Geologic Mapping and Subsurface Well Log Correlations of the Late Cretaceous Fruitland Formation coal beds and carbonaceous shales – the Stratigraphic Mapping Component of the 3M Project, San Juan Basin, La Plata County, Colorado

WRAY, LAURA L., Colorado Geological Survey, Denver, Colorado

Geologic mapping done by Randall K. Streufert, Summit Geology and Consulting, LLC

ABSTRACT

The Late Cretaceous Fruitland Formation of the San Juan Basin of Colorado and New Mexico contains more than 200 billion tons of coal from which over 2 trillion cubic feet of methane and 246 million barrels of water have been produced. Historically, this production has raised numerous environmental questions including its contributions to coal mine explosions, coal fires, methane and hydrogen sulfide seeps along the outcrops, and methane contamination of domestic water wells.

In addition to well-documented historical accounts of surface methane leaks, there are recent data on the Southern Ute Indian Tribe (SUIT) reservation that appear to link increased methane seeps at the outcrop to the dewatering of coalbed methane (CBM) wells drilled less than one mile downdip. CBM wells have not been drilled that close to the outcrop north of the SUIT reservation, thereby providing an opportunity to compare baseline data related to coal continuity and possible methane migration pathways with data on the reservation.

In response to the task of collecting these data, the Colorado Oil and Gas Conservation Commission (COGCC) secured Severance Tax Funding for a series of scientific studies known collectively as the 3M Project (**M**apping, **M**odeling, and **M**onitoring). The Colorado Geological Survey (CGS) was asked to provide the basic mapping components in the form of a geological map of the Fruitland Formation coals as well as subsurface well log cross sections from the outcrop to the Colorado-New Mexico border.

A 1:16,000 geologic map was produced along the Fruitland Formation and Pictured Cliffs Sandstone outcrop. It shows the surface extent of the various Fruitland coal beds from the north end of the Southern Ute Indian Reservation at Ridges Basin to the Archuleta County line, a distance of approximately 26 miles. The stratigraphic relationship and lateral continuity of these coalbeds is demonstrated, as are areas of major seeps, distressed vegetation, clinker, springs, coal mines, and high soil gas readings.

To further understand the relationships between surface seeps and downdip production, a correlation framework tying the coals and coal-rich intervals of the surface outcrop measured sections to the subsurface well logs has been created using A2D Interpretive Imaging's smartSECTION TM raster-image software. This network of cross sections, illustrating the degree of lateral and vertical continuity of the individual coal intervals, provides the basic underpinnings for determining the stratigraphy of Fruitland Formation coals and carbonaceous shales and their relationships to known seeps and contamination occurring along the northern boundary of the San Juan Basin.

ACKNOWLEDGEMENTS

A geologic subcommittee of the 3M Technical Peer Review Team (TPRT) was established in early 1999 to guide the mapping and construction of subsurface well log cross sections. I was the recipient of the collective expertise that was represented at these meetings held over the course of 15 months. I wish to express my sincere thanks for the magnitude and variety of assistance received: to Bill Pelzmann, BP-Amoco (and to BP-Amoco itself) for his geologic advice, his historical perspective on coalbed methane development in the San Juan Basin, his review of the stratigraphic cross sections and of this report, the gross thickness isopach map of the Pictured Cliffs Sandstone Tongue provided for this report, and the invaluable contribution of correlated cross sections within three miles of the Fruitland outcrop that were enthusiastically endorsed by the 3M Geologic Subcommittee as a stratigraphically manageable way of handling complex coal correlations; to Harry TerBest, Huber Corporation, for his technical coaching, his well-honed observations and theories, his review of the stratigraphic cross sections, and his historical knowledge of coalbed methane development in the San Juan Basin; to Debbie Baldwin, Colorado Oil and Gas Conservation Commission (COGCC), for providing global understanding of this project and for introducing me to a host of technical experts; to Dick Baughman, Southern Ute Indian Tribe (SUIT), for guiding me in the recognition of many surface seep observations and mitigation techniques on the Southern Ute Indian Tribe (SUIT) Reservation and for reviewing this report; to Dave Swanson and Matt Janowiak, Bureau of Land Management (BLM) Durango office, for graciously furnishing seep, soil gas, and distressed vegetation data which was added to Randall Streufert's geologic maps; to Rusty Riese, VASTAR, for providing a selected digital log and API database for constructing the subsurface cross sections and for providing a thorough review of this report; to TomAnn Casey, Enervest, for generously donating previously unavailable log data that was incorporated in the cross sections; to Bob Kirkham, Colorado Geological Survey (CGS), for overseeing the field mapping conducted by Randall Streufert; to Jim Thomson, Applied Hydrology, for his hydrology tutorials and ability to understand the geologic complexities of the Fruitland coals; to Steven Condon, U.S. Geological Survey (USGS), Bob Kirkham and Christopher Carroll, CGS, for reviewing the geologic maps; to John French, Linda Santiago and Peter Bucknam, A2D Technologies, for providing prompt and thorough instruction about the A2D smartSECTION TM software; to the other original 3M Geologic Subcommittee members (Glenn Raby, US Forest Service; Dave Cox, Questa Engineering; Bruce Kelso, Redstone Resources, Inc., and Barbara Wickman, Southern Ute Indian Tribe); to Jim Milne, Colorado Oil and Gas Conservation Commission for providing the coordinates for the Fruitland Formation/Pictured Cliffs Sandstone outcrop on the basemap; and finally, a special thanks to Matt Morgan, Colorado Geological Survey, for compiling and reformatting all these data for the final report.

