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CORRELATION OF PRODUCING FRUITLAND FORMATION COALS
WITHIN THE WESTERN OUTCROP AND COALBED METHANE
LEAKAGE ON THE SOUTHERN UTE RESERVATION

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By
Christopher J. Carroll, Colorado Geological Survey
Stephanie Mathews, M&M Consultants
Barbara Wickman, Southern Ute Division of Energy Resources

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Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

Nancy Comstock, Project Manager
National Petroleum Technology Office
P.O. Box 3628
Tulsa, OK 74101

Prepared by
Colorado Geological Survey
1313 Sherman St. #715
Denver, CO 80203

Subcontractors:
Stephanie Mathews, M&M Consultants
3601 Allen Parkway #487
Houston, TX 77019

Barbara Wickman, Southern Ute Division of Energy Resources
116 Mouache Dr., P.O. Box 737
Ignacio, CO 81137

Table of Contents

Executive Summary	Page 1
Introduction	Page 1
Location of Study Area	Page 2
Previous Work	Page 4
Regional Geology	Page 4
Results and Discussion	Page 5
Subsurface Correlations	Page 5
Methodology	Page 5
Coal Correlations	Page 6
Faulting	Page 8
Isopach Maps and Structural Implications	Page 9
Cross Section Details	Page 10
Surface Mapping	Page 11
Methodology	Page 12
Clinkers	Page 13
Cleat and Fracture Data	Page 13
Methane Seeps and Distressed Vegetation	Page 15
Surface to Subsurface Correlations	Page 15
Production Data	Page 17
Conclusion	Page 19
Bibliography	Page 21
Appendices	Page 24

List of Graphical Materials:

- Four Photographs of Field Work on Geologic Map, pgs. 12-16
Figure 1. Project Location Map showing Mapping Boundaries, pg. 3.
Figure 2. Stratigraphic nomenclature of the San Juan Basin, pg. 5.
Table 1. Highest producing Gas Wells within the Study Area, pg. 18.

ABSTRACT

The Colorado Geological Survey and Southern Ute Indian Tribe proposed to determine the cause of several gas seeps which are occurring on the western outcrop of the coalbed methane producing Fruitland Formation on the Southern Ute Indian Reservation. Correlation between outcrop coals and subsurface coals was necessary to determine seep source in the northern part of the study area. Subsurface studies include structure and net coal isopach maps, stratigraphic cross-sections, production maps, and a production database. Detailed coal stratigraphy was correlated through production wells near the outcrop region. These maps and cross-sections were correlated to new surface coal outcrop maps generated by the Colorado Geological Survey and the Southern Ute Division of Energy Resources. Methane gas seepage has been noted historically within the study area. The total investigation may help determine if gas seepage is natural, a result of coalbed methane development, or some combination of the above.

Stratigraphic cross-sections were produced to correlate subsurface coals in both the dip-elongate and strike-elongate directions. Coal terminology used by the Southern Ute Division of Energy Resources was adopted in the southern part of the study area. This coal nomenclature was carried through to the northeast area near Bridge Timber Mountain and Indian Creek areas. The lowermost Fruitland Formation coal group, Coal 1, includes subcoals 1a, 1b-1 and 1b-2/1b-3. This coal group can be traced nearly continuously around the outcrop immediately above the Pictured Cliffs Sandstone. A tonstein, or ash bed, occurs at the top of Coal 1 and was used successfully for correlations where present, but is eroded away in many locations. Within Indian Creek, the Coal 1 subcoals become thinner, separate, and grade into shale. Coals 2, 2.5, and 3 consistently form a single group in the southwestern part of the study area. Towards the northeast, an increase in sandstone and shale separates these coals. Coal group 3 thickens locally near Blackwater Canyon but is thin in other areas. Coals 3.5 and 4 are localized and thin, are comprised of discontinuous coal stringers, and shale out in the northeast part.

Structure maps indicate where scattered positive or erosional features are located, mainly within Coal 1, as well as defining the structural hingeline of the basin. The pattern formed by thin and thick areas within the net coal isopach maps for Coal 3, and Coals 3.5 and 4 indicate a northeast-southwest alignment. Surface outcrop mapping indicates that the basal coal groups 1 and 2 are widespread and mostly continuous throughout the northern area. Coal 3.5 is thickest in the upper Indian Creek region. Coal 3.6 is mapped discontinuously in the northeast, stratigraphically equivalent to coal 3.5 in the southern part of the study area, but not necessarily correlