density logs. The locations of borehole gravity stations are also shown with the intervals numbered to facilitate discussion.

Density Characteristics

The principal constituents of the Devonian shales are quartz, feldspar, clay, mica, pyrite, and organic matter (Conant and Swanson, 1961). The average grain density of the minerals is 2.7 g/cm^3; the density of the organic matter is near 1.0 g/cm^3 (Smith and Young, 1964). Because of this marked density

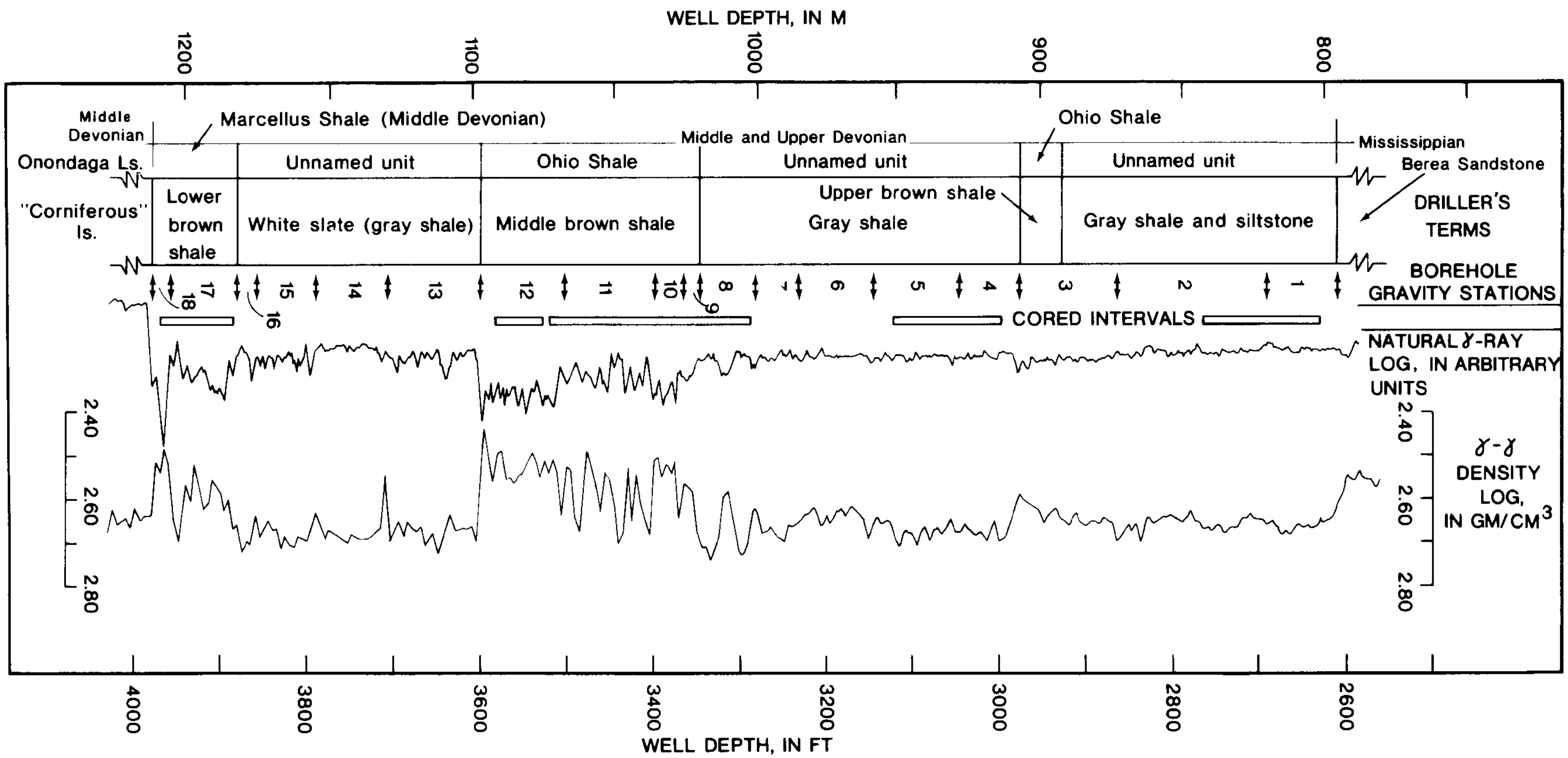

Figure 1. Stratigraphic section, gamma-ray log, and gamma-gamma density log for the Middle and Upper Devonian shale section penetrated by the Columbia Gas 20402 well, Lincoln County, West Virginia. Borehole gravity stations (with intervals numbered) and cored intervals are also shown.

difference, the overall specific gravity is strongly affected by the organic content of the shales.