TABLE OF CONTENTS

Figure 1 Northern San Juan Basin Base Map with the Fruitland Formation and Pictured Cliffs Sandstone outcrop and the locations of all stratigraphic cross sections (a larger, identical version of this map appears in Appendix B)

Figure 2 Northern San Juan Basin Geologic Column

Figure 3 Upper Cretaceous Time-Stratigraphic Chart, San Juan Basin

Figure 4 Map of joint, cleat and shear fracture orientations, San Juan Basin, Colorado and New Mexico

Figure 5 Schematic cross section of a coalbed methane reservoir

Figure 6 Schematic cross section showing the designation of coal intervals

Figure 7 Accumulated precipitation deficit with major seep-related events superimposed (from Colorado Water Resources Research Institute, Water Balance Series No. 9, 1999)

Appendix A Geologic maps along the Fruitland Formation/Pictured Cliffs Sandstone outcrop from Ridges Basin north of the Southern Ute Indian Tribe Reservation to the Archuleta County line.

Appendix B Northern San Juan Basin Map with the Fruitland Formation and Pictured Cliffs Sandstone outcrop and the locations of all stratigraphic cross sections

Appendix C Subsurface stratigraphic cross sections of the Fruitland Formation

MS 1-25 – cross sections of all 25 outcrop measured sections
EW – 1 - east-west cross section south of the northern-most outcrop
N – 0.5 to N-6 - southwest to northeast cross sections parallel to depositional strike
E-1 to E-7 – northwest to southeast cross sections perpendicular to depositional strike

Appendix D Gross sand isopach map of the Pictured Cliffs Sandstone Tongue

Appendix E Three southwest-northeast cross sections, each hung on a different datum, to illustrate the resultant stratigraphic variations

INTRODUCTION

The Late Cretaceous Fruitland Formation of the San Juan Basin of southwestern Colorado and northwestern New Mexico contains in excess of 200 billion tons of coal in which as much as 50 trillion cubic feet of gas is estimated to be stored. In the first 100 years of coal mining, from the late nineteenth to the late-twentieth centuries, the methane gas contained within the Fruitland Formation coals was considered a dangerous nuisance. Coal mine explosions, coal fires along the outcrop, methane and hydrogen sulfide seeps along the outcrop, and contamination of domestic water wells were all caused primarily by methane, an odorless and highly explosive gas that is a natural by-product of many coals.

La Plata County, home to Fruitland Formation coal mines and coalbed methane wells, has been plagued historically with methane problems. The above-mentioned environmental and safety factors have been well documented as frequent occurrences for over one hundred years. However, there are recent data collected on the Southern Ute Indian Tribe (SUIT) Reservation to suggest that increased methane seeps at the outcrop may have been accelerated by dewatering of downbasin coalbed methane wells.

In order to collect and document baseline data north of the SUIT line, the Colorado Oil and Gas Conservation Commission (COGCC) secured Severance Tax Funding to support a variety of scientific studies known collectively as the 3M Project. The '3M' designation stands for **M**apping, **M**odeling, and **M**onitoring. The Colorado Geological Survey (CGS) was subcontracted by the COGCC to provide the mapping components of this study which was to include both outcrop mapping and subsurface correlations of the Fruitland Formation.

The 3M Project as a whole was designed to collect baseline data for evaluating the surface outcrop and subsurface reservoir changes in groundwater levels and flow, methane seepage at the outcrop, and changes in aerial extent of distressed and/or dying vegetation on the outcrop. The concepts for these studies were modeled and enhanced from similar studies done on the SUIT Reservation. By examining the relationships on the SUIT Reservation between coalbed methane drilling within one-half mile of the outcrop and pronounced changes in observed outcrop seep conditions, the COGCC designed the integrated mapping, modeling and monitoring studies to collect baseline data to guide the coalbed methane development north of the Reservation.

This report documents both the distribution of mappable Cretaceous Fruitland Formation coals along the northwestern and northern outcrop of the San Juan Basin monocline and provides a grid of correlated subsurface cross sections in La Plata County, Colorado. Figure 1 delineates the 26 miles of outcrop mapped along the San Juan Basin monocline northeast from Ridges Basin north of the SUIT Reservation to the Archuleta County line. Also shown are the locations of the surface and subsurface cross sections that demonstrate the Fruitland Formation coal correlations.

