Techniques To Determine Natural and Induced Fracture Relationships in Devonian Shale

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Summary

Extensive study of natural fractures in oriented core, well logs, induced fracture orientation, lineaments, and Seisviewer™ surveys resulted in a log-core correlation of subsurface fracture systems and established a relationship between surface and subsurface directional aspects of Devonian shale. Core and well log analysis techniques discussed have the potential to identify the major producing intervals in Devonian shale.

Introduction

The primary objectives of the U.S. DOE's Eastern Gas Shales Project (EGSP) are to characterize the nature of the reservoir, determine how gas can be extracted in a cost-effective manner, and reduce the uncertainty of the resource base.

The unconventional reservoirs in Devonian shale are considered potentially the most productive underdeveloped source of natural gas in the northeastern U.S.[1] Field data indicate that gas is produced from Devonian shales mainly as a function of the presence and density of natural fractures.[2] Although the detection of a fracture system does not guarantee commercial production, it increases that probability. In support of this effort, a series of joint industry/U.S. DOE research projects was designed to investigate and study the nature, orientation, and density of natural fractures in Devonian shales. Within several project areas in the Appalachian basin, holes were drilled, cored, and logged (Table 1). This paper deals with the detailed correlation of the natural fractures determined from these cores and geophysical well logs to determine the validity and reliability of logging tools to locate fractured intervals in Devonian shales. In the latter part of the paper, correlation of natural and hydraulically induced fracture orientations, along with surface photolineaments traces, are discussed for a specific project area.

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Background

The Morgantown Energy Technology Center (METC) is responsible for the management and technical direction of the U.S. DOE research and development activities related to the unconventional gas recovery (UGR) program. As part of the UGR program, the EGSP was formulated in 1975 to determine the resource potential of Devonian shale that underlies the Appalachian, Illinois, and Michigan basins. Within the EGSP, resource characterization activities including drilling, coring, and logging of Devonian shale wells are complete. This paper addresses primarily the coring and logging activities related to the identification of fractures.

Correlation of natural fracture density and orientation as derived from well logs and oriented formation cores may aid in defining and identifying gas reservoirs and improving prospects of commercial gas production from shales.

The objective of coring various Devonian shale intervals is to provide chemical and physical characterization of the cored formations. Formation characteristics studied include mechanical rock properties, geochemistry, and natural fracture incidence and orientation.[3]

Two types of fractures are detected in Devonian shales: existing natural fractures and fractures that occur as a result of stresses produced by the core extraction process. A classification scheme[4] for identifying and defining the coring-induced and natural fractures has been developed. Kulander *et al.*[4] defined such terms as hackle, petal, and torsion to classify coring-induced fractures. These coring-induced fractures have (1) a fracture origin at the core boundary or within the core itself; (2) hackle marks diverging and attempting to meet the core boundary or pre-existing fracture surface orthogonally; (3) hackle marks becoming coarser, with hackle-shaped steps increasing in relief of the immediate vicinity of core boundary or pre-existing fracture surface; (4) twist hackle originating near the core margin or pre-existing

TABLE 1—DEVONIAN SHALE WELLS UNDER STUDY IN THE APPALACHIAN BASIN

	Project Area
Beckholt Well 1	Mount Vernon, Knox County, OH
Black Well 1	Mount Vernon, Knox County, OH
Carpenter Well 1-5	Gallia County, OH
White Price Newberry Well 1-7	Gallia County, OH
L. McCombs Well 1-6	Gallia County, OH
Well EGSP/OH-4	Ashtabula County, OH
Baler Well 11940	Cottageville, Jackson County, WV
Pinnel Well 12041	Cottageville, Jackson County, WV

