A case history study of fracture detection methods used to locate open fractures in coal

by

A.D. Decker[1], T.L. Davis[2] and A.J. Klawitter[1]

[1]Advanced Resources International, Inc. [2]Department of Geophysics, Colorado School of Mines

ABSTRACT

Permeability is an essential reservoir characteristic for effective drainage of methane from coal reservoirs. This paper presents results of detailed laboratory and field studies which show that coal petrography data, remote sensing, surface geology, curvature analysis of subsurface structure and seismic data may be useful in identifying areas of higher permeability. The ability to high-grade areas of enhanced coal permeability can reduce the risk and uncertainty related to the exploitation of coalbed methane.

The inability to predict open fracture systems within coal reservoirs in advance of drilling presents an undesirable risk. Methods described in this paper are designed to increase the certainty of identifying areas in the subsurface with adequate permeability. Permeability is essential in achieving effective methane drainage in coal reservoirs. Its importance is enhanced due to gas adsorption on the coal and the need to effectively draw-down reservoir pressure over a large area to maximize gas desorption. Although the permeability of the solid coal matrix is very low, fluid flow is possible in the coal seam through diffusion and darcian flow through natural cleats and tectonically-stratigraphically induced fracturing. While diffusion may control early-time production, permeability controls long-term production and overall well economics. Due to coal compressibility, for coal to retain permeability at depth, the in-situ stresses must be low enough to allow the cleats and tectonic-stratigraphically fractures to remain open. The density of cleats and fractures is shown to be related to specific coal rank and lithotype. Trends of higher productivity are shown to correlate with areas predicted as having potentially-lower in-situ stresses using curvature analysis and remote sensing data of detailed subsurface structure. Combined, these techniques provide a method to identify areas of potentially higher permeability.

Cleat and fracture density has been related to specific coal lithotypes and the level of ash dispersed in the coal. Therefore, using high resolution density measurements and detailed coal petrography, areas of increased cleat and fracture density can be identified.

Detailed studies from coal degasification fields indicate that remote sensing and curvature analysis can identify areas of greater productivity. Faulted areas, as interpreted from remote sensing and/or geophysical data, and confirmed through surface geology, were shown to correlate with areas of higher productivity. Finite satellite imagery was shown to be useful in surface fracture studies on a regional perspective. Regional landforms and large structures can be identified and mapped. Larger-scale high altitude infrared photography provided detail to allow projection of the surface fracture system into the subsurface. Surface geology was used to confirm these observed features. It is our belief that faulting both increases the amount of fractures within the coal seam and more importantly, alters and lowers the in-situ stress resulting in higher permeability. The lower stress may come from either a direct relief of in-situ stresses or an anisotropic redistribution of the horizontal stress components.

Areas of structural flexure defined by curvature analysis were also found to be related to areas of higher productivity. Curvature analysis of detailed surface structural data identifies areas of greater flexure. It is believed that flexure may cause an increase in fracturing and lower in-situ stress. Three high-quality stratigraphic datums were mapped. Attempts were made to eliminate stratigraphic influences. In some areas, subsurface control could not distinguish faulting from flexure.

In summary, these studies indicated that areas of higher permeability can be identified using exploration concepts combining 1) techniques to identify coals most likely to have a high cleat fracture density, i.e., use of coal forming and thermal maturity models to identify coals of suitable rank, maceral composition, and low mineral content; 2) the integrated use of remote sensing geophysical data and surface geology to identify areas of more intense faulting; and 3) identification of subsurface structure with curvature analysis.

STUDY RATIONALE

The inability to predict the presence of permeability orientation and magnitude with respect to location in potential coalbed methane reservoirs prior to drilling represents an undesirable risk to operators. Permeability is an essential reservoir property that strongly influences the producibility of methane from coal reservoirs. The permeability of coal matrices in northern San Juan Basin coalbed methane reservoirs is typically very low, perhaps in the sub-microdarcy range[1]. The fracture permeability component can be in excess of several millidarcies.

Fractures in coal provide the natural "plumbing system" that allows flow of water and gas to the wellbore. Other low matrix permeability reservoirs such as tight gas sands and Devonian shales rely on tectonically or stratigraphically induced natural fractures for permeability systems. This analogy can likewise be applied to coal. Highly cleated coals are common, where high permeability coal reservoirs are not. Rubbilized fault zones or highly broken intervals along flexured or zones of curvature provide the primary permeability system where as cleats are second-order fractures feeding into the primary system.

It is often assumed that permeability development will be along the face cleats in the coals, which is not always true. It is essential to realize that the face cleats in a given reservoir may or may not be present-day open fracture system. Subsequent tectonic events may superimpose later, more well developed and preserved fracture systems with higher permeability on the pre-existing face and butt cleats. In another scenario, the orientation of the present-day stress field may be such that the face cleats are probably closed, which implies that the orientation of permeability may be along some other fracture system. Also, it should not be assumed that a pervasive cleat system with appreciable permeability is present in every potential coalbed methane reservoir. The ability to predict permeability orientation and magnitude will have a direct bearing on well placement and spacing for maximum drainage and most efficient production. This ability will hinge upon the accuracy of predictions concerning relationships between surface fracture orientations, locations and frequency, and permeability orientations, locations and magnitudes (open cleat orientations, lengths, aperture widths and frequencies) at reservoir depths.

Although it is common knowledge that permeability is an essential requirement for commercial production, over 500 million dollars in the United States alone have been spent on projects where there is little possibility of economic return due to encountering low coal permeability. This paradox could be anticipated due to the lack of fracture detection techniques and is further encouraged by workers[2] who recommend siting wells based on little more than the hope that coal cleats will provide adequate permeability.

The San Juan Basin has a broad development platform several thousand miles in extent where high permeability coals are commonly encountered. This provides the perfect setting where random drilling is a commercially viable development method. To date, no other basin has been found where permeability has been so pervasively distributed. A more realistic scenario may be extensive low permeability settings containing occasional pockets of high permeability. Identifying high permeability areas in advance of drilling, at minimum cost, is the future to continued coalbed methane development.

Initial Australian coalbed methane production efforts from 1976 to 1988 were hampered by low permeability. As a result, the perception that Australian coals were characteristically low permeability was commonly held. The first indication that permeability did exist in Australian coals came out of an effort utilizing an integration of multiple and overlapping fracture detection tools[3]. Unfortunately, data and interpretations from that program remain confidential and cannot be presented in this paper. As such, the lessons learned and capacity to build on that knowledge will be limited to a few people.

REMOTE SENSING METHODS USED TO LOCATE OPEN FRACTURES IN COAL THROUGH SURFICIAL FRACTURE DETECTION

The use of remote sensing data and methods to identify fault/fracture systems is well documented in literature. Linear features, distinct non-culture linear elements interpreted directly from imagery, may represent geologic structure in subsurface rocks[4]. Relationships between mapped surficial linear and curvilinear features to subsurface faults and fractures in coal has been established by the U.S. Bureau of Mines[5,6]. Identification of regions exhibiting fracture enhanced fluid permeability in coals through linear feature mapping have been documented[7,8]. The following is a brief review of orbital and airborne remote sensing imagery and methods used to locate regions portraying open fractures in coal.

The basic assumption behind imagery to assist in identifying areas displaying enhanced permeability in subsurface coals is that fractures, or results of the fractures, are expressed at the Earth's surface. These expressions may be linear features associated with structures, geobotanical anomalies, and/or rock/soil alteration anomalies. If these features are expressed at the surface, which systems have the spatial and/or spectral resolution to detect these features?

Historically, orbital platforms provided synoptic imagery for the identification of regional structures and trends of structures. Inferences concerning the tectonic history and stress regimes may be drawn from the imagery. This information may prove valuable in locating areas of low in-situ stress. Examples of imagery types are: Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM), SPOT panchromatic (P), and SPOT Multispectral (XS). Linear features interpreted from imagery through photogeologic techniques[9] have been related to subsurface fracture trends in coals on a regional basis[10] and on a local basis[11]. Methods of identifying and analyzing statistically significant trends are described by Sawatzky and Raines[12], and Knepper[13]. Small features: i.e., less than a few meters in length or width, cannot be resolved by these systems because of either their relatively coarse spatial resolution or low spatial frequency of the surface being imaged.

Systems that provide higher spatial resolution are aerial photography and airborne multispectral scanners. Typical types of data are panchromatic and false color infrared photographs and multispectral images. Spatial resolution depends on flight altitude, focal length of the optical systems, and instantaneous field of view of scanning instruments. Interpretation and methods of linear feature analysis are similar to those used for orbital data.

In any linear feature analysis scheme, "ground truthing" of the interpreted features before data processing is essential to the success of the project. Mapped linear features must be interpreted in the light of any available ancillary data to improve the geological model of the project area. Any applied data enhancements or processing techniques must be fully understood to assist in interpretation of derived products; i.e., grouping of azimuthal data into sectors for processing filters the data. Data deemed insignificant on a regional scale may be significant; indeed, earlier "conclusions" and assumptions must be continually reviewed.

Linear feature analysis of remote sensing imagery used in conjunction with other data and techniques such as curvature analysis and soil gas geochemistry, has proven valuable in predicting and locating fracture enhanced permeability in coal beds[7,10,8]. Linear feature analysis methods similar to those described by Sawatzky and Rains[12] have been successful. Size and location of interpreted linear features depend on the spatial resolution of the imaging system.

Locating Low Stress Settings Using Remote Imagery: A Bowen Basin Case Study

Testing in the Bowen Basin indicated a generally low inherent permeability, with a decrease in permeability towards reverse faults despite highly rubblized coal zones. The general decrease in permeability when approaching fault zones supports the interpretation that fractures in coal are compressed closed in high stress settings.