PREVIOUS WORK

Extensive research has been conducted relating to the Late Cretaceous Fruitland Formation, underlying Pictured Cliffs Sandstone, and overlying Kirtland Formations in the San Juan Basin. Figure 2 presents a simplified geologic column for the northern San Juan Basin with a key to those formations that produce natural gas, oil, a combination of gas and oil, or water. Comprehensive structural and stratigraphic articles have been published that explain the complicated origins of the coalbed methane in the Fruitland Formation coals: (Fassett and Hinds, 1971; Kelso and others, 1980; Fassett (ed.), 1988; Kelso and others, 1988; Ayers and others, 1990; Ayers and others, 1991; Schwochow and others, 1991; Ayers and others, 1994; Fassett, (in press). Isopach maps of the Fruitland Formation coals and coal intervals as well as of the Fruitland and Pictured Cliff sandstones are well-illustrated in articles by Fassett and Hinds, 1971; Fassett (ed.), 1988; Aubrey, 1991; AMOCO, 1994; Ayers and others, 1994 and Fassett, (in press). Fruitland Formation stratigraphy is highlighted in articles by Zapp, 1949; Fassett and Hinds, 1971; Fassett (ed.), 1988; Molenaaer and Baird, 1989; Ayers and others, 1991; AMOCO, 1994; Ayers and others, 1994; Bureau of Land Management, 1999; and Fassett (in press).

Figure 3 depicts the time-stratigraphic chart for the San Juan Basin during Late Cretaceous time. The transgressive/regressive patterns for both the Fruitland Formation and the Pictured Cliffs Sandstone appear in bold font on figure 3. A number of specific structural and cleat orientation articles are contained in Tremain and Whitehead, 1991; Tremain and others, 1991; Ayers and others, 1994; and Whitehead, 1997. A summary of structural domains incorporating cleat, joint, shear fracture, and trends of igneous dikes are compiled in Figure 4.

Beyond the scope of this study but well worth considering are the numerous references to Fruitland Formation coal and coalbed methane resources (Barnes, 1954; Kelso and others, 1980; Ayers and Kaiser, 1994; Choate and Rightmire, 1984); hydrologic research in the San Juan Basin (Oldaker, 1991; Scott and Nance, 1996); groundwater modeling (COGCC and BLM, 1995; Oldaker, 1999) and reservoir studies of the Fruitland Formation and Pictured Cliffs coals and sandstones (Cox, 1994). Considerable data on these topics also resides as non-published, proprietary industry reports and studies. Data relating to the hydrologic and reservoir studies of the Fruitland Formation, Pictured Cliffs Sandstone, and Kirtland Formations will be forthcoming as part of the 3M Project.

An integrated data and software package developed by A2D Technologies/Interpretive Imaging known as smartSECTION TM was purchased and utilized for creating and displaying the stratigraphic cross sections. An excellent User's Guide provided instructions for managing the data and creating clear, accurate, and functional cross sections (Interpretive Imaging, 1996)

There are many historical references to health, safety, and environmental problems associated with methane gas contained within the Fruitland Formation coal beds in La Plata County. Oldaker (1995) has compiled extensive reports of the following events: historical seeps along rivers, stream drainages, and coal outcrops; methane contamination in well water; coal mine explosions; mine fires; and coal fires along the outcrop. Kelso and others, 1980, documented historical information concerning gassy mines, mine fires, and methane seeps in La Plata County. Various seep studies have been conducted: AMOCO, 1994; Fontana, 1996; Stonebrooke, 1996; Baldwin, 1997. A collection of monitoring well data from the Pine River Ranches has been compiled by Oldaker (1999) and is representative of the types of information that can be collected and analyzed when the 3M monitoring wells are drilled along the outcrop study area. Data collected on the SUIT Reservation also confirms natural methane seeps and coal fires along the outcrop. What remains to be determined, however, is to what extent, if any, the downdip coalbed methane production is accelerating or reducing the documented seeps and whether new seeps will be initiated or prevented by dewatering that occurs during coalbed methane production.

The geologic mapping conducted along the outcrop for this study did not identify any new seeps that were not already recognized and documented historically. Soil gas and soil vapor monitoring, conducted by industry groups and independent consultants hired by the COGCC, and supplemented by the Bureau of Land Management, have provided data since 1993 and are still being monitored to evaluate the fluctuations in seep discharges and gas composition. This report, supplemented with the hydrologic and reservoir models as well as with any future data from near-outcrop monitoring wells to be installed by the COGCC in 2000, will collectively provide the data necessary for evaluating the potential relationships between the outcrop seeps and down-basin production.

DISCUSSION

GEOLOGIC MAPPING

Randall K. Streufert, Summit Geology and Consulting, LLC, was hired to map the Fruitland Formation coals along the 26 miles of outcrop from Ridges Basin to the La Plata County/Archuleta County line (Figure 1). This length of outcrop spans six separate 7.5-minute quadrangle maps. All mappable coal beds and carbonaceous shales were mapped at a 1”:16,000’ scale, using aerial photos as base maps (Appendix A). Completed geological quadrangle maps and additional published maps were consulted (Carroll and others, 1997; 1998; 1999; Kirkham and others, 1999; Fassett and others, 1997). The individual coals and carbonaceous shales were initially identified following the nomenclature used by Carroll, 1998 and Wickman, 1997 on the SUIT Reservation. This nomenclature was applied to the 25 measured sections which were described at approximately one-mile intervals along the length of the project outcrop. Following the correlations of the measured sections along the outcrop as well as those identified on cross sections perpendicular to the outcrop, the nomenclature for the coal beds and carbonaceous shales were changed to match the coal interval scheme adopted on all the cross sections.