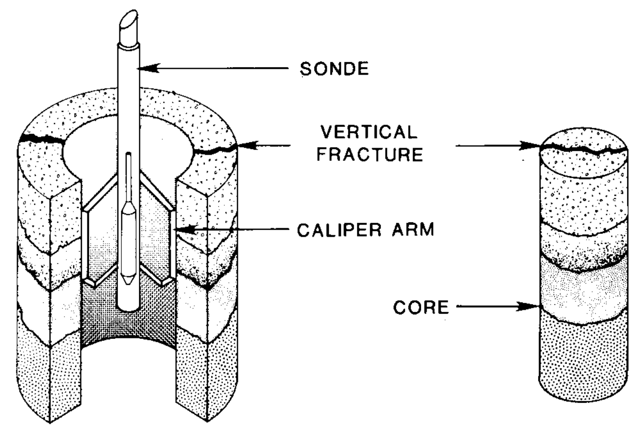

Fig. 1—Schematic showing operational log/core correlation.

fracture surface; (5) hackle plumes diverging in a spiral fashion from the central part of the core on a subhorizontal fracture surface, indicative of torsional or torque stress; and (6) hackle marks on a vertical or subvertical planar fracture, diverging down the core from the center of the plane toward the margins.

These common features are categorized further into four groups: (1) petal fractures and petal/center-line fractures, (2) torsion fractures, (3) bedding plane fractures and disk fractures, and (4) knife-edge and core-bit spalls.

Natural Fractures

Subsurface natural fractures in the Appalachian basin can be related to the Alleghenian deformation.[5] This phenomenon was caused by faulting and crustal spreading along the mid-Atlantic ridge as a result of tectonic compressive stresses during deformation.

The pre-cored existing fractures exhibit unique patterns of characterization: (1) smooth, polished planar fracture facies, with or without slickensides; (2) mineralized and/or coated crystallized fractures indicating minerals such as calcite, dolomite, anhydrite, and barite; (3) a smooth fracture extending across the core, against which later fractures terminate; and (4) small conchoidal chips or hook fractures at the intersection of an inclined fracture plane and the core margin (the chips hook to meet the inclined fracture orthogonally).

Natural fractures in the core were examined in detail during core analysis. The fractures are classified into different types, allowing the observation of fracture densities and correlation with the fracture identification log (FIL™) as shown in Fig. 1. Although the classified genetic fracture consists of simple and compound joints, faults, and microfaults, most natural vertical fractures represent the simple joint features. The dipping angle of this fracture group is primarily vertical or subvertical, illustrating intervals of vertical fracture continuity. The faults and microfaults exhibit relatively lower dip angles, thus contributing to a more or less horizontal fracture system. The latter fracture groups show little correlation between log and core analyses.

Logging

Natural fracture detection from well logs has been investigated for more than 20 years. Early work[6-9] in the 1960's was concerned with the use of acoustic amplitudes, spontaneous-potential curves, borehole televiewers, and lithoporosity crossplot techniques to give either indirect or qualitative indications of the presence of natural fractures. Over the past 10 years, numerous well logging techniques have been identified for use in fracture detection.[10-14] Many of these methods have limited capability to determine fracture extent and orientation as well as the producibility of a well. Of particular interest would be a quantitative verification of natural fractures and their orientation as seen both from fracture detection logs and from oriented cores.

Considerable interest in naturally fractured reservoirs (e.g., the Austin chalk formation) resulted in the development of the modified high-resolution four-arm dipmeter tool, derived from the four-arm high-resolution dipmeter.[15] This logging tool is capable of identifying natural fractures along with their orientation for the determination of fracture trends, which help to identify areas of high productivity. In areas where natural fractures dominate reservoir production, quantitative formation evaluation methods are required.