With this understanding, the exploration areas can be partitioned on the basis of stress settings. Compressional thrust features can create a high stress, low permeability setting. As the Bowen Basin is thrust dominated, locating isolated low stress areas within regional high stress regimes becomes fundamental in locating high permeability. Detailed surface fracture analysis maps are critical for the structural interpretation necessary to locate low stress structures. Recent advances in low altitude multispectral imagery coupled with computer enhanced analysis permits generating the necessary surface fracture analysis maps, regardless of vegetative cover and thick alluvials.

Landsat imagery at a scale of 1:100,000 can be used for regional structural and stress interpretation. A multispectral imagery acquisition system was mounted in a light aircraft, for low altitude fly overs, to improve resolution as compared with landsat imagery. The imagery was interpreted and displayed as a lineament map for exploratory well site selection. For field delineation and selection of development wells a high resolution lineament map is required. By further reducing elevation of the fly over, increased resolution can be achieved.

Figure 1 illustrates the trends relating permeability, stress and depth. Note that high to moderate permeability was not encountered under a high stress setting.

In all cases, high permeability has only been identified in low stress, structurally relaxed settings. Unfortunately, stress data for coal seams with permeability in the 20 - 40 md range could not be obtained as the coal seams would accept injected water too easily preventing formation breakdown necessary for calculation of closure pressure.

Some coal seams within the low to moderate stress settings have low permeability. It appears that inherent low permeability may be common even in low stress settings due to cleat filling material such as calcite, siderite and kaolinite. In such cases, high permeability is wholly attributed to tectonically induced fracturing along fault planes and flexured zones. A low stress setting is then crucial in permitting fractures to remain open.

Photogeology Study Area at Cedar Hill Field: San Juan Basin, New Mexico

The objective of the photogeologic investigation is to utilize available aerial photographs and remote sensing imagery to delineate surface structural, fracture and geomorphic linear features within the Cedar Hill area, and map the prominent trends present.

A photogeologic study of surface fractures at Cedar Hill Field[14] was completed under funding from GRI to evaluate geologic tools to define reservoir fracture permeability and anisotropy. The study covers the Cedar Hill Field in San Juan County, New Mexico (Figure 2), which includes Sec. 3-10, T31N, R10W.

Photograph and Base Map Acquisition

High altitude color infrared and black and white photographs of Cedar Hill Field were purchased from EOSAT Corporation, Sioux Falls, South Dakota. The scale of these photographs is 1:58,000 and 1:80,000 respectively. Low altitude black and white photographs of cedar Hill Field were purchased rom the U. S. Geological Survey, Denver, Colorado. The scale of these photographs is approximately 1:28,000. Satellite imagery (LANDSAT) at various scales (smaller than 1:80,000) was purchased from EOSAT to provide a regional perspective for the fracture mapping.

Topographic base maps from the U.S. Geological Survey at a scale of 1:24,000 were used for the fracture mapping. Films of the topographic maps were generated at the same scales as the aerial photographs to facilitate fracture mapping.

Side looking airborne radar (SLAR) coverage is not available for the study area.

Photogeologic Surface Fracture Mapping

Surface fracture mapping in may areas can be completed using photogeologic interpretations. Maps of surface fracture patterns can provide the key to inferences concerning fracture locations, orientations and development in shallow reservoirs where detailed subsurface fracture data are not available. The surface photogeologic interpretations must be field checked. However, in the Cedar Hill Field, outcrops of the two major bedrock units, including the clastics of the Nacimiento and San Jose Formations (Tertiary), are generally sparse and of very poor quality, because of mass wasting, Pleistocene terrace gravel caps on mesas, Quaternary soil cover, and Holocene fluvial clastic cover associated with the Animas River[15].

The interpretation of aerial photographs and remote sensing imagery, when used to obtain geological information, is based on the recognition of photographic feature tone, texture, pattern, shape, location, size and orientation. Photographic tone is a measure of the relative amount of light reflected by a feature, and actually recorded on black and white film. Tone is an integral component of the other photographic recognition elements listed above, except color[16]. Texture is due to the repetition of tonal value, and can range from very rough to smooth. A change in texture can be recognition of rock types. Pattern can be recognized where areas of homogeneous texture can be delineated. Pattern boundaries can be extremely sharp, which may indicate the surface expression of a fault. More diffuse boundaries may be present in a drainage network. Shape is closely related to pattern. Various landforms such as a meandering stream valley, have definite shapes as opposed to patterns. The location, or proximity of photogeologic features to one another, when considered with the other recognition elements, may be used for inferences on the origin of the landforms. Parallel lineations along the Animas River in the Cedar Hill Field, for example, are alluvial fault-line scarps. Since the scales of the aerial photographs used for interpretations are known, features can be recognized and ordered with respect to size. Orientation and spatial arrangement of various features can be helpful in recognition and description of geomorphic units representing structural control on landform evolution.

Geologic information that can be gleaned from remote sensing data includes two types which are closely interdependent: geomorphic, and structural. Structural features often mappable with remote sensing data include fracture faults. These features are mappable because of differential erosion along surfaces of heterogenous resistance, which is a geomorphic process of landform evolution. The ability to distinguish features on remote sensing imagery is strongly dependent upon the photo-enhancement of minor physical features, and the contrast between gray tones. Geomorphic units are distinguishable due to a combination of three indicators, including the physical distribution of an outcrop, the distribution of a soil derived from a specific rock type, and associated vegetative cover. Recognition of tone, texture, shape and/or pattern is essential to geomorphic unit mapping. Terrace deposits in Cedar Hill Field are readily distinguishable using the above geomorphic criteria.

Other geomorphic indicators include drainage patterns and associated topographic expression. Most of the drainage patterns in the Cedar Hill area are probably controlled by the structural grain, or fracture fabric. Comparison of the trends of Animas River meander reaches and related features of probable fluvial origin (canyons and arroyos), with the interpretations of surface fracture orientation and location, shows that these fluvial systems are strongly influenced by the fracture fabric in Cedar Hill Field. Observation of large topographic maps of Cedar Hill Field (including the Cedar Hill and adjacent 7.5 minute quadrangles) indicates that the major stream drainage in this area is the Animas River, which flows towards the southwest on a township scale. This flow direction is closely parallel to the northeast trend of one set of the primary systematic fracture sets determined in the oriented core and mapped using photogeologic techniques. More detailed scrutiny on a section by section basis reveals that major meander reaches of the Animas River in Cedar Hill Field trend roughly northeast-southwest, northwest-southeast, and north-south (listed in order of relative abundance). These meander inflection points are characterized by sharp changes over distances of less than half a mile. Furthermore, arroyos in Cedar Hill Field that terminate in the Animas River alluvial plain, such as Ditch and Cox Canyons, trend northeast-southwest and northwest-southeast respectively. Other less aerially significant arroyos trend northwest-southeast and east-west.

Structural and geomorphic linear data have been extracted from the aerial photographs and satellite imagery for Cedar Hill Field. A map summarizing: 1) prominent linear trends interpreted using all available photogeologic techniques and data, 2) geomorphic linear features interpreted using aerial photographs, and 3) major linear trends mapped using satellite imagery for Cedar Hill Field has been prepared (Figure 3).

Regional structural trends can be determined from the satellite images, but only the aerial photographs, because of a significant change in scale, can served as the basis for detailed photolinear maps.

Subsurface Confirmation of Photolinear Interpretations

Surface photolinear evaluations are important to the explorationist only if the information can be reliably extrapolated to the subsurface. The oriented core fracture analysis of coals and enclosing clastic rocks from the Hamilton # 3 well serves as this subsurface data control point. Observation of the photolinear trends mapped from the aerial photographs in the area immediately adjacent to the Hamilton # 3 (Sec. 30 and surrounding areas in Figure 3) shows that the surface fracture trends correlate closely with the core fracture trend data. Open fractures trending N. 70 to 80 E. in the core correspond to the N. 80 to 90 E. aerial photograph linear trend. Butt cleats trending N. 50 to 60 W. correspond to the prominent northwest-southeast photolinear trend. The face cleats, which trend N. 30 to 40 E., correspond to prominent mapped trends in the vicinity of the well. This northeast trend is also a prominent trend recognized using the entire photogeologic data set for the Cedar Hill area.

Summary of Photogeologic Interpretations

Several conclusions summarizing the photogeologic investigation in Cedar Hill Field are as follows:

1. Alluvial fault line scarps along the Animas River have trends of N. 40 E., N. 60 to 65 E., N. 45 to 55 W., and N. 10 W.

2. Structural, fracture and geomorphic linear data mapped using aerial photographs of various scales have prominent trends oriented N. 10 to 20 E., N. 30 to 60 E., N. 70 to 80 W., and N. 50 to 60 W. Less prominent trends are N. 30 to 40 W. and N. to N. 20 W.

3. Trends of linear features mapped using satellite imagery are oriented N. 50 to 60 W., N. 10 to 20 W., N. 20 to 30 E., N. 45 to 50 E., and east-west (N. 90 E., or N. 90 W.).

4. An evaluation of the aerial photographs for the area in the immediate vicinity of the Hamilton # 3 shows prominent photolinear trends oriented N. 50 to 60 W., N. 20 to 40 E., and N. 80 to 90 E. Face cleat orientations in the Hamilton # 3 oriented core correspond to the N. 20 to 40 E. trend mapped at the surface. Butt cleat orientations correspond to the N. 50 to 60 W. photolinear trend. The open fractures documented in the core trend N. 70 to 80 E., which correspond to the N. 80 to 90 E. trend documented using the photogeologic interpretations.