In addition to identifying coal beds, Streufert mapped all carbonaceous shale beds as well. The rationale for this relates directly to field and subsurface observations which indicate that methane gas can be stored in and produced from carbonaceous shales. The subsurface cross section correlations were based upon a log density cut-off of 2.0 gm/cc, a value that equates to a lithology that can be classified as carbonaceous shale.

Appendix A shows the distribution of the coal and carbonaceous shale beds along the outcrop. The beds have been color-coded to conform to the coal interval designation used on all the cross sections. Each coal bed is confined within a specific coal interval labeled I-1 through I-5 (abbreviations for Interval 1 through Interval 5). Some intervals will have more than one coal bed in them; in this case, there will be two coals that bear the same interval designation. For example, two coals within Interval 3 will both be labeled I-3 and will have the same color to correspond with the Interval 3 color used on the cross sections.

Other data are included on the geologic maps shown in Appendix A. Some of these data were collected during the field mapping in the summer of 1999. Additional data, compiled from other sources and referenced on the map legends, are included to supplement the data originally requested by the COGCC. The maps now contain the outcrop pattern of coal and carbonaceous shale beds to which are added: strikes and dips on the underlying Pictured Cliffs Sandstone; active seeps and springs; areas of distressed/dead vegetation; known coal mine adits; areas of clinker; high soil gas values recorded from several previous studies; formation contacts with the underlying Pictured Cliffs Sandstone and overlying Kirtland Shale; alluvial, colluvial and artificial fill areas; faults; gravel pits; and locations of each of the 25 measured sections.

All mapping was done with available geologic and topographic maps as well as black and white 1":16,000' aerial photographs. A separate GPS database was compiled for the locations of the measured sections, key seeps and springs, and significant stratigraphic field observations. A Trimble GeoExplorer II was used to collect the 3D GPS positions that were later real-time corrected. However, these data were not used to construct the geologic map.

Appendix B, which shows the locations of the subsurface cross sections in relationship to the Fruitland Formation/Pictured Cliffs Sandstone outcrop, incorporates the GPS positions for 23 of the 25 measured sections along the southwest-northeast Cross Section MS 1-25. The corrected GPS locations for 23 of the measured sections (Appendix C) were used in the smartSECTION cross section correlations. However, be aware of the fact that the GPS-correct measured sections on the base map and in the cross sections do not match the hand-drafted lines of measured sections on the geologic maps.

One of the more interesting observations at several locations along the outcrop was the nature of the Pictured Cliffs Tongue pinchout. By tracing the Pictured Cliffs Tongue to the southwest in Ridges Basin, Carbon Junction Canyon, and Edgemont Ranch, it was possible to see the relatively rapid thinning of the sandstone from greater than fifty feet to less than five feet along a horizontal distance of approximately two hundred feet along the outcrop. With careful examination, both the underlying coals of Interval 1 (referred to as the Fruitland Tongue in some literature) and the overlying coals of Interval 2 were recognizable. The subtle and gradual stratigraphic rise of the Pictured Cliffs Tongue is difficult to characterize with subsurface cross sections because the wells are often too far apart for these rapid thickness changes to be obvious. The relationships mapped along the outcrop have been used as a model for characterizing the nature of the Pictured Cliffs Tongue pinchout in this report's cross sections. The inferred nature of the Pictured Cliffs Tongue pinchout in the subsurface varies dramatically from previous representations in the literature but is consistent with outcrop observations made by Randy Streufert, the geologic mapper for this study.

Appendix D contains a gross sand isopach map for the Pictured Cliffs Sandstone Tongue in the Colorado portion of the San Juan Basin that has been generously provided by Bill Pelzmann, BP-Amoco. On this map, the northwest-southeast linear sandstone trends shown in red and orange indicate the position of the Pictured Cliffs Sandstone Tongue for which the gross thickness exceeds one hundred feet. The yellow areas represent gross thickness between fifty and one hundred feet, while the areas shaded in blue indicate thickness less than fifty feet. A 10-foot contour interval was used to construct this isopach. Compared to the abundance of well logs used to construct this isopach map, the relatively few wells obtained to characterize the Fruitland Formation coal intervals for this report do not adequately characterize the nature and extent of the Pictured Cliffs Tongue as well as the isopach map does. The author expresses her thanks to BP-Amoco and to Bill Pelzmann for supplementing this report with the Pictured Cliffs Sandstone Tongue isopach map.