FIL

The FIL service consists of a four-curve presentation of microresistivity along with a dual two-curve overlay (stacked)* made on 5-in. (12.7-cm) and 25-in. (63.5-cm) per 100-ft (32.81-m) vertical scales.[6] More specifically, the modified high-resolution dipmeter tool (FIL) uses four microresistivity type pads applied to the wellbore walls by means of two independent pairs of caliper arms. The pads are oriented radially 90° apart, with Pad 1 as the reference electrode. The tool responds to conductivity anomalies of the formation, represented by the separation of two pairs of previously superimposed dipmeter curves across Tracts 2 and 3. The type of log presentation or display used in the Appalachian basin is superimposition of Dipmeter Curves 1, 2, 3, and 4, which correspond to Caliper Pads 1, 2, 3, and 4, respectively.

The FIL service aids in detecting fractures and their orientations, in addition to gauging the borehole. The elongation of the borehole to the fracture plane is

*The suggestion for this overlay presentation is credited to John Humston of Hughes and Hughes, Beeville, TX.

TABLE 2—LOG/CORE CORRELATION OF NATURAL FRACTURES AND THEIR ORIENTATIONS FOR CARPENTER WELL 1-5

Fracture Orientation, FIL	Fracture Orientation, Core	Observed Footage of Core Fracture (ft)	Observed Footage of Log Fracture (ft)	Corrected Fracture Orientation Log	Core Depth (ft)
N25°E	N41°E	0.1	*	—	—
N50°E	N44°E	3.0	7	N46°E	2,325.6 to 2,328.6
N50°E	N58°E	—	*	—	—
N37°E	N54°E	2.0	*	—	—
N40°E	N61°E	1.5	*	—	—
N40°E	N51°E	2.0	*	—	—
N40°E	N57°E	1.7	*	—	—
N37°E	N58°E	11.7	10	N48°E	2,477.5 to 2,489.2

*Not detectable.

TABLE 3—LOG/CORE CORRELATION OF NATURAL FRACTURES AND THEIR ORIENTATIONS FOR WHITE PRICE NEWBERRY WELL 1-7

Fracture Orientation, FIL	Fracture Orientation, Core	Observed Footage of Core Fracture (ft)	Observed Footage of Log Fracture (ft)	Corrected Fracture Orientation Log	Core Depth (ft)
N54°E	N70°E	1.2	*	—	—
N54°E	N70°E	2.8	3	N61°E	2,305.8 to 2,308.5
N54°E	N70°E	1.0	*	—	—
N54°E	N65°E	2.1	3	N61°E	2,307.9 to 2,310.0
N54°E	N70°E				
N39°E	N60°E	11.7	12	N46°E	2,425.4 to 2,437.1
N39°E	N60°E	18.2	16	N46°E	2,443.5 to 2,461.7

*Not detectable.

represented by constant values of azimuth, which reconfirms the responses of conductivity anomalies.[16,17] In addition, extensive fracturing may cause the borehole to crumble and wash out on opposite sides. This is easily recognizable by the response of the dual calipers of the four-arm dipmeter.[18]

Natural fractures derived from cores of wells have been compared with those fractures located by FIL's from these wells (Table 1). Results show that good correlations may be obtained for core fractures of significant length [$L>2$ ft (0.61 m)] intersecting the wellbore, especially when dipping angles of the fracture system approach 90° (a common characteristic of simple joint fracture systems). Selected correlations of fractures [$L>2$ ft (0.61 m)] can be observed from Tables 2 and 3. Of all the core natural fractures observed in wells listed in Table 1, only those fractures having lengths greater than 2 ft (0.61 m) were detected and identified.

The identification of a naturally fractured interval from the FIL for Carpenter Well 1-5 and White Price Newberry Well 1-7 is shown in Figs. 2 and 3. The fracture azimuths also are indicated. The comparison of all natural fractures and their orientations derived from cores and FIL's for these wells is shown in Tables 2 and 3. Common correlations are achieved when the length of the fracture is significant [$L>2$ ft (0.61 m)]. The compared recorded values of fracture orientation show some variations; however, these orientations correlate closely after the applied declination and pad width corrections, as shown in Tables 2 and 3. The latter correction accounts for the error in the recorded azimuth, which is introduced by the width of any given pad(s) detecting a vertical or subvertical fracture plane. An arc having a length of 1½ in. (38.1 mm) (electrode width of the pads) is equivalent to 22° of arc; thus, the range of this correction factor may be as large as ±11° for 7⅞-in. (200-mm) wellbores. Note that the range of previously mentioned FIL azimuth correction factors can be found for any given hole size; however, the determination of case-specific values is highly unlikely at this time. Thus, the main focus of this concept is on future applications of this logging tool in Devonian shale.