5. Although there is a significant scale change between the aerial photographs and the satellite imagery, similar trends are observed using both types of data. However, the satellite imagery cannot provide the detailed information concerning fracture orientation and location required by most exploration programs. This detailed information can be obtained by combining photogeologic interpretations of aerial photographs with field reconnaissance checks and oriented core data.

6. Not all of the mapped photolinear features are faults or fractures. However, the preliminary field reconnaissance data indicate that a significant number of the features are fractures, and that these fractures are consistent with regional tectonic trends. Also, the mapped features are not assumed to be the total data set, but are considered to be a representative sampling of the significant structural trends present in the Cedar Hill Field.

7. The major northeast-southwest trending fracture system mapped at Cedar Hill Field using photogeology, which corresponds to the face cleat trends documented by the core fracture analysis, is parallel to the trend of fold axes in Cedar Hill Field as shown on the basal Fruitland coal seam structure map (see Figure 4).

8. Areas with better cleat development or open fractures are not apparent from the photogeologic study alone.

Explanation of Curvature Analysis

Curvature analysis of the Cedar Hill Field[17] was initiated and funded by GRI to investigate relationships between flexures and high coal permeability. The boundaries of the study area are the same as those listed for the photogeologic study. Since "curvature analysis" is a rather uncommon technique that can be used to identify areas of higher permeability, a detailed discussion on the fundamentals of curvature analysis, and application to the Cedar Hill Field follows.

Peats and sediments composing coals and enclosing clastic rocks were not deposited in their present deformed, or folded shape (structure). It is reasonable to assume that such sediments were deposited in a horizontal to relatively horizontal manner. Subsequent compressional and/or extensional forces on very small to large scales dictate, with respect to the mechanical properties of the rocks, the shape of the fold. Locally, folds may be fitted with an elliptical, hyperbolic or a parabolic surface.

One of the geometrical attributes of folds is the location on the fold surface at which maximum flexure is present. These locations, when connected by drawing an imaginary set of lines on the fold, define the fold surface. In many cases, these fold axes are zones along which maximum compression or extension has occurred. Sedimentary rocks often fail in a brittle manner, and the zones of maximum flexure are therefore typically characterized in part by appreciable fracture development. Curvature analysis techniques identify and highlight the zones of maximum flexure, and hence, zones of greatest fracture development. In turn, it is these fold areas with appreciable fracture development that probably have the permeability. Since the coal permeability also has a directional competent, areas of maximum flexure, and their trends, must be documented using curvature analysis.

In many fractured reservoirs, the fracture network is not homogeneously distributed, but has, in addition, an overprint of tectonically induced fracturing related to the structural geometry.. Structurally complex areas occur where curvature is rapidly varying both in trend and intensity. This variability can result in spatially varying fluid and gas flow potential. A mappable subsurface parameter that can characterize this spatial variability as "curvature".

Objective of Curvature Analysis

In some fractured reservoirs, curvature anomalies correlate with production anomalies. Because coalbed methane production requires the presence of natural fractures, curvature was examined. The primary objectives of this research is to assess the applicability of the curvature attribute as a significant mappable subsurface parameter with respect to coalbed methane production. In other words, the usefulness of curvature analysis as applied to picking locations for potential new coalbed methane wells has been investigated.

Cedar Hill Field Curvature Analysis Procedures and Results

Curvature analysis of the upper and lower Fruitland coal seams (Figure 5) in the Cedar Hill Field was completed[16] using two structure maps for control (one being the structure on the base of the lower Fruitland coal, and the other being the structure on the base of the upper Fruitland coal). All available well control for the Cedar Hill Field was utilized in the construction of the structure maps (Figures 4 and 6) prior to onset of the curvature analysis.

Structural interpretation of fracture development utilizing curvature analysis requires the portrayal of three-dimensional surfaces at reservoir depths on maps. However, curvature maps are not to be confused with structural contour maps. For each curvature surface, there are three structural attributes that are mappable; the z-value, the dip vector, and the curvature. The z-value is the elevation of the key horizon of interest. The dip vector equates to geologic dip, which is the lateral rate of change of the z-value. The dip vector has both magnitude and direction with respect to the defined key horizon. Curvature is the lateral rate of change of the dip vector with respect to the mapped surface of interest. Since the dip vector has both magnitude and orientation, determination of the rate of the dip vector change may show that curvature is present when the orientation of the vector changes while the magnitude is invariant. This type of relationship often occurs on the downdip ends of the plunging folds, or along structural re-entrants.

Locations and trends of high mean curvature magnitude and large mean curvature change (Figures 7 and 8) correlate rather closely with surface fracture locations and trends mapped on the aerial photographs of Cedar Hill Field. By overlaying these maps, it is apparent that a slight lateral (downdip) displacement of maximum curvature areas with respect to overlying surface alignment locations due to the geometry of asymmetrical folds that usually trend northeast. The curvature analysis maps highlight the northeast-southwest, northwest-southeast, and east-west fracture orientations mapped using photogeologic techniques and topographic map interpretations, and were confirmed with the core fracture analysis.

Seventeen Fruitland coalbed methane wells in Cedar Hill Field were plotted with respect to location on the curvature maps, and 15 out of the 17 wells are present in areas characterized in part by mean curvature magnitude and/or large mean curvature change (Figures 7 and 8). This suggests that the majority of Fruitland coalbed methane wells in the Cedar Hill Field are in areas of high permeability. High permeability should be reflected in production history of the wells. To determine whether production trends are similar to high curvature (high permeability) trends, a field production map has been assembled.

CEDAR HILL FIELD PRODUCTION TRENDS

Publicly available gas (and water) production rates for several wells in Cedar Hill Field indicate that favorable reservoir properties are not simply related to coal continuity, thickness, or gas contents. Maps of month-by-month gas production rates were averaged on a year-to-year basis for 1985 and 1986 (Figures 9 and 10). A third map showing the maximum month-by-month gas production rate for 1982 through 1988 is also included to emphasize long-term Cedar Hill production trends (Figure 11). It should be noted that production data are not known for all wells in the Cedar Hill Field with respect to year and variations in the onset of production with respect to well.

With the above in mind, the following conclusions are considered: 1) high rates of gas production are present in an elongate east-west trending area occupied by Sections 32, 33, and 34, T32N, R10W, and NE Sec. 6, T31N, R10W. This area is characterized in part by high curvature magnitude and change (Figures 7 and 8). The oriented core fracture analysis for the Hamilton # 3 documented the presence of prominent open east-west trending fractures just to the northwest of Section 32, T32N, R10W. It is reasonable to interpret that this fracture system is present in the above described elongate east-west area. As indicted in the section on curvature, this particular area could have enhanced permeability, which would mean that greater rates of production are linked in part to higher permeability zones in Cedar Hill Field; 2) A significant northeast-southwest gas production trend is present for the eastern portion of the field on the 1985, 1986, and 1982-1988 maps (Figures 9-11). This trend is parallel to the face cleat orientation determined for the Hamilton # 3 cores. This can be interpreted to indicate that the face cleats in Cedar Hill Field do have an important, but not all inclusive, effect on location and orientation of enhanced permeability and greater gas production rates. In the western field boundary, a prominent northwest-southeast trend and more subtle east-west trend are apparent. The apparent 90° shift in permeability anisotropy direction, as compared with the eastern portion of the field, is perpendicular to the face cleat direction , and is being further investigated using advanced seismic technologies.

Seismic Application to Fracture Detection, Cedar Hill Field

At Cedar Hill Field, San Juan Basin, coalbed methane gas is produced from thick (4-5m) upper and lower coal seams of the Cretaceous Fruitland Formation. Wells of greatest productivity produce from zones of high fracture permeability in the coals. Multicomponent seismic surveys in the vicinity of the Hamilton # 3 well, on the west side of the field (Figure 11), indicate a polarization direction of N60°W. This open fracture direction corresponds to the butt cleat orientation in the coals from oriented cores. On the eastern side of the field, the open fracture direction appears to be orthogonal, paralleling the face cleats.

Open fractures are conduits for fluid flow. For fractures to remain open at depth in a reservoir, stress relief must occur. The presence of open fractures in the subsurface can be interpreted from multicomponent seismic data if the fracture zone is sufficiently large in areal and vertical extent so at to be detectable. Compressional (P) wave data are relatively insensitive to detecting vertical fracture zones, whereas shear (S) waves are especially suited to this goal.

Shear waves that propagate through a parallel, unidirectional, open fracture set will have components of displacement parallel and perpendicular to the fracture plane. The component of displacement parallel to the fracture direction will propagate faster than the perpendicular component, causing the polarized shear waves to split and be recorded at different times (Figure 12). The resulting separation of shear waves with different polarizations is known as shear-wave birefringence or shear-wave splitting[18].

Natural fracturing constitutes a major source of reservoir heterogeneity by inducing permeability anisotropy. This same permeability anisotropy induces velocity anisotropy between split shear-waves. By observing time differentials between the split shear-wave arrivals, velocity anisotropy can be directly related to permeability anisotropy. Permeability anisotropy in a fractured reservoir may be directly mapped from 3-D multicomponent seismic data.

Coal is an ideal medium to detect with seismic surveys because of its low density and acoustic velocity (Figure 13). Because of their strong reflectivity, the coals can be confidently imaged and mapped at Cedar Hill.