High gamma-ray intensities tend to correlate with low densities, as shown in Figure 1. Schwietering (1970) reports that uranium is the primary source of gamma rays in the Devonian shales, and a synthesis of analytical data shows that the shales richest in organic matter have the most uranium (Conant and Swanson, 1961). Lower densities caused by increased organic content should, therefore, be associated with higher gamma-ray values, whereas density changes due to pore-fluid composition, pyrite content, porosity variation, drilling damage, etc., should not be reflected in the gamma-ray log.

DENSITY DATA

On March 25, 1976, nineteen borehole gravity stations (Figure 1) were obtained in the Devonian shale section at points where conventional logs indicated variations in formation properties. Depths were referenced to other wireline data by correlating gamma-ray logs. The borehole gravity values have been previously released without interpretation or comment (Schmoker, 1976).

Tide and terrain corrections were applied to the subsurface gravity data. The density corrections for terrain were less than .01 g/cm^3 for all intervals. In situ bulk densities were computed using equation 1, assuming the free-air gradient of gravity was 1.9% less than the so-called normal value of .09406 mgal/ft (.3086 mgal/m). This assumption is not unreasonable (McCulloh, 1966) and lowers all borehole gravity densities by .07 g/cm^3, bringing them into general agreement with gamma-gamma densities and core measurements from the 20402 well and adjacent wells. Density changes from interval to interval are not affected by the value of the free-air gradient.

Experimental Errors

To assess the experimental significance of apparent density changes, an estimate of the indeterminate measurement error was made. From previous experience with this borehole gravity meter, the error associated with a single interval gravity measurement was assumed to be ± .011 mgal. The error in measuring the vertical separation was about ± .35 ft (.11 m). Using these values and an error expression derived from equation 1, the experimental uncertainty in the borehole gravity density determinations is given by:

$$\delta(\rho) = \pm\ .5726/\Delta z, \qquad (2)$$

where $\delta(\rho)$ = the indeterminate error in bulk density (g/cm^3) and
Δz = the vertical separation (ft).

As vertical separation increases, interval density determinations become more accurate. For intervals greater than 20 ft (6 m) or so in the 20402 well, density differences are measured with an accuracy equal to or better than that of conventional density logs. In addition, the radius of investigation is large enough to insure a representative sampling of the formations penetrated by the well.

Data Tabulation

Table 1 lists borehole gravity intervals in the 20402 well, and densities computed from equation 1 with errors estimated from equation 2. Densities from two gamma-gamma logs (run by different companies) are also shown. The gamma-gamma logs were digitized using a 2 ft (.61 m) sample spacing, and an average density was determined for each of the eighteen intervals.

Table 1. -- Columbia Gas 20402

Interval No.	Interval Depths		Interval Density (g/cm^3)		
	ft	m	Borehole Gravity Meter	γ-γ Log	
				Company A	Company B
1	2616-2696	797.4-821.7	2.660 ± .007	2.673	2.659
2	2696-2868	821.7-874.2	2.661 ± .003	2.682	2.659
3	2868-2982	847.2-908.9	2.631 ± .005	2.646	2.641
4	2982-3052	908.9-930.2	2.636 ± .008	2.659	2.676
5	3052-3150	930.2-960.1	2.642 ± .006	2.654	2.674
6	3150-3236	960.1-986.3	2.700 ± .007	2.689	2.635
7	3236-3286	986.3-1001.6	2.635 ± .011	2.672	2,668
8	3286-3350	1001.6-1021.1	2.668 ± .009	2.672	2.686
9	3350-3370	1021.1-1027.2	2.594 ± .029	2.573	2.593
10	3370-3402	1027.2-1036.9	2.451 ± .018	2.525	2.533
11	3402-3506	1036.9-1068.6	2.554 ± .006	2.588	2.594
12	3506-3603	1068.6-1098.2	2.509 ± .006	2.526	2.525
13	3603-3710	1098.2-1130.8	2.653 ± .005	2.652	2.660
14	3710-3792	1130.8-1155.8	2.642 ± .007	2.662	2.671
15	3792-3860	1155.8-1176.5	2.620 ± .008	2.643	2.682
16	3860-3882	1176.5-1183.2	2.655 ± .026	2.661	2.692
17	3882-3960	1183.2-1207.0	2.578 ± .007	2.582	2.607
18	3960-3981	1207.0-1213.4	2.445 ± .027	2.493	2.523

Table 1. -- In situ density data from the Devonian shale section penetrated by the Columbia Gas 20402 well, Lincoln County, West Virginia.