STRATIGRAPHIC CROSS SECTIONS

An original grid of cross sections was constructed by Rusty Riese, VASTAR, and Bill Pelzmann, BP-Amoco and accepted by the 3M Geological Subcommittee as a representative distribution of coalbed methane producing wells in Colorado. As the 3M correlation project progressed, it became apparent that some of the well logs were unavailable in a raster format for inclusion in the A2D smartSECTION cross sections. It was, therefore, necessary to modify the grid to account for this problem while adding one additional cross section, N – 0.5, to include the subsurface wells closest to the outcrop. (See Appendix B) This cross section also contains the stratigraphic nomenclature for coals seen in shallow, near-outcrop U.S. Geological Survey (USGS) wells drilled and logged in T. 33N-11W and R. 32N-12W (Wickman, 1997). The correlation between the individually named coals and the coal intervals described in this study is excellent.

The smartSECTION software was purchased to construct the stratigraphic cross sections using raster images of well logs. A2D Technologies, the parent company for this software, has scanned a large number of well logs in the San Juan Basin and these were available for a modest price. In some cases, the company supplied depth-registered logs; the rest of the logs were depth-calibrated by the author. The final result was a collection of depth-corrected logs that could be correlated and whose measured depths and/or subsea depths could be calculated and included in a tabular format within the software program. Sections could be hung on any datum with ease, allowing an opportunity to examine the stratigraphic implications of using different datums.

The Fruitland Formation coals were grouped into five intervals Interval 1 through Interval 5 (abbreviated on both the geologic map and the cross sections as I-1 through I-5). After much discussion during several 3M Geologic Subcommittee meetings regarding a correlation scheme for the individual coals, Bill Pelzmann, BP-Amoco, proposed assigning the coals to intervals. The Subcommittee adopted that suggestion as a manageable way of grouping the coals into depositionally similar coal intervals that record an overall time-transgressive sequence from the oldest interval (I-1) to the youngest (I- 5). Bill Pelzmann secured permission from BP-Amoco to provide a grid of correlated cross sections using these intervals for wells within three miles of the outcrop. I used these sections as springboards for establishing the correlations along the outcrop and deeper in the basin.

The interval correlation approach has the potential for mimicking the stratigraphic and spatial relationships of the individual coals in the basin. The depositional nature of the Late Cretaceous Fruitland Formation peat swamps, transected by Fruitland Formation fluvial channels and Pictured Cliffs marine sandstones, insures that individual coal beds are discontinuous in a regional sense. These discontinuities can be caused by coal splits, facies changes, and coal bed truncations by fluvial channels. Add to that stratigraphic complexity the potential for discontinuities caused by structural faulting and bed offset and one can understand why individual coal beds are so difficult to correlate within even a dense grid of control. Figure 5 demonstrates those discontinuities clearly. Whereas the interval approach is not perfect, it does suggest a larger stratigraphic volume through which the individual coals can be connected. (See Fig. 6)

Gamma ray, density and density-neutron logs are the prevalent curves utilized in the correlations. After many discussions with 3M Geologic Subcommittee members, I decided to use a density cut-off of 2.0 gm/cc to include both coals and carbonaceous shales. This assumes that intervals with density less than or equal to 2.0 gm/cc on a log curve approximates the coal and carbonaceous lithologies described on the outcrop. These are the lithologies that are capable of producing significant volumes of methane. For ease of recognition, these lithologies have been shaded in light gray on all the cross sections.

The measured sections were scanned, depth-corrected, scaled appropriately, and added to the cross sections as log data. In reviewing the field descriptions of the measured sections, I noted that the lithology symbol designating carbonaceous shales or siltstones had been omitted in many places throughout the measured sections. I have corrected those symbol omissions by using light gray shading for all coal and carbonaceous beds. In other words, the shading designation, and not the lithology symbols, accurately reflects whether a bed is either a coal or a carbonaceous shale lithology.

The datum chosen to hang these cross sections is the base of Interval 3. The coals and carbonaceous shales included at the base of Interval 3 are the most well-developed regionally and the easiest to pick on subsurface logs. This datum is a time-transgressive surface with coal deposition progressing from southwest to northeast. Appendix E contains three scaled-down versions of a southwest-northeast cross section oriented perpendicular to depositional strike. Each cross section is hung on a different datum (the base of Interval 3, the top of the main Pictured Cliffs Sandstone and the base of Interval 2). These sections demonstrate the flexibility afforded in examining the stratigraphic relationships between the various intervals when multiple datums are used.

The critical outcrop data relating to the coal stratigraphy has been superimposed on cross section MS 1-25 which contains all 25 measured outcrop sections recorded by Randy Streufert. This display also shows the stratigraphic position of coal mines, seeps, and high soil gas readings over the 26 miles of outcrop. For the first time, it is demonstrated that **all** the coal intervals, at one or more locations, have sufficient quality and thickness to have been mined along the outcrop sometime in the past century. Each interval also possesses sufficient permeability and gas content near the surface to allow the release of methane at certain localities along the outcrop. Cross section MS 1-25 clearly demonstrates that coal beds in all five intervals throughout the Fruitland Formation have been mined historically and contribute presently to the surface seeps recognized along the outcrop in La Plata County. It is now possible to investigate the lateral continuity and reservoir characteristics for the coals within each interval as well as the spatial relationships of each interval to the outcrop.