Other logs—e.g., temperature, sibilation, gamma ray, and density—have been used to detect gas-bearing zones in Devonian shale. However, these logs have made little contribution to fracture characterization and do not reduce uncertainty in the selection of potentially productive intervals when gas influx is nonexistent.

Fracture Orientation

The orientation of natural fractures has been recognized as an important criterion in the selection of drilling sites for development wells along a fracture trend.[16,18] The FIL service has been used to determine the composite fracture or joint trend from multiple wells. The usefulness of natural fracture orientation data for reservoirs where fracturing dominates the production mechanism has not been recognized fully, particularly for the tight reservoirs being developed today.

Basically, there are two distinct types of fracture orientation methods: those that deal with naturally occurring fractures and those that deal with fractures hydraulically induced in wellbores. A variety of techniques for understanding the directionality of a Devonian shale reservoir was used at one of the EGSP sites near Mt. Vernon, OH. The project area covers about 25 sq miles

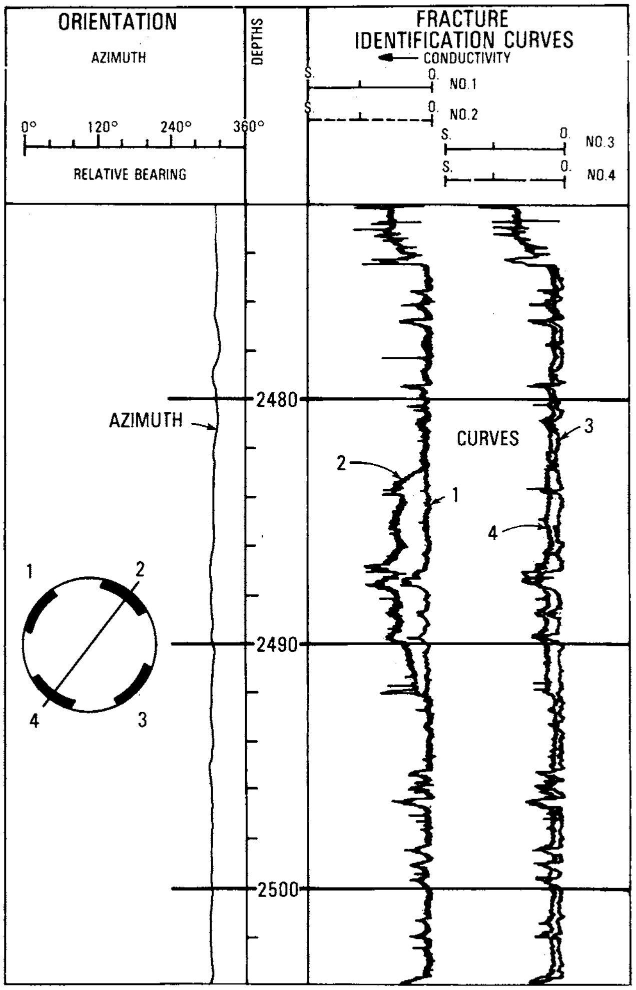

Fig. 2—Fracture detection log indicating natural fracture system and orientations for Carpenter Well 1-5, Gallia County, OH.