Comparison of In Situ Density Data

The investigation depth of the gamma-gamma density log is less than 1 ft (.30 m), whereas that of the borehole gravity meter is tens of feet. Because the densities of different volumes of rock are measured, a difference in results does not necessarily mean that one log or the other is faulty. The densities obtained in the 20402 well by each method are compared graphically in Figure 2. In Panel A (Figure 2), the stratigraphic section and gamma-ray intensity averaged over the borehole gravity intervals are shown. Panels B, C, and D show the difference between density obtained from the borehole gravity log and that given by the gamma-gamma log from Company B, the borehole gravity log and that given by the gamma-gamma log run by Company A, and the two gamma-gamma logs.

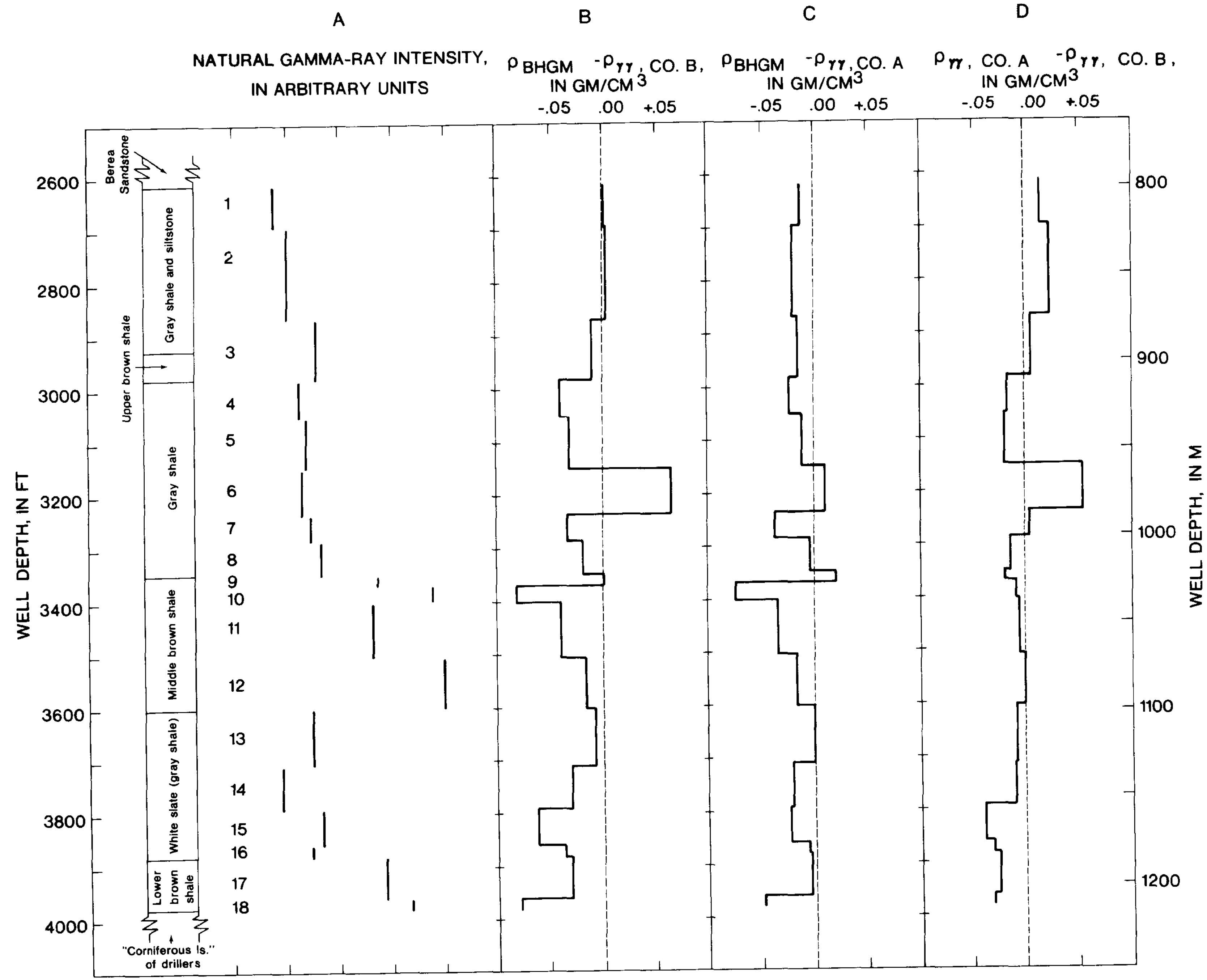

Figure 2. Stratigraphic section and gamma-ray intensity in the Columbia Gas 20402 well and comparisons of the three sets of in situ density data. Panel B shows the difference between the density from the borehole gravity log and that from the gamma-gamma log of Company B; Panel C, the difference between the borehole gravity density and that of Company A; and Panel D, the difference between the gamma-gamma logs of the two companies.

In Panel B (Figure 2) a trend is apparent, with gamma-gamma density obtained by Company B increasing with depth relative to the borehole gravity density. A similar trend is not present in Panel C, indicating that the two gamma-gamma logs differ, and Panel D displays this difference. The discrepancy between the gamma-gamma logs is cumulative with depth, and amounts to .034 $g/cm^3/1000$ ft (.112 $g/cm^3/km$), as determined by a least-squares fit. A t-test (Till, 1974) indicates a better than 99% probability that the apparent density divergence with depth is actually present in the data. Through the entire Devonian shale section, the total density discrepancy amounts to .046 g/cm^3, an effect which would be significant if it had a geologic cause, but which is attributable to deficiencies in one or both gamma-gamma logs.