Multicomponent seismic surveys in Cedar Hill field indicate tectonic and stratigraphic controls on fracture permeability of the coalbed reservoir(s) (Figure 14). 3-D seismic data show that the upper and lower coal seams are offset by faults. These faults are basement controlled and have exhibited recurrent movement. The faults were active during coal deposition in the Late Cretaceous and have exhibited more recent movement to create folding and fracturing of the coals In proximity to the faults. Fault movement has created folding which has increased fracture permeability in the coals. These faults also controlled stratigraphic change during coal formation.

Stratigraphic features including channels were controlled by deep seated fault movements during time of deposition. Differential compaction may also play a role in controlling fracture permeability in the coals (Figure 14).

These structural, stratigraphic and fracture trends cannot be mapped from well control alone. Imaging of fracture trends and enhanced permeability zonation within the coals by multicomponent seismic surveys could substantially improve the economics of coalbed methane development. The strength and rigidity of the rock mass controls the success of new cavity type completions. The potential to image fractures, rigidity and lithology from multicomponent seismic surveys closely aligns new seismic and completion technologies and together they could significantly impact future coalbed methane development[19].

Influence of Ash Content on Cleat Development

Permeability in coalbed methane reservoirs is positively influenced by the degree of cleat development. For this reason, cores from the Mesa Hamilton # 3 were examined to document coal compositional controls on cleat development. Core 1, which contains mostly shale and bone coal with minor amounts of sandstone, contains abundant face and butt cleats in the coal intervals interbedded with shales. Cleat lengths averaging 4.0 cm (1.6 inches) and widths averaging 0.03 mm (0.0012 inches) are the most common, and the cleat frequency ranges from 1 cleat per cm (0.4 inches) to 16 cleats per cm (0.4 inches). Core 2, which contains thicker, lower ash coals, displays a better developed cleat system as compared to core 1. Cleat lengths up to 9 cm (3.6 inches) and widths from 0.01 mm (0.0004 inches) to 0.20 cm (0.008 inches) are present, and cleat spacing varies from 1 to 8 cleats per cm (0.4 inches). Core 3, which contains the thickest, lowest ash content coals, has the most well-developed cleat system of the three cores analyzed. Cleat lengths vary from 0.1 mm (0.004 inches) to 18 cm (7.2 inches), and widths vary from 0.02 mm (0.0008 inches) to 0.38 mm (0.0152 inches). Cleat frequencies up to 12 per cm (0.4 inches) are present in many intervals.

Scrutiny of polish blocks (polished slabbed coal core) of Hamilton # 3 coals shows that cleat frequency is inversely proportional to mineral matter content (roughly numerically correlative with ash contents as determined via proximate analysis), since the Hamilton # 3 coals have less than 2% moisture and 1.5% sulfur, and northern San Juan Basin Fruitland coals typically have less than 5% inertinite (extremely carbon-rich noncombustible coal macerals). In other words, layers with less mineral matter (lower density) have higher cleat frequencies (Figure 15). Additionally, face cleat development is compositionally controlled: face cleats in layers with lower mineral matter contents usually terminate at contacts with layers with higher mineral matter content.

Layers with higher mineral matter contents have higher densities as shown by detailed comparison of densities derived from computerized axial tomography (CAT) scans of whole core # 3 from the Hamilton # 3 (Figure 16), and the respective coal lithotypes. The CAT scan density log shows similar signatures as compared to the geophysical density (Figure 17) log run for the Hamilton # 3 core coal with progressive lesser mineral matter content have higher cleat frequencies, it can then be reasonably inferred that intraseam zones of lower density (as determined from interpretation of the geophysical density log) have better cleat development, and in turn, higher permeability. It is recommended that a density of less than or equal to 1.75 gm/cc as interpreted from geophysical density logs be used as the upper limit for mapping areas with better "quality" coal that may in turn have better permeability development.

Therefore, maps of coal quality with respect to ash content as interpreted from geophysical density logs can also potentially be used in conjunction with techniques described in this paper to infer areas of higher permeability.

DISCUSSION

All coalbed methane operators seek areas where sufficient permeability is available for commercial flow rates. Also it is important to determine permeability direction so gas recovery may be maximized with a minimum number of wells. This paper presents the combined use of photogeology, curvature analysis, seismic data and coal petrography to accomplish these goals. Fracture detection techniques are complex, interpretative tools that when mindlessly used or reviewed by the inexperienced can result in erroneous and occasionally desperate conclusions. For example, due to the relatively small amount of structural relief in the Cedar Hill Field, Close[2] flippantly concluded that "the degree of fold flexural magnitude and flexural change requisite to brittle deformation and ensuing fracture genesis in rocks is not present in the Cedar Hill Field". The confusion here is the fundamental misconception that larger structures correlate to more fracturing. In reality, the Cedar Hill Field has met the requirements of flexure related fracture due to it structural complexity where curvature varies rapidly both in trend and intensity. Recent seismic surveys found the Cedar Hill to be intensely faulted with small scale (less than 20') normal faults bounding low amplitude synclines and anticlines.

Utilization of fracture detection tools will likely remain limited and therefore inadequately developed until their results become repeatable, quantifiable and diagnostic. Until that time, multiple and overlapping techniques are recommended to increase the probability of locating open fractures in the subsurface.

Another rate controlling factor not necessarily associated with permeability is diffusion. First gas must diffuse from the matrix surrounding the fractures, then gas flows from the fractures to the wellbore. In this two-step process, whichever step is the slowest will control the overall gas flow rate. In previous work[20], it was established that gas flow rate is bound by diffusion where permeability exceeds 0.1 md. Further, sensitivity modeling[21], using the COMETPC coalbed methane reservoir simulators, graphically demonstrates the importance of diffusion on early time production (Figure 18). Higher initial gas production, hence shorter pay out time, is a direct influence of gas diffusion from the coal matrix. Gas desorption work performed[22] on the Fruitland coal at Cedar Hill Field shows extremely rapid diffusion time. Therefore, commercial flow rates encountered at Cedar Hill Field may be attributed to both permeability associated with high deformation zones, and favorable diffusion properties. The origin of diffusion variability may be related to gas storage sites in coal fabric.

CONCLUSIONS

This paper described techniques to predict both the orientation and location of areas with higher coalbed methane reservoir permeability prior to drilling. The methods that can be used are surface fracture mapping based upon photogeologic interpretations of fracture orientations and locations, and curvature analysis to identify trends and areas of maximum fold flexure and greater fracture development at reservoir depths. Seismic and soil geochemistry are promising exploration tools which to this point have been under-utilized and as such their value remains unknown.

The results from the photogeologic investigation show that the orientations of fractures in Fruitland Formation reservoirs and enclosing rocks at Cedar Hill are northeast-southwest, northwest-southeast, north-south, and east-west. These interpretations are confirmed by oriented core fracture analysis of the Mesa Limited Partnership Hamilton # 3 well. However, the Cedar Hill photogeology has limited use for determining areas with better permeability, but may be useful elsewhere.

The results of the curvature analysis of the upper and lower Fruitland coal seams corroborate the northeast-southwest, northwest-southeast and east-west photogeologic interpretations of reservoir fracture trends and locations. The curvature maps also highlight less obvious east-west fracture trends and locations with maximum flexure and higher inferred permeability. The Cedar Hill curvature analysis does locate higher permeability trends.

Multi-component, 3D seismic have confirmed that surface fracture orientation parallel and overly subsurface faults. Fractures and stress relief associated with the faulting are thought to be the dominant permeability system in Cedar Hill Field. The presence of faults, which previously had been a matter of debate, also are closely aligned with the location and orientation of areas of maximum curvature.

Cleat frequency, length and aperture width is inversely proportional to ash content. Coals with progressively lesser ash content have better cleat development. Therefore, coal intraseam zones of lower density, and hence lesser ash content, as determined from openhole geophysical density logs, have better cleat development and higher permeability.

The combined techniques of photogeology, curvature analysis, seismic and coal petrography have succeeded in defining areas of higher permeability in Cedar Hill Field. More work applying techniques described in this paper to other coalbed methane fields is needed to statistically verify our results.

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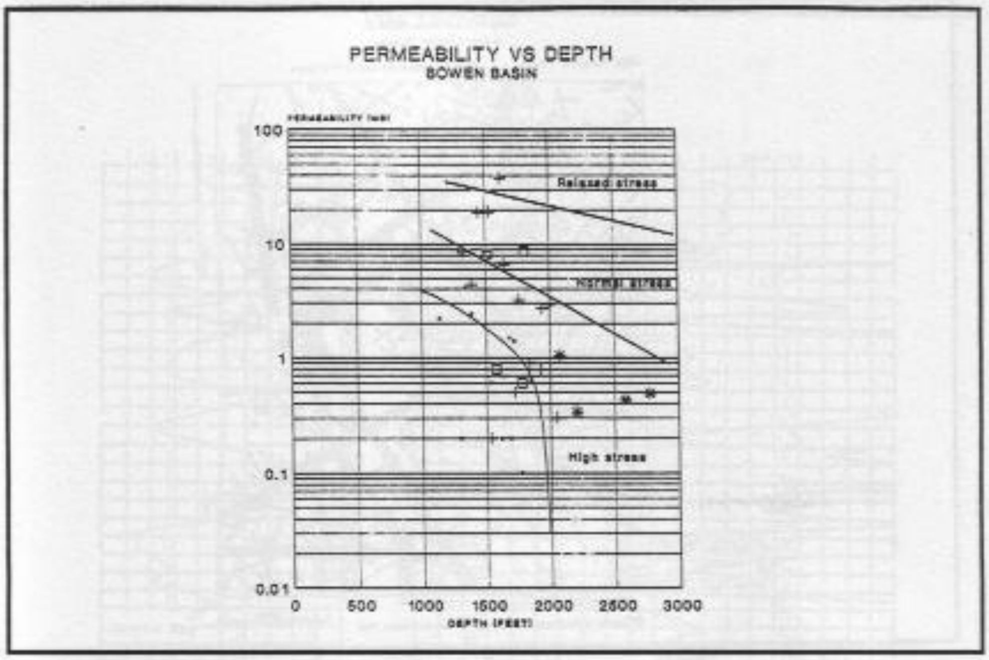