The cross sections presented in this study provide the baseline correlation assumptions. More importantly, the individual coals and carbonaceous shales, because they are shaded on every cross section, demonstrate the vertical and lateral stacking of the beds that comprise each interval.

SUMMARY AND CONCLUSIONS

This study was undertaken to provide a stratigraphic framework for the Fruitland Formation coals as they appear along both the La Plata County outcrop from Ridges Basin to the Archuleta County line as well as on selected subsurface well logs in the Colorado portion of the San Juan Basin. The geologic map locates the individual coal and carbonaceous shale beds and identifies them according to the interval in which they have been correlated. The color designation for each bed conforms to the interval color scheme used on all of the stratigraphic cross sections. The geologic map also contains pertinent outcrop data and observations: locations of seeps and springs; mapped areas of clinker and distressed/dead vegetation; high soil gas readings from a previous study (Stonebrooke, 1996; Bureau of Land Management, 1999); coal mine adits; and strikes and dips on the Pictured Cliffs Sandstone.

The Fruitland Formation coals and carbonaceous shales are subdivided into five stratigraphic coal intervals. The color designation for each interval on the cross sections is the same as the color scheme used on the geologic map. Coals and carbonaceous shales have been shaded light gray on all the cross sections. Visual outcrop descriptions were used to classify coals and carbonaceous shales for the 25 measured sections (MS-1 through MS-25). A 2.0 gm/cc density cut-off on subsurface logs was the criterion used to determine these two lithologies.

The present value of these maps and cross sections is that they offer a stratigraphic framework for understanding the complex vertical and lateral distribution of the Fruitland coals and carbonaceous shales distributed over as much as five hundred feet of stratigraphic thickness on the outcrop and in the subsurface. The interval correlation scheme groups the individual coals into five intervals representing an overall time-transgressive sequence, making it easier to characterize the degree of coal interval continuity from the outcrop into the subsurface as well as parallel to the outcrop. Though the intervals themselves appear somewhat continuous despite local thickening and thinning, the coal and carbonaceous shale beds within each interval are regionally discontinuous both in a paleostrike and dip direction. For each interval, there will no doubt be disagreements as to the correlations presented. Any attempts to correlate the individual coal and carbonaceous shale beds within each interval will undoubtedly create even more disagreement. This is due to the fact that these individual beds are so discontinuous and difficult to correlate in a regional sense. Grouping the beds into intervals, however, allows a more simplified way of considering the interconnectedness of those beds within each interval. The residual benefit of the cross sections is that the raw data in the form of the measured sections and subsurface well logs are available for scrutiny and reinterpretation. As for the map, the locations of the coal and carbonaceous beds are identified geographically and can be referenced on accompanying measured sections and cross sections.

The future value of these data lies in the collective ability to add data to this stratigraphic framework. When the 3M monitoring wells are drilled, the smartSECTION software will allow the easy integration of the logs into the cross sections. The logs, as well as the future monitoring data, will prompt a reevaluation of the interval correlations. The introduction of any new data will encourage the scientific reviews necessary to resolve past, present, and future observations, and will promote a better understanding of the extent of coal bed continuity. Additionally, continued outcrop data collection and observations can now be plotted on or near a specific coal/carbonaceous shale bed that is tied to a specific interval, thereby allowing the nature of those Fruitland Formation coals and carbonaceous shales to be examined with the cross sections. The outcrop to subsurface cross sections (E-1 to E-7), as well as those sections perpendicular to depositional strike (N – 0.5 to N-6), will illustrate the degree of continuity of each bed within that identified interval (Appendix C).

The fundamental purpose of this study is to create the geologic framework for evaluating the potential relationships between coalbed methane production (and specifically dewatering of the coals) and any fluctuation in existing seeps or the creation of new seeps at the outcrop. An interesting graph was presented by Paul Oldaker at the "Coalbed Methane in the Rocky Mountains" Symposium in Denver from June 20-21, 2000 (Figure 7). A CD-ROM containing the abstracts and slides from that conference is in press. Oldaker plotted the periods of time between 1893 and 2000 during which the northern San Juan Basin was either in precipitation surplus or deficit versus the major methane-related events – mine explosions, coal fires, and acceleration of methane seepage at the outcrop. In every case, the occurrences of these major methane-related events coincided with periods of surplus precipitation (Oldaker, 2000). This may suggest that during times of substantial precipitation at the outcrop, recharge waters displace the methane adsorbed in near-surface coals, liberating the methane which then migrates updip to the outcrop. Clearly, the task of understanding the naturally-occurring phenomena that affect methane movement in the Fruitland Formation coal and carbonaceous shale beds is critical in assessing the contributions that downbasin coalbed methane production make towards surface methane seepage. Only continuous observations and monitoring will help to sort out the roles played by nature and by human activity.