The borehole gravity densities of a few intervals differ significantly from the corresponding gamma-gamma densities. Interval 6 is the highest density interval in both the borehole gravity and gamma-gamma (Company A) data sets, but has a lower density than adjacent intervals in the gamma-gamma (Company B) data (Table 1). The agreement between the former measurements tends to discredit the latter. The densities of intervals 10 and 18 are the lowest in the borehole gravity data and deviate conspicuously from the higher densities of both gamma-gamma logs. Based on these two examples, zones in the Devonian shale of lowest density (and presumably highest organic content) may not be properly measured by the gamma-gamma tool.

INTERPRETATION OF BOREHOLE GRAVITY DENSITIES

Panels A and B of Figure 3 show the informal stratigraphic designations of the shale sequence penetrated by the 20402 well, gamma-ray intensity averaged over the borehole gravity intervals, and the borehole gravity densities (Table 1).

Range of Densities

Densities calculated from borehole gravity measurements range from 2.70 g/cm^3 to about 2.45 g/cm^3. Lower density corresponds to higher gamma-ray intensity for most intervals, as would be expected if organic content is the primary factor affecting both bulk density and uranium concentration. Density variations due to changes in porosity or in the mineral matrix would not be indicated by the gamma-ray data. Intervals 6 and 8, where higher bulk densities do not correspond to lower gamma-ray intensities, may be examples of this effect.

The middle brown shale and lower brown shale have significantly lower densities than the rest of the section, confirming the high organic content subjectively indicated by the gamma-ray log. Within these zones, the density data indicate substantial variations in the amount of organic matter.

The densities of nineteen core samples from the adjacent 20403 well, 4,700 ft (1,433 m) away, are plotted in Panel B of Figure 3. These data show considerable variation from sample to sample, illustrating the vertical heterogeneity of small intervals. The core densities range from 2.725 g/cm^3 to 2.435 g/cm^3.