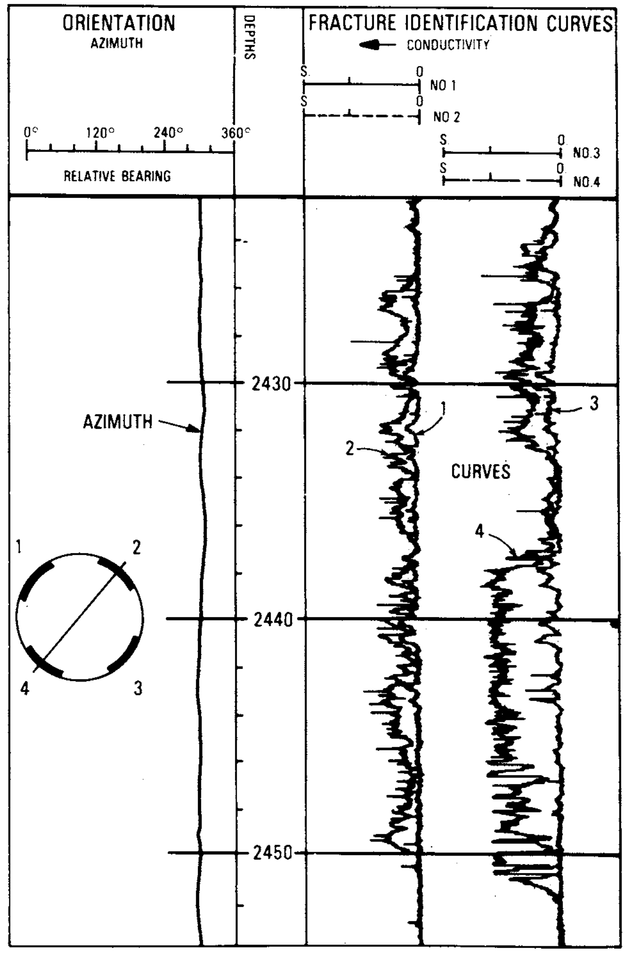

Fig. 3—Fracture detection log indicating natural fracture system and orientation for White Price Newberry Well 1-7, Gallia County, OH.

(65 km^2) northwest of Mt. Vernon, where a detailed photolineament analysis was conducted along with coring and hydraulically induced fracturing experiments to delineate fracture orientation.

The results of the Mt. Vernon project are discussed to define the correlation of various techniques for acquiring both natural and hydraulically induced fracture orientations over the project area.

Previous work by Komar *et al.*[19] in 1971 indicated that surface joints and lineaments from aerial photographs are related to the orientation of the hydraulically induced vertical wellbore fractures.

Shafer Exploration Co. prepared a lineament analysis from a combination of high- and low-altitude photography and a topographic map of the project area. Results in Fig. 4 show two major orientation sets: the primary set runs in the N30°–40°W direction, and the secondary set runs in the N70°–80°E direction. From rock mechanics theory, the preferred orientation of both natural and induced fractures is controlled by current and past stress orientations within the reservoir. Hydraulically induced fracture orientation usually follows one of the two major lineament orientations that may indicate preferred fracture direction at depth.

Additional fracture orientation analysis was performed at Mt. Vernon with wellbore Seisviewer images in Black Well 1. The Seisviewer[20] is an acoustic device primarily designed to evaluate fractured reservoirs. The downhole scanning instrument, comprising a motor-driven acoustic transducer and a fluxgate magnetometer, rotates at 3 rev/s to produce a high-resolution acoustic picture of the borehole. The resulting log is oriented to a north marker signal from the fluxgate magnetometer. The acoustic transducer is pulsed at a rate of 2,000 times per second with the focused acoustic beam directed at the borehole wall. The amplitude of the signal reflected from the wall depends on the acoustic impedance of the wall rock and on associated physical properties of the wall. Fractured or highly disturbed zones are recognized by a poor or no reflected signal. The detected acoustic signals are amplified along with the magnetic north marker pulse and are transmitted to the surface through the multiconductor cable. The surface panel combines this downhole information to produce the acoustic picture of the borehole wall.