CITED BIBLIOGRAPHY

AMOCO, 1994, Pine River Fruitland coal outcrop investigation:
Southern Rockies Business Unit, Amoco Production Company, Denver, Colorado, September 15, 1994.

Bureau of Land Management, San Juan Field Office, December, 1999,
Coalbed methane development in the northern San Juan Basin of Colorado - a brief history and environmental observations: A working document compiled by the Bureau of Land Management, San Juan Field Office, 72 p. plus appendices.

Aubrey, W.M., 1991, Geologic framework of Cretaceous and Tertiary rocks in the Southern Ute Indian Reservation and adjacent areas in the northern San Juan Basin, southwestern Colorado: U.S. Geological Survey Professional Paper 1505-B 24 p.

Ayers, W.B., Jr., and Kaiser, W.R., eds., 1994, Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Bulletin 146, 216 p.

Ayers, W.B., Jr.; Kaiser, W.R.; Ambrose, W.A.; Swartz, T.E.; Laubach, S.E.; Tremain, C.M.; and Whitehead, N.H., III, 1990, Geologic evaluation of critical production parameters for coalbed methane resources; Part 1, San Juan Basin: The University of Texas at Austin, Bureau of Economic Geology, annual report prepared for the Gas Research Institute, GRI-90/0014.1, 175 p.

Ayers, W.B., Jr.; Kaiser, W.R.; Laubach, S.E.; Ambrose, W.A.; Baumgardner, R.W., Jr.; Scott, A.R.; Tyler, Roger; Yeh, Joseph; Hawkins, G.J.; Swartz, T.E.; Schultz-Ela, D.D.; Zellers, S.D.; Tremain, C.M.; and Whitehead, N.H., III, 1991, Geologic and hydrologic controls on the occurrence and producibility of coalbed methane, Fruitland Formation, San Juan Basin: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5087-214-1544 (GRI-91/0072), 314 p.

Baldwin, Debbie, 1997, Update of further studies of the Pine River gas seeps, San Juan Basin, Colorado: Presented at the 1997 Rocky Mountain Symposium on Environmental Issues in Oil and Gas Operations, July 14-15, 1997, 16 p.

Barnes, Harley; Baltz, E.H., Jr., and Hayes, T.T., 1954, Geology and fuel resources of the Red Mesa area, La Plata and Montezuma Counties, Colorado: U.S. Geological Survey Oil and Gas Investigations Map OM-149, scale 1:62,500.

Bureau of Land Management, San Juan Field Office, December, 1999, Coalbed methane development in the northern San Juan Basin of Colorado - a brief history and environmental observations: A working document compiled by the Bureau of Land Management, San Juan Field Office, 72 p. plus appendices.

Carroll, C.J., 1998, Correlation of producing Fruitland Formation coals within the western outcrop and coalbed methane leakage on the Southern Ute Reservation: Colorado Geological Survey Open-File Report 99-10, CD-ROM.

Carroll, C.J., Kirkham, R.M., and Wracher, A., 1997, Geologic map of the Rules Hill Quadrangle, La Plata County, Colorado: Colorado Geological Survey Open-File Report 97-01, 12 p, 1 plate (1:24,000).

Carroll, C.J.; Gillam, M.; Ruf, J.; Loseke, T.D.; and Kirkham, R.M., 1999, Geologic map of the Durango East Quadrangle, La Plata County, Colorado: Colorado Geological Survey Open-File Report 99-06, 45 p., 1 color plate (1:24,000).

Carroll, C.J., Kirkham, R.M., and Wilson, S.C., 1998, Geologic map of the Ludwig Mountain Quadrangle, La Plata County, Colorado: Colorado Geological Survey Open-File Report 98-02, 23 p, 1 plate (1:24,000).

Choate, R., Lent, J., and Rightmire, C.T., 1984, Upper Cretaceous geology, coal, and the potential for methane recovery from coalbeds in San Juan Basin – Colorado and New Mexico, *in* Rightmire, C.T., Eddy, G.E., and Kirr, J.N., eds., Coalbed methane resources of the United States: American Association of Petroleum Geologists Studies in Geology Series #17, p. 185-222.

Colorado Oil and Gas Conservation Commission, and U.S. Bureau of Land Management – San Juan Resource Area, March 20, 1995, 1994 groundwater monitoring San Juan Basin, La Plata County, Colorado – comprehensive infill testing including data obtained in the Pine River Fruitland Coal Outcrop Investigative Team Study: Final Report, 102 p.

Cox, D.O., October 6, 1994, Reservoir engineering analysis, Pine River study area- presented to the Pine River Fruitland coal outcrop investigative team and the geological and reservoir engineering subcommittee: Advanced Resources International, Inc.

Fassett, J.E., (in press), Geology and coal resources of the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, *in* Kirschbaum, M.A., Roberts, L.N.R., and Biewick, L.R.H., eds., Geologic assessment of coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah: Chapter Q of U.S. Geological Survey Professional Paper 1625-B.

Fassett, J.E., ed., 1988, Geology of coal-bed methane resources of the northern San Juan Basin, Colorado and New Mexico: Rocky Mountain Association of Geologists, 1988, 351 p.