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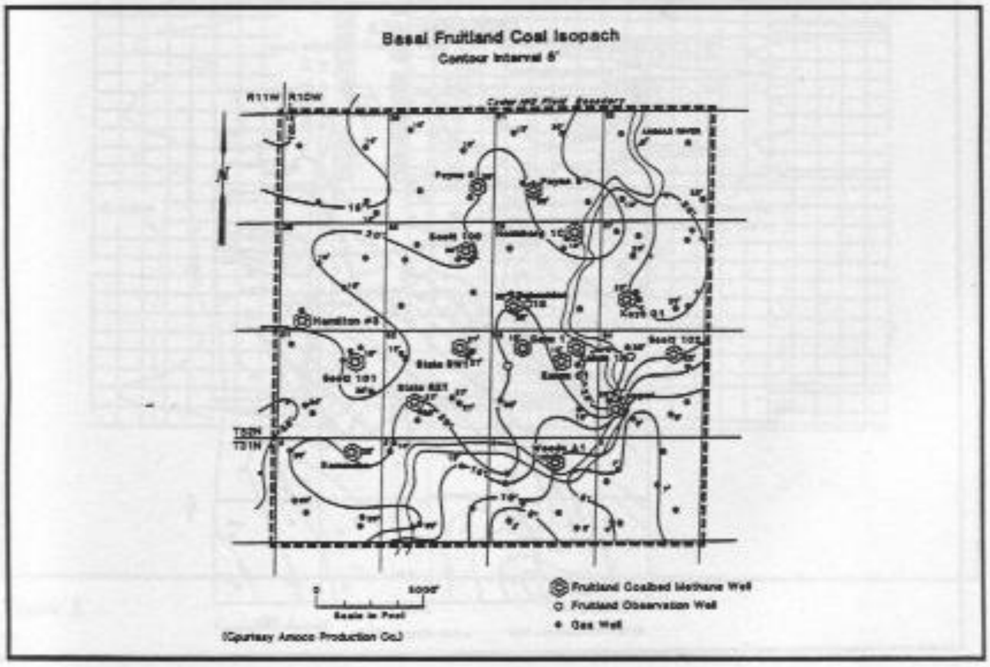

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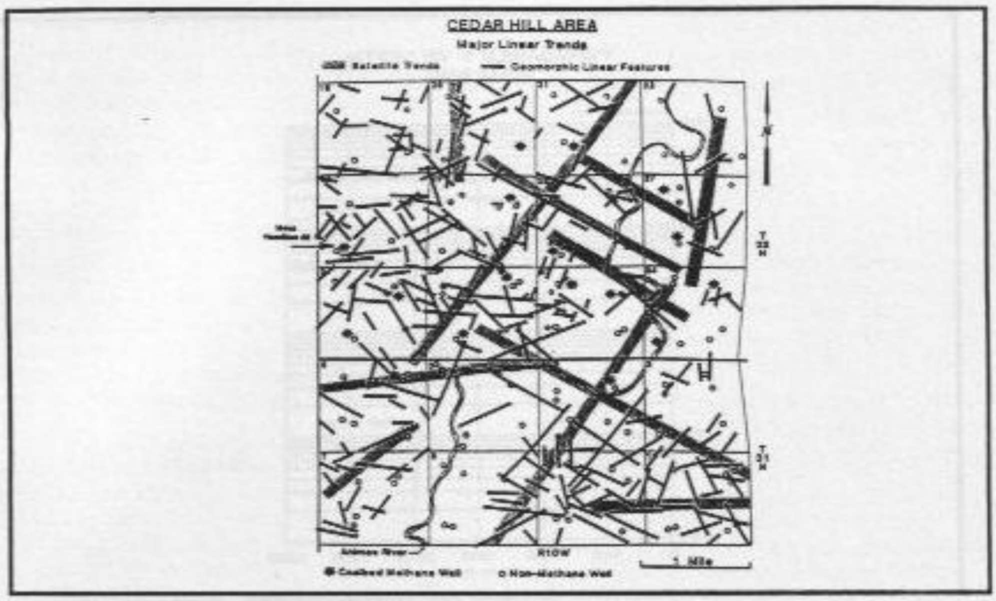

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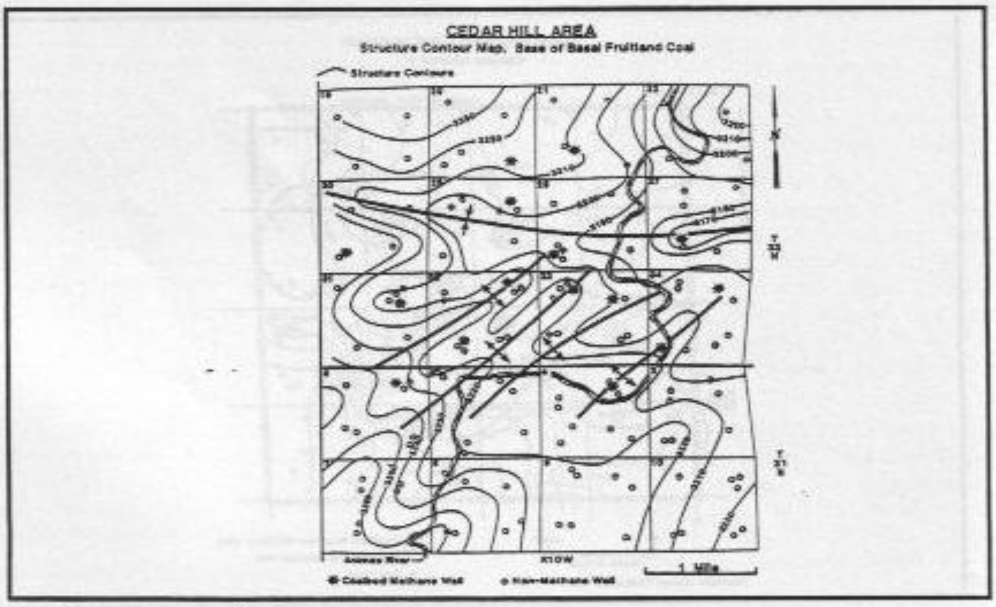