Results of this seisviewer survey indicated a natural fracture extending over a 10-ft (3.043-m) interval in Devonian shale, with an average strike direction of N73°E along with an average dip angle of 88½°SE,[21] a nearly vertical natural fracture joint.

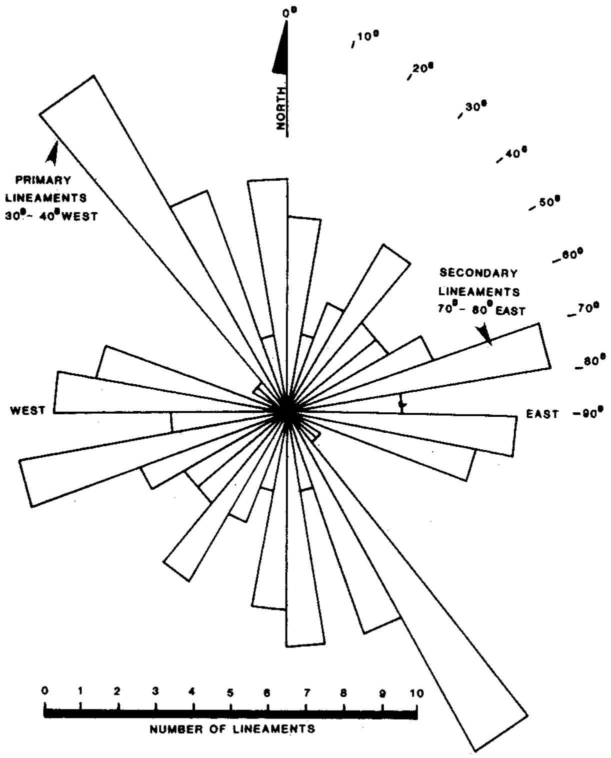

Fig. 4—The surface lineaments and their orientations for Mt. Vernon area, Knox County, OH.

TABLE 4—NATURAL FRACTURES IN BECKHOLT WELL CORE, KNOX COUNTY, OH

Number	Interval (ft)	Length (ft)	Strike Dip
1	631.2 to 631.6	0.4	N20°W vertical
2	684.1 to ?	0.3?	N80°E vertical
3	861.1 to 861.8	0.7	N60°E vertical
4	862.3 to 862.4	0.1	N55°E 45°SE
5	965.5 to 966.3	1.3	N62°E vertical
6	978.9 to 979.0	0.1	Nearly horizontal
7	1,012.2 to 1,012.2	0.2	N45°E 60°SE
8	1,013.1 to 1,013.2	0.1	N65°E 50°NW

To understand the induced fracture orientation in the field test area, a highly instrumented fracturing experiment was designed to determine the induced fracture azimuth by means of both a borehole seismic approach and a surface tiltmeter system. Results of the borehole seismic interpretation indicated that the largest induced fracture activity appeared in the N62°E direction[22]; the surface tiltmeter system also indicated an orientation of N62°E.[23] Thus, both systems independently obtained similar findings of preferred direction of a hydraulically induced fracture.

An additional hypothesis was tested to verify that the orientation of natural fractures in core material is related to the preferred direction of induced hydraulic fractures. A core taken from Beckholt Well 1, an offset to Black Well 1, was analyzed, and more than 700 ft (213 m) of oriented core was collected from Devonian shale to characterize the natural fracture system of the test area. Fracture analysis from seven natural fractures in the core (Table 4) indicated that the natural fracture orientations were in the range of N45°-80°E.

The Mt. Vernon project results show a good correlation between natural fracture direction in the cored Beckholt Well 1 and from Seisviewer in the offset well. The secondary major surface lineament direction had similar orientation to the natural fractures detected from the core and Seisviewer. Furthermore, the direction of natural fractures in the Beckholt Well 1 is related directly to the preferred direction of induced hydraulic fracture(s) as obtained from the downhole seismic and surface tiltmeter systems.