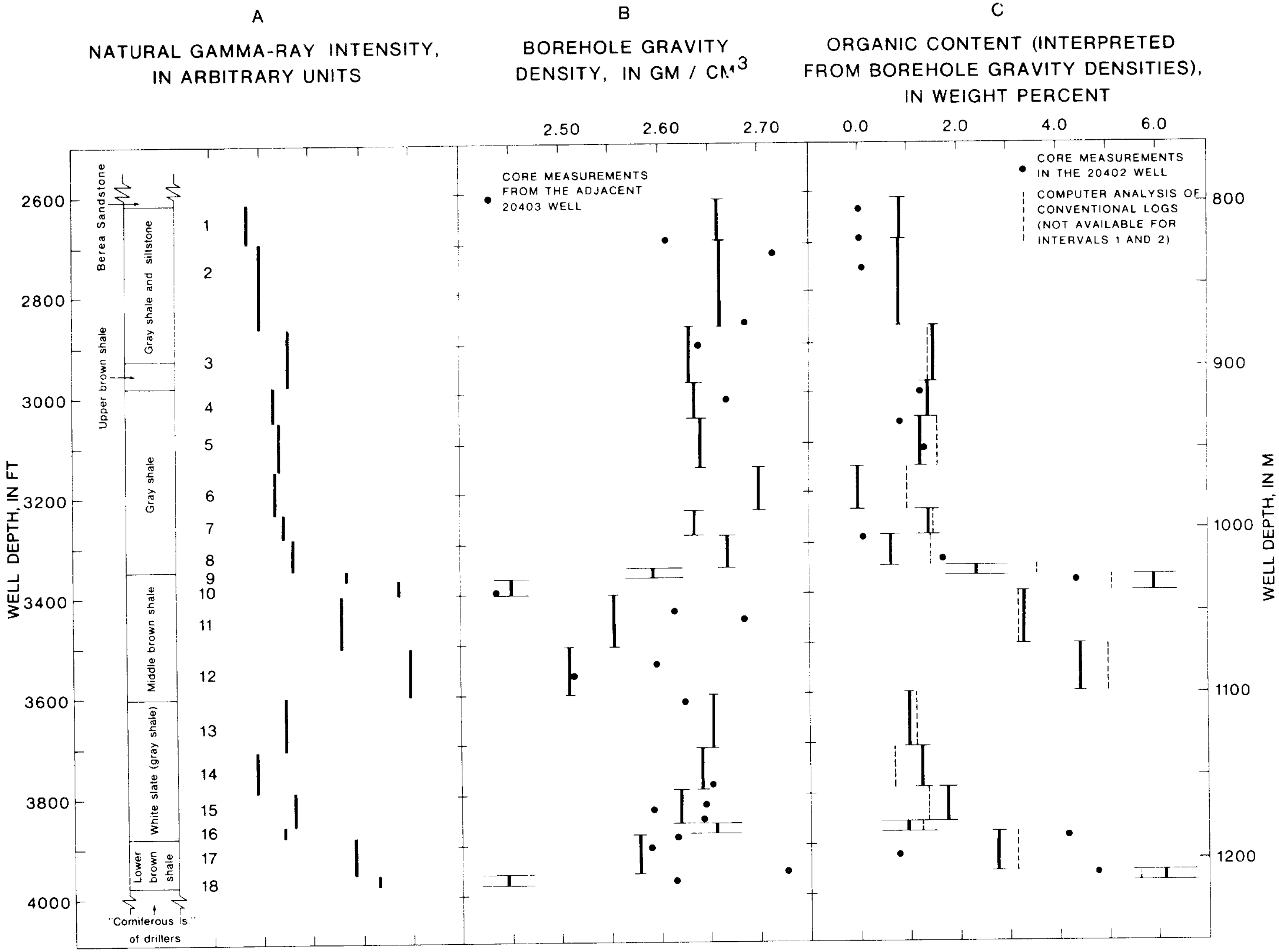

Figure 3. Stratigraphic section and gamma-ray intensity in the Columbia Gas 20402 well, borehole gravity density (Table 1), and weight-percent organic content calculated from the borehole gravity data assuming that density changes are caused only by variations in the amount of low-density organic matter. Data from core measurements and the computer analysis of conventional logs are also shown.

Organic Content

On the assumption that organic content is the primary variable affecting bulk density, variations of borehole gravity density with depth were interpreted in terms of weight-percent organic content (Panel C, Figure 3). This calculation is in error to the extent that other variables, such as pyrite content and porosity, change with depth and affect the bulk density. Panel C also shows the weight-percent organic content of twelve core samples from the 20402 well.

Organic content determined from subsurface gravity data ranges from 0-1.8% in the "gray" shales, and from 2.4-6.1% in the middle and lower brown shales. The core measurements reflect the heterogeneity of the shales for small vertical intervals, but generally confirm the range of values indicated by the borehole gravity data.

Digital computers make it feasible to estimate formation parameters using statistical methods applied to suites of log data. In the 20402 well, an estimate of organic content was generated by a commercially available computer program that used the resistivity, acoustic, gamma-gamma density, and neutron logs. Results are plotted on Panel C (Figure 3).