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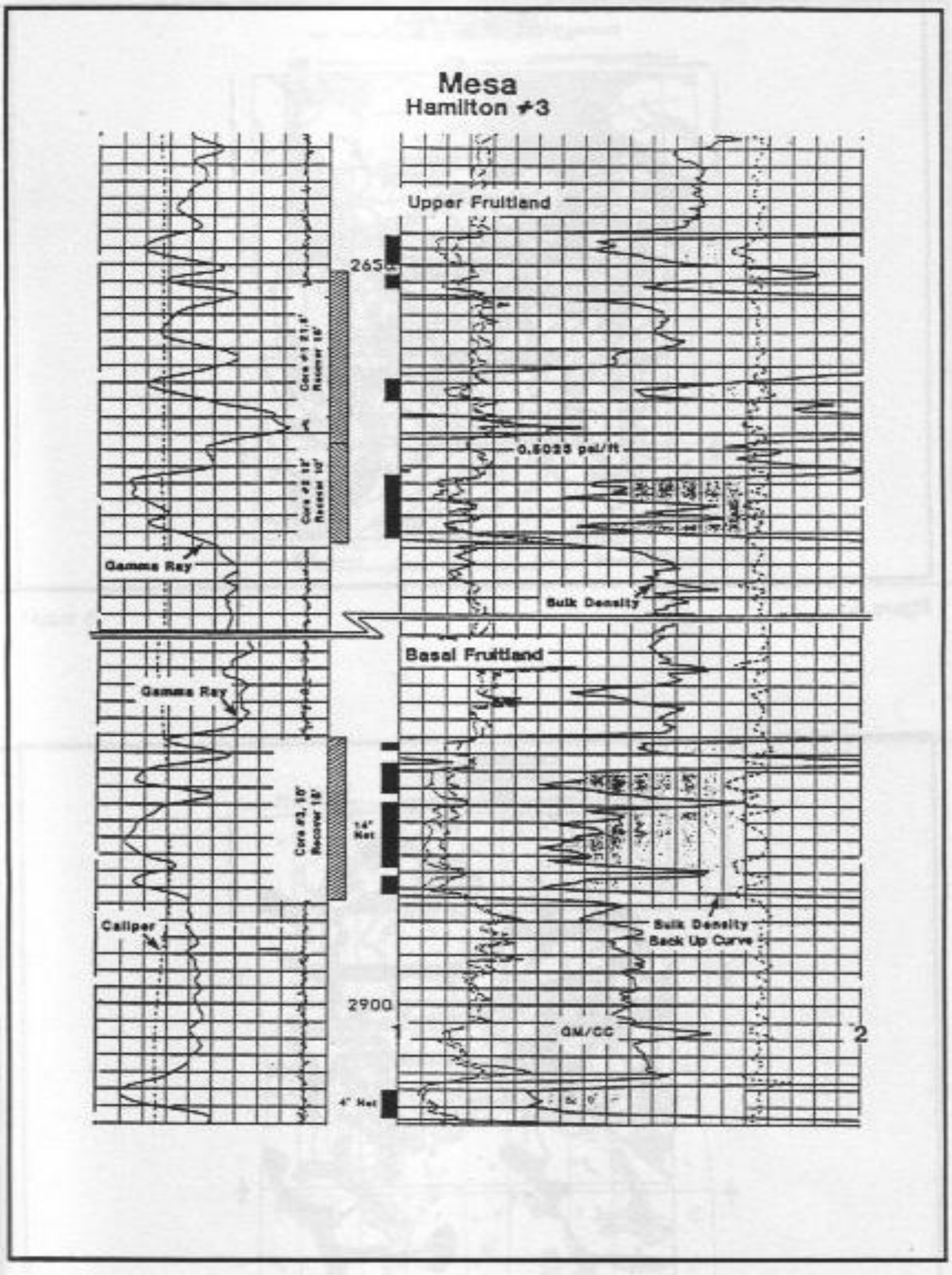
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Recover 18'
Core #2 12'
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0.5033 psi/ft
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Bulk Density
Basal Fruitland
Gamma Ray
Core #3, 18'
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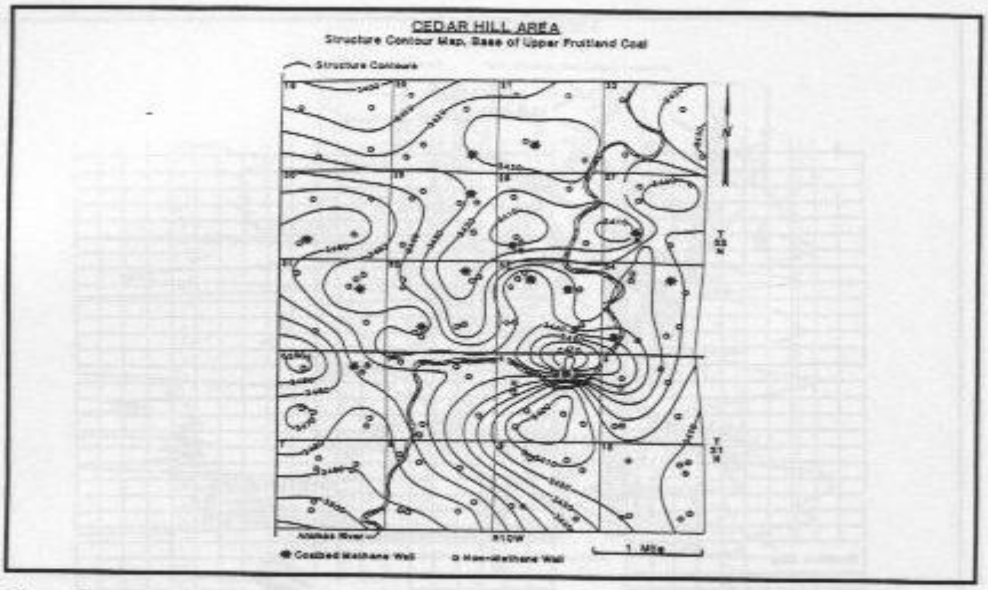
Caliper
Bulk Density
Back Up Curve
2900
1
GM/CC
2
4' Net

Figure 5.



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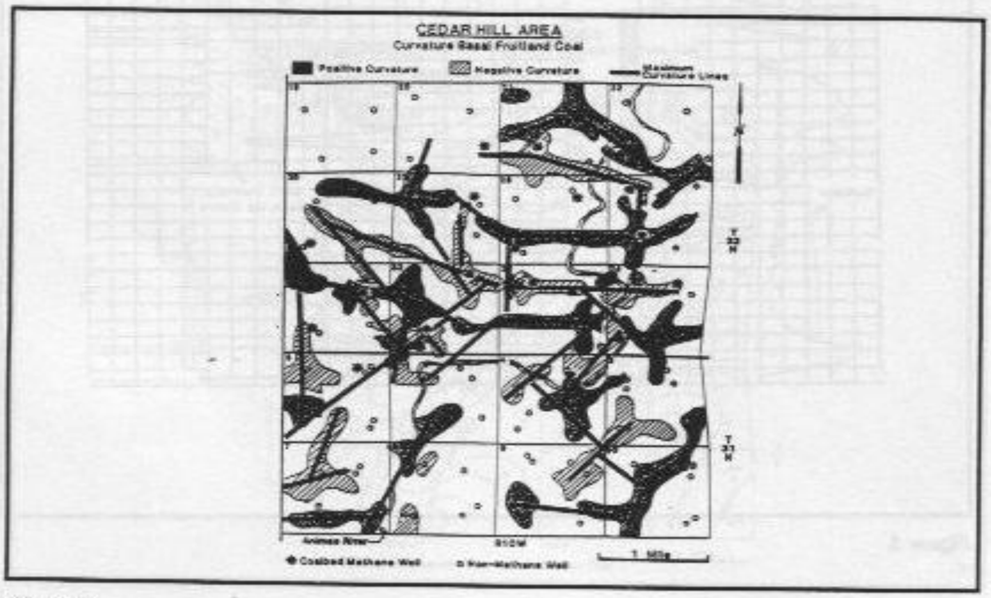

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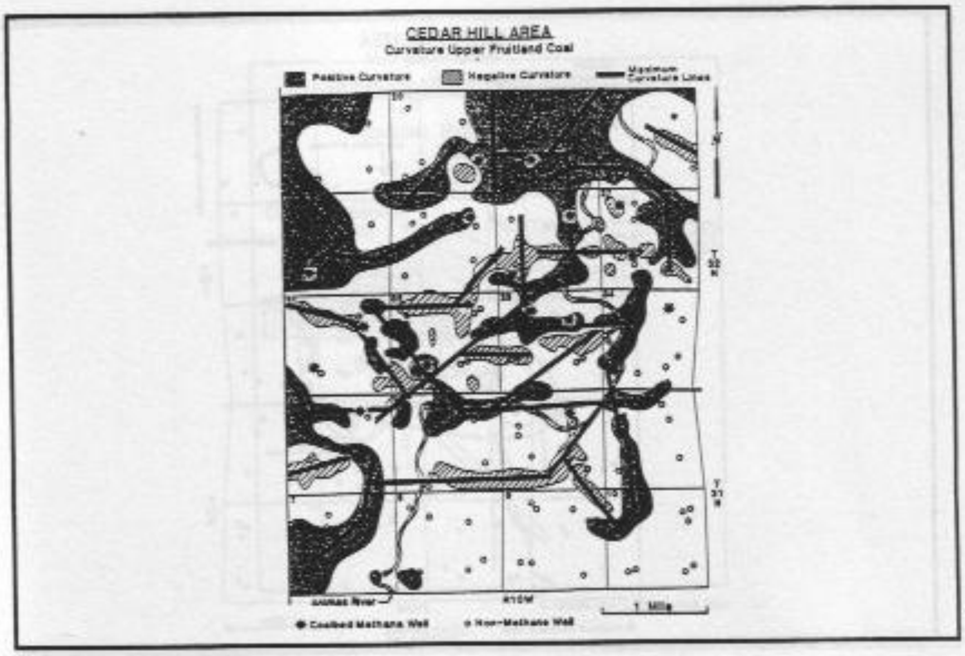

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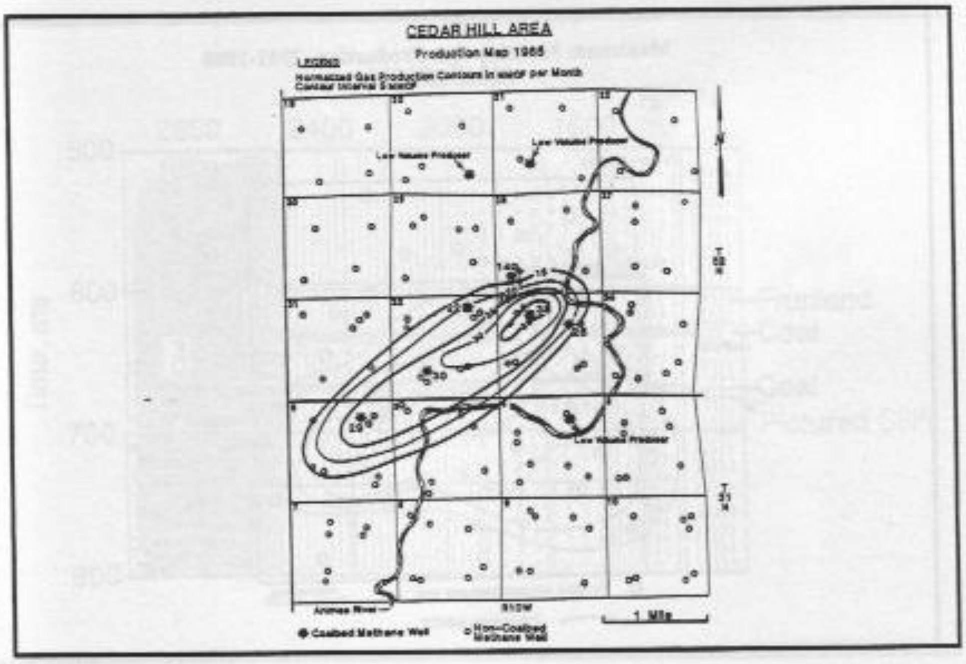