Lineament analysis over the Cottageville field, Jackson County, WV, indicated a primary orientation set at N45°-70°E, while the secondary orientation set was N35°-45°W. From core analysis on both Baler Well 11940 and Pinnel Well 12041, N45°E was the primary orientation of natural fractures in the cores. The primary lineaments orientation correlates with the primary natural fracture orientation detected by oriented core.

Production from Natural Fractures

Consolidated Gas Supply Corp. and the U.S. DOE conducted a joint research drilling, coring, and stimulation program in Devonian shale near Cottageville, WV. Specifically, the core data extracted from two wells characterized those zones of brown shale containing natural fractures and their orientations. The two wells, approximately 3 miles (4.828 km) apart, were located in the Cottageville gas field. Pinnel Well 12041 was cored through the shale from 3,220 to 3,690 ft (1056 to 1211 m), and Baler Well 11940 was cored from 3,410 to 3,500 ft (1119 to 1148 m) and 3,600 to 3,794 ft (1181 to 1245 m). Following drilling, the open-flow potential of Pinnel Well 12041 was too small to measure, or nearly 0 cf (0 m^3). A correlation of gamma ray log vs. composite vertical fracture orientations observed in the core is shown in Fig. 5. Results indicate that over the target organic shale intervals, the preferred natural fracture orientations are highly concentrated in the direction of N45°E. Pinnel Well 12041 was completed from 3,238 to 3,629 ft (1062 to 1191 m) with a 158,000-gal (598-m^3) foam fracturing treatment with a resulting postfracture open flow of 171 Mcf/D (4899 m^3/d). The well was placed in line producing 35 Mcf/D (1002 m^3/d) natural gas against 80-psig (551.6-kPa) line pressure. Cumulative production for the first 24 months totaled 13

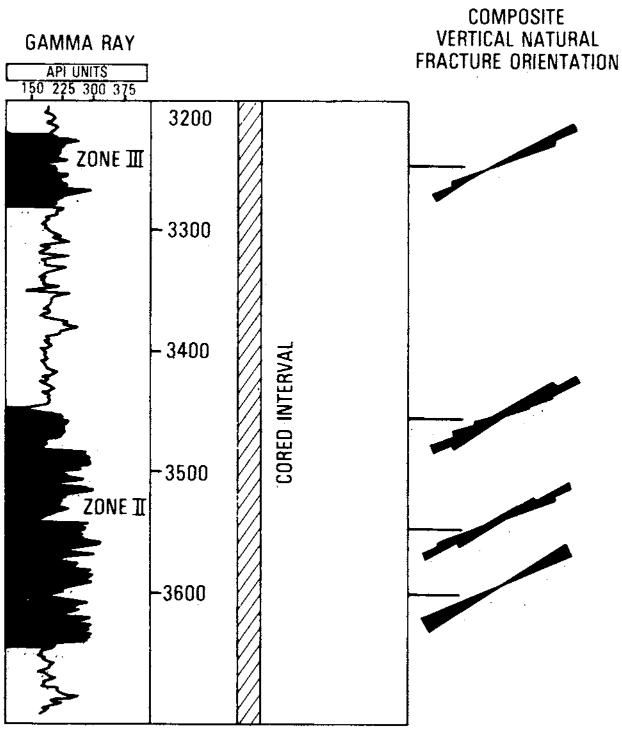

Fig. 5—Gamma ray vs. composite vertical fracture orientations for Pinnell Well 12041, Jackson County, WV.