Fassett, J.E.; Condon, S.M.; Huffman, A.C.; and Taylor, David, 1997, Geology and structure of the Pine River, Florida River, Carbon Junction, and Basin Creek gas seeps, La Plata County, Colorado: U.S. Geological Survey Open-File Report 97-59, 126 p. and 7 plates.

Fassett, J.E., and Hinds, J.S., 1971, Geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado: U.S. Geological Survey Professional Paper 676, 76p.

Fontana, J.V., May, 1996, Fruitland outcrop gas seep study, Phase I and Phase II, La Plata County, Colorado, August-December, 1995: Prepared for Stonebrooke Resources, Amoco Exploration and Production Company, J.M. Huber Corporation, Emerald Gas Operating Company, and La Plata County Planning Department: Direct Geochemical, Golden, Colorado, 19 p. plus appendices.

Gas Research Institute, 1998, GRI Coalbed Methane Guides, Volumes I and II: Gas Research Institute GRI-98/0365.1 and GRI-98/0365.3, 2 CD-ROMS.

Interpretive Imaging, July 1999, A2D Technologies/Interpretive Imaging's smartSECTION TM user's guide: A2D/Interpretive Imaging, 176 p. plus appendices.

Kelso, B.S., Goolsby, S.M., and Tremain, C.M., 1980, Deep coalbed methane potential of the San Juan River coal region, southwestern Colorado: Colorado Geological Survey Open-File Report 80-2, 56 p.

Kelso, B.S., Wicks, D.E., and Kuuskraa, V.A., 1988, A geologic assessment of natural gas from coal seams in the Fruitland Formation, San Juan Basin: topical report prepared for the Gas Research Institute (GRI 87/0341), 56 p.

Molenaar, C.M., 1983, Major depositional cycles and regional correlations of Upper Cretaceous rocks, southern Colorado Plateau and adjacent areas, *in* Reynolds, M.V., and Dolly, E.D., Mesozoic paleogeography of the west central United States, Rocky Mountain Paleogeography Symposium II, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 201-224.

Molenaar, C.M., and Baird, J.K., 1989, North-South stratigraphic cross sections of Upper Cretaceous rocks, northern San Juan Basin, southwestern Colorado: U.S. Geological Survey Map MF-2068, 3 sheets.

Oldaker, Paul, June 26, 2000, Personal communication.

Oldaker, Paul, April 9, 1999, Pine River Ranches Monitoring: Prepared for the Colorado Oil and Gas Conservation Commission and Amoco Production Company (USA), 108 p.

Oldaker, Paul, 1995, Historical timeline for Colorado hydrocarbons including coal, oil and gas seeps, shallow shows, and discovery wells up to 1927: Presented to the Four Corners Geological Society, November 17, 1995.

Oldaker, Paul, September 9, 1991, Animas Valley hydrogeology study: Prepared for the San Juan Basin Industry Action Team, 36 p. plus figures and appendices.

Schwochow, S.D., Murray, D.K., and Fahy, M.F., eds., 1991, Coalbed methane of western North America: Rocky Mountain Association of Geologists, fall conference and field trip guidebook, 336 p.

Scott, A.R., and Nance, H.S., 1996, Coal reservoir and geochemical heterogeneity of water and coalbed methane production trends: Fruitland Formation, San Juan Basin, Colorado and New Mexico: topical report prepared by the Texas Bureau of Economic Geology for Gas Research Institute Contract No. 5091-214-2261, 135 p.

Stonebrooke Resources, Inc., May 10, 1996, Fruitland Formation outcrop gas seep study, La Plata County, Colorado: Stonebrooke Resources, Inc., Evergreen, Colorado, 48 p. plus appendices.

Tremain, C.M., Laubach, S.E., and Whitehead, N.H., III, 1991, Coal-fracture (cleat) patterns in Upper Cretaceous Fruitland Formation, San Juan Basin, Colorado and New Mexico – implications for coalbed methane exploration and development: *in* Schwochow, S.D., Murray, D.K., and Fahy, M.F., eds., 1991, Coalbed methane of western North America: Rocky Mountain Association of Geologists, fall conference and field trip guidebook, 336 p.

Tremain, C.M., and Whitehead, N.H., III, 1991, Natural fractures (cleat and joint) characteristics and patterns in Upper Cretaceous and Tertiary rocks of the San Juan Basin, New Mexico and Colorado, *in* Ayers and others, 1990, p. 73-97.

Whitehead, N.H., 1997, Fractures at the surface, San Juan Basin, New Mexico and Colorado: *in* Hoak, T.E., Klawitter, A.L., and Blomquist, P.K.,eds., 1997, Fractured Reservoirs: Characterization and Modeling Guidebook: Rocky Mountain Association of Geologists, p. 27-42.

Zapp, A.D., 1949, Geology and coal resources of the Durango area, La Plata and Montezuma Counties, Colorado: U.S. Geological Survey Oil and Gas Investigations, Map OM-109, 2 sheets.