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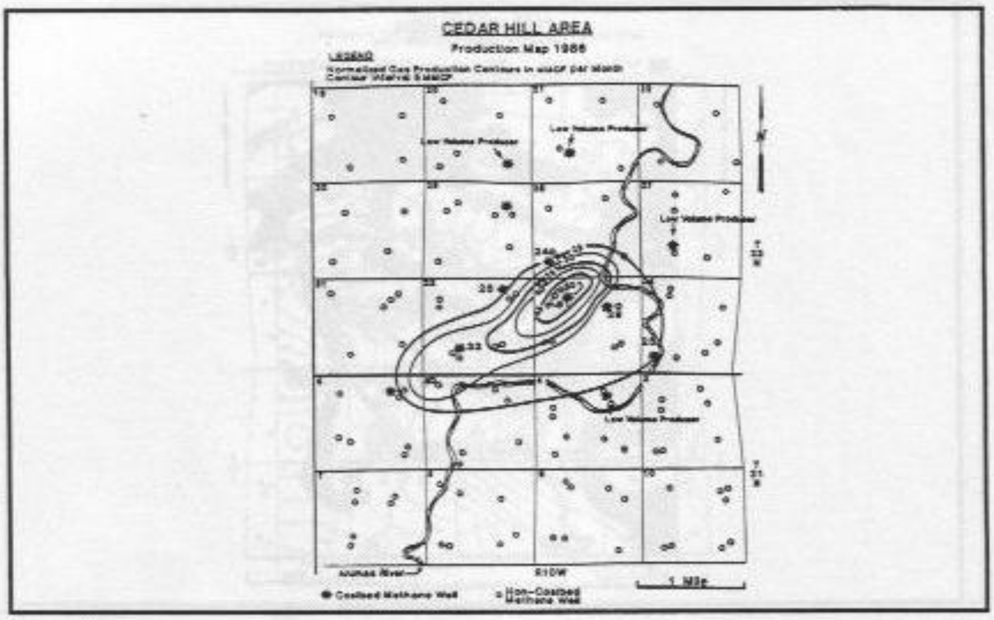

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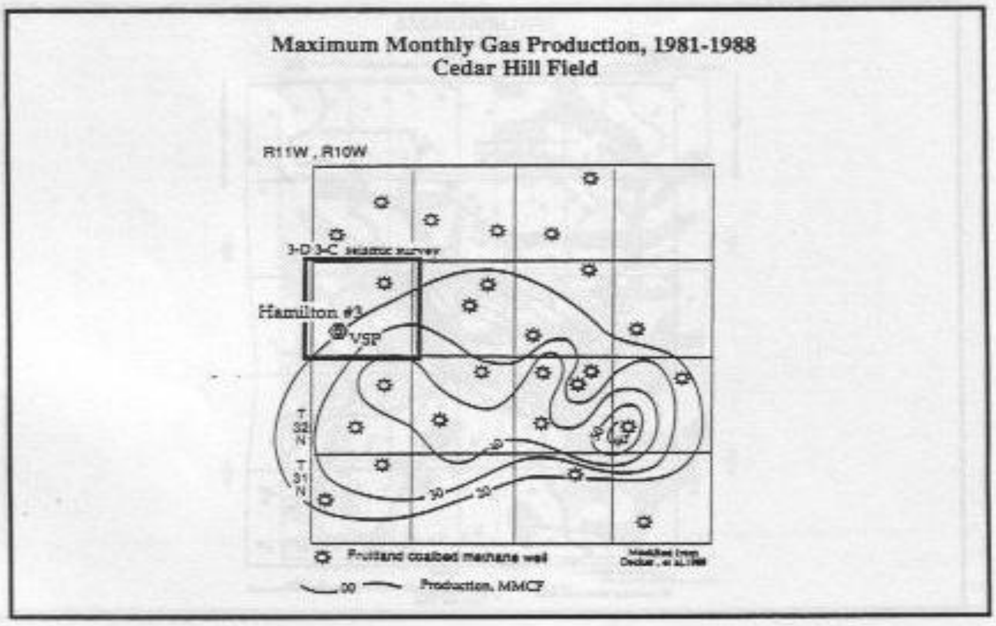

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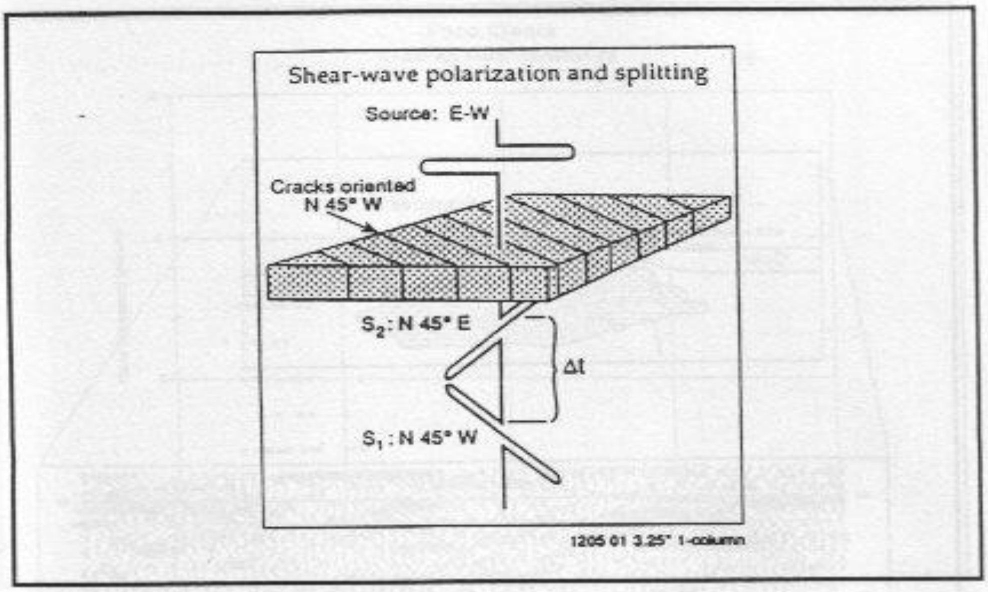

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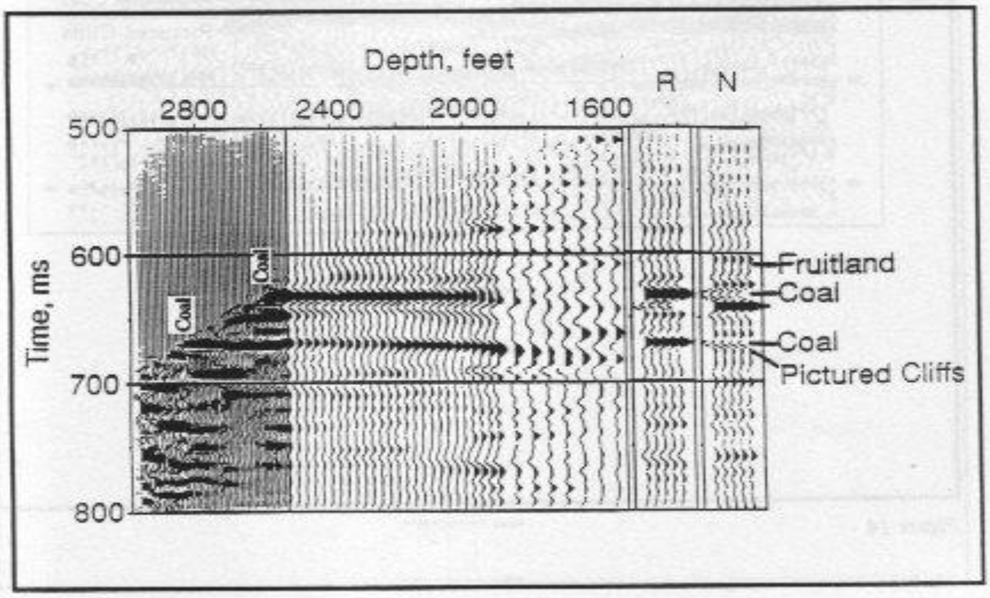