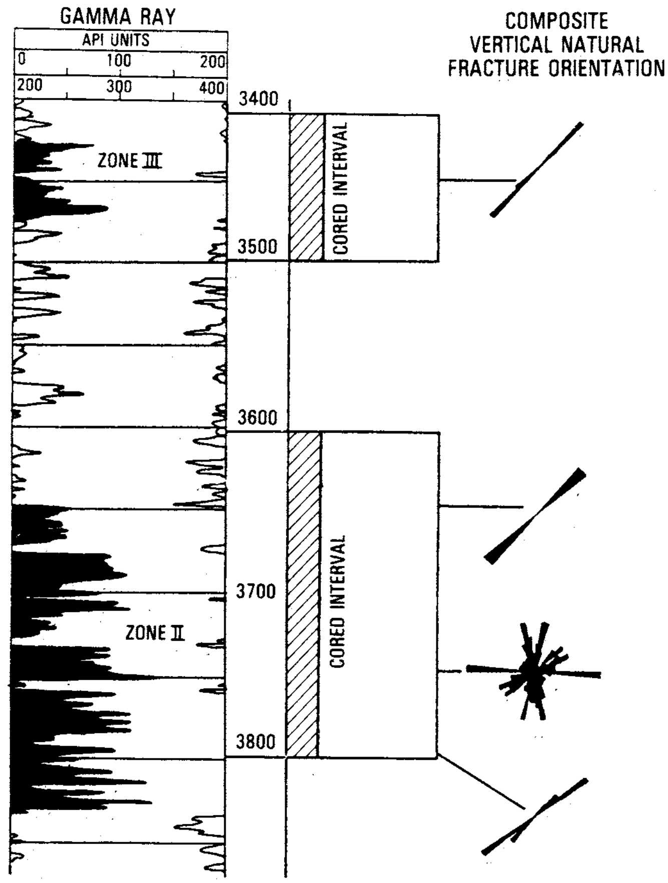

Fig. 6—Gamma ray vs. composite vertical fracture orientations for Baler Well 11940, Jackson County, WV.

MMcf (372×10^3 m^3) and the well currently is making less than 10 Mcf/D (288 m^3/d).

A correlation of gamma ray log vs. a composite vertical fracture orientation from core analysis for Baler Well 11940 is shown in Fig. 6. Results over part of the cored interval indicate a preferred fracture orientation of N45°E, similar to Pinnel Well 12041. However, in one particular interval from 3,725 to 3,775 ft (1221 to 1239 m) a series of multiple fracture orientations was noted (Fig. 6) along with an unexpectedly large natural open flow of 1,050 Mcf/D (30 068 m^3/d). The presence of these multiple natural fracture orientations in the core is related to the high natural open flow and production in Baler Well 11940. Coring of this well continued for a few more feet (1 m) below this zone and was terminated because of potential drilling safety problems under stiff foam/air coring conditions. The well was placed on production without stimulation, producing 250 Mcf/D (7159 m^3/d) natural gas against 200-psig (1379-kPa) line pressure. Cumulative production for the first 24 months totaled 90 MMcf (2549×10^3 m^3). An openhole temperature log shows an extremely good temperature anomaly over this naturally fractured interval, confirming gas production from the interconnected natural fracture system.

Conclusions

1. Natural fractures observed from fracture detection logs and confirmed by oriented cores are of a simple joint genetic group. These natural fractures are characterized by vertical/subvertical dip angles.

2. Detection of low-angle joints or natural fractures along bedding planes is not defined adequately on logs.

3. The directional aspects of a naturally fractured reservoir in Devonian shale have been investigated both with surface and with subsurface data on natural and induced fractures in the Mt. Vernon project. Results have shown a good correlation between natural and hydraulically induced fracture directions derived from oriented cores and hydraulic fracturing experiments.

4. The secondary major surface lineament direction is similar to the orientation both of natural and of hydraulically induced fractures in the Mt. Vernon area. Also, the primary major surface lineament direction is similar to the natural fracture direction observed in cores taken from the Cottageville field.

5. An adequate correlation has been established between the FIL and oriented core fractures and their orientations for fractures longer than 2 ft (0.61 m).

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SI Metric Conversion Factor

$$\text{ft} \times 3.048^* \text{ E}-01 = \text{m}$$

*Conversion factor is exact.

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