The overall agreement between organic content derived from the computer analysis of conventional logs and that derived from the borehole gravity densities is good, confirming the supposition that the primary variable affecting bulk density is organic content. For seven intervals (numbers 3, 4, 7, 9, 15, 16, 18), the density and organic content from borehole gravity data are within two standard deviations of the same values determined from conventional logs, indicating that the sonic, neutron, and electric logs added no significant information about organic content.

In five intervals (numbers 5, 8, 12, 14, 17), however, the borehole gravity and gamma-gamma densities agreed within two standard deviations, but the calculations of organic content did not. This suggests that additional information was supplied by the sonic, neutron, and electric logs, refining the estimation of organic content. The organic content determined from density alone is <u>less</u> than that determined from the computer analysis for intervals 5, 8, 12, and 17, implying that the bulk density may have been affected by an increase in the density of the shale matrix, possibly due to an increase in the density of the shale matrix, possibly due to an increase in the amount of pyrite. The organic content determined from density alone is <u>greater</u> than that determined from the computer analysis for interval 14, suggesting that the bulk density was affected by an increase in porosity.

Oil-Shale Yields

The Devonian shales of the Appalachian Basin have long been known as low-grade oil shales. Over 50 years ago, Crouse (1925) reported yields of 16-21 gallons of oil/ton from black shales at unspecified locations in Kentucky. More recently, Conant and Swanson (1961) assayed samples of Devonian and Mississippian Chattanooga shale from twenty localities in Tennessee. Maximum yields of 17 gallons/ton were established for small intervals, but yields over larger vertical intervals ranged from 2.5-9.0 gallons/ton. Smith and Young

(1964) sampled three cores from the Devonian and Mississippian New Albany shale of south-central Kentucky and obtained yields of 5-16 gallons/ton. They found a nearly linear relationship between decreasing bulk density and increasing oil yield.

Applying this relationship to the borehole gravity densities, the yield of the richest (lowest density) intervals of the 20402 well would be about 9 gallons/ton. Most of the "gray" shales would yield from 2-4 gallons/ton. These yields appear consistent with the findings of Conant and Swanson (1961) for the Chattanooga shale, and somewhat lower than Smith and Young's (1964) results from the New Albany shale.

Effect of Pyrite on Density

The frequent occurrence of pyrite in the Devonian shales has been reported by Smith and Young (1967), and Conant and Swanson (1961), and noted in the description of a core from Perry County, Kentucky (Byrer and Trumbo, 1976). If pyrite--a heavy mineral--varies at the expense of other constituents of the shale matrix, a weight-percent variation of 1% in pyrite would cause a bulk density change of .012 g/cm^3. If the pyrite occurs in void spaces so that a pyrite increase causes a porosity decrease, a weight-percent variation of 1% in pyrite would cause a bulk density change of .025 g/cm^3.

Effect of Porosity Change on Density

A change of 1% in intergranular or secondary porosity would cause a change in bulk density of .026 g/cm^3. A density change of this size could be measured by the borehole gravity meter. To interpret density in terms of porosity changes, however, variations in organic content and perhaps pyrite content would have to be accurately known.

SUMMARY

This study reports the first application of borehole gravimetry to the organic-rich Devonian shales of the Appalachian Basin. In a sense it is a preliminary report, analyzing the data from one well with the results giving an indication of future directions.

Reliable in situ densities reflecting the physical characteristics of large rock volumes were calculated from the borehole gravity data. Results confirmed the suspicion that one or both of the conventional density logs was faulty. In the two intervals of lowest density, the conventional logs recorded higher densities than the borehole gravity meter. The significance of this effect will be investigated in future surveys.

A strong correlation between high natural gamma-ray intensity, low density, and high organic content was evident in the data. Because the 20402 well was logged with an unusually complete suite of conventional logs and core data were available, it was established that accurate determinations of organic content could be made from the borehole gravity data alone. The borehole gravity meter is not affected by casing; thus, it could assay the organic content of the Devonian shales in any well penetrating the section. This capability could be extended to the evaluation of oil shales.

The gamma-ray log, like the borehole gravity meter, can be run in casing. In future studies, a quantitative relationship between gamma-ray intensity and borehole gravity density will be sought. Perhaps, with borehole gravity data providing the calibration parameters for an area, the gamma-ray tool can be utilized as a density logging device in the Devonian shales.

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