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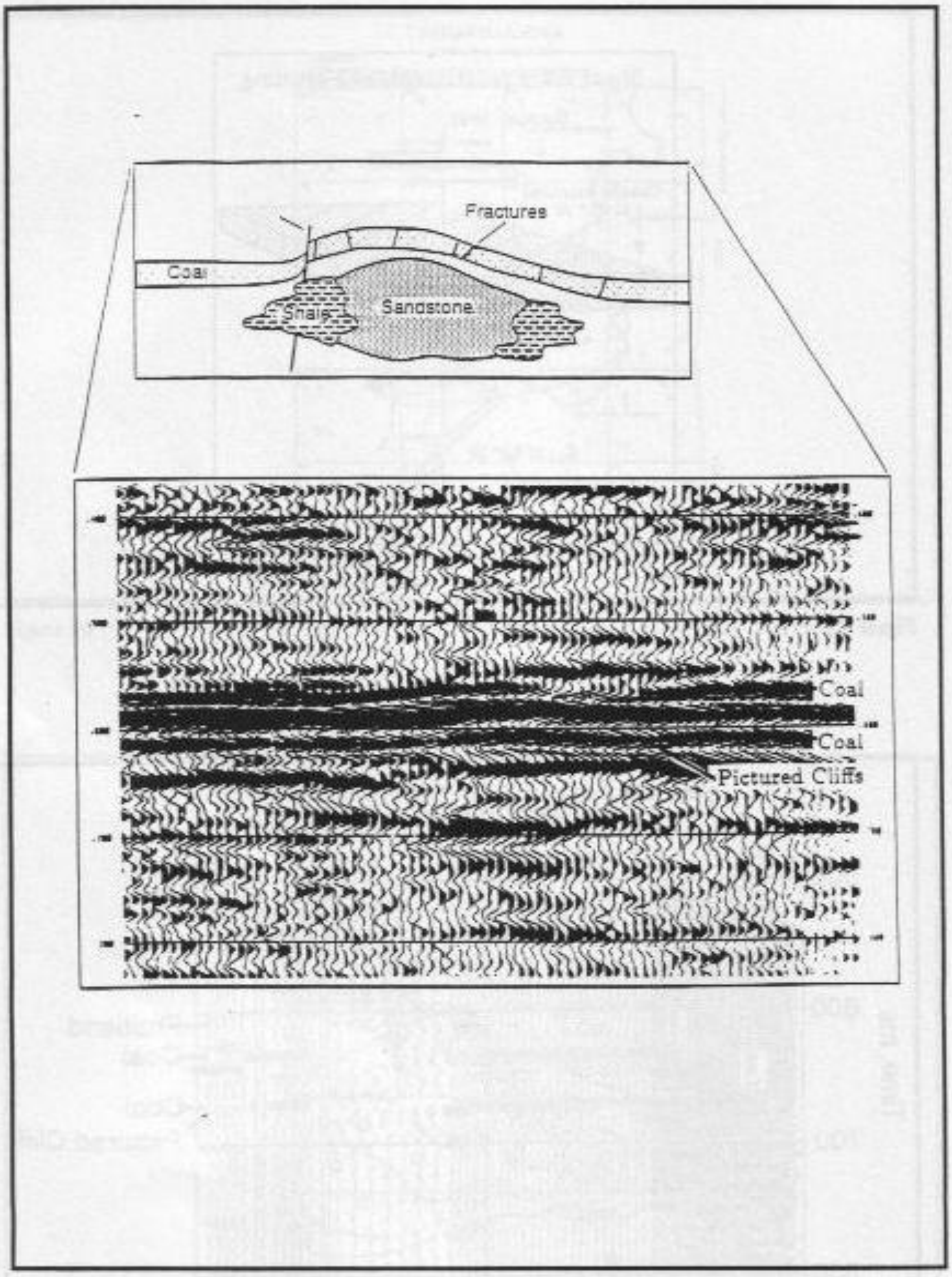

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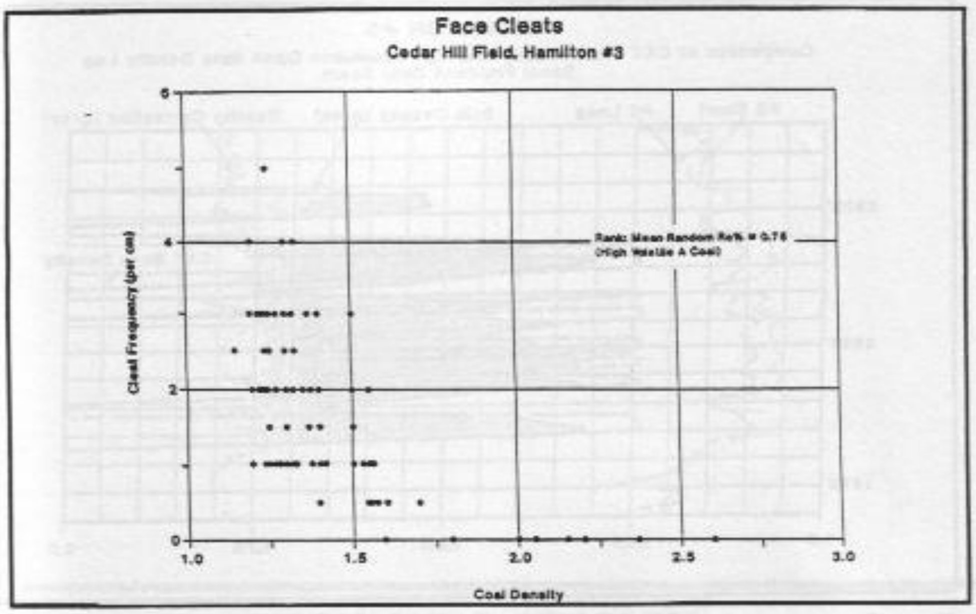

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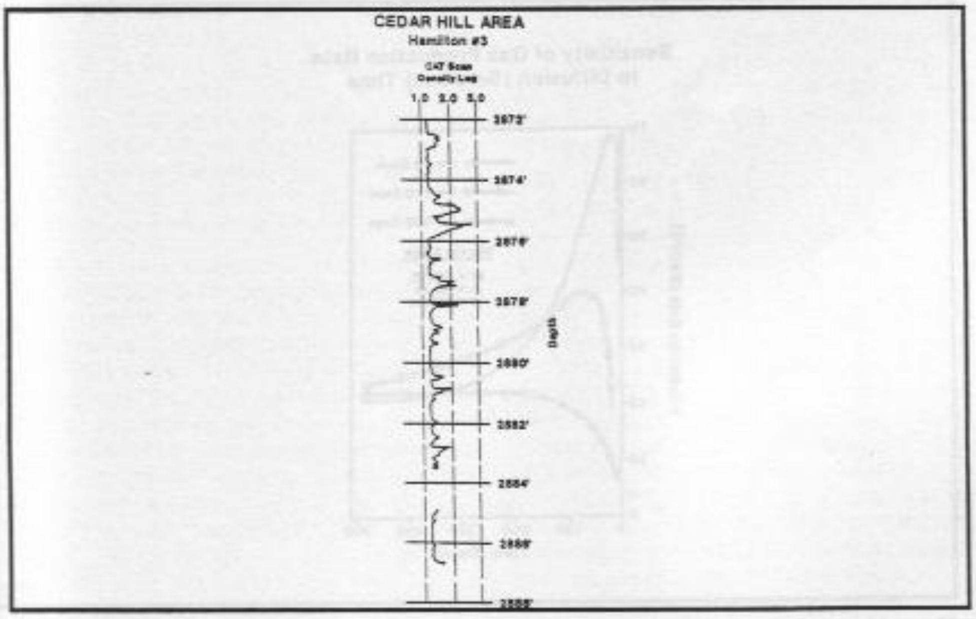

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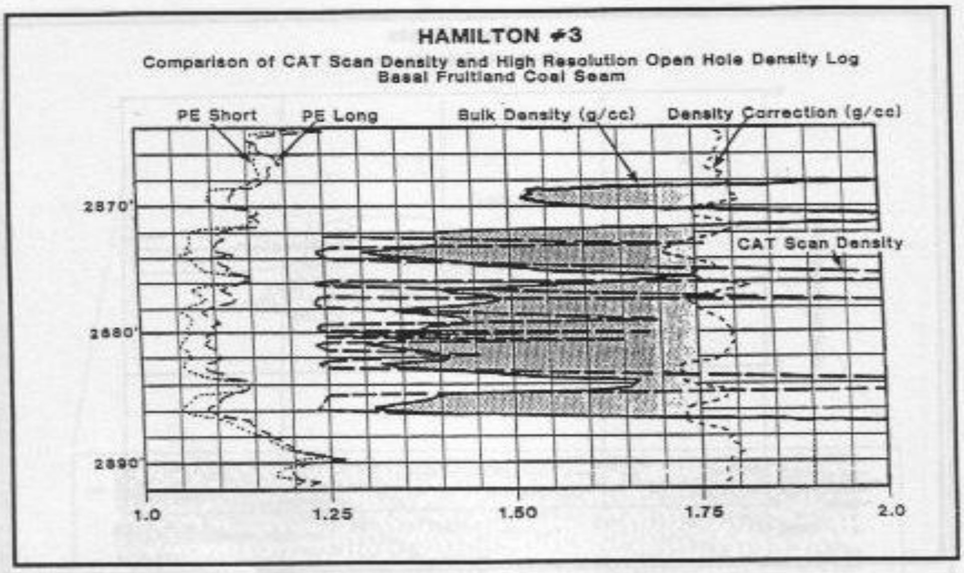

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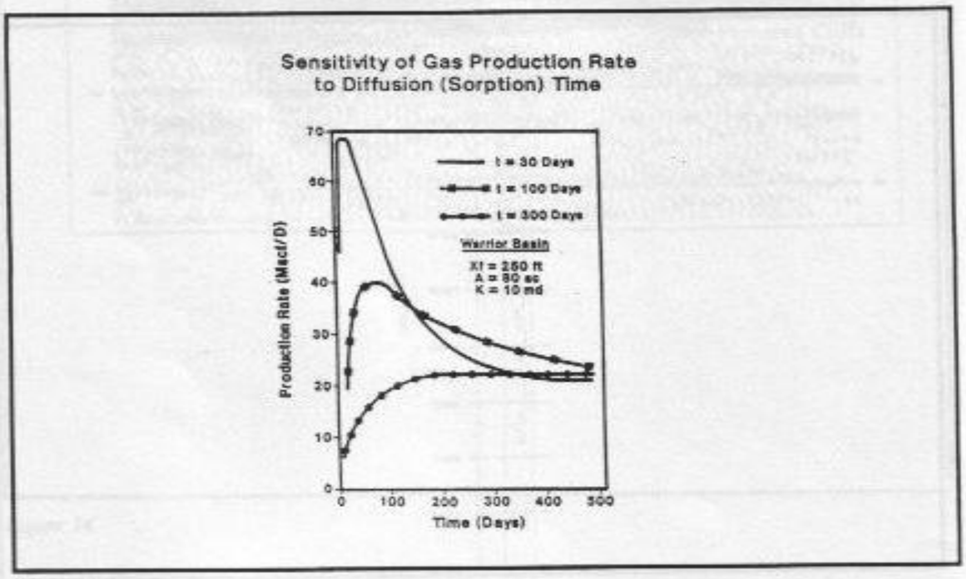

Figure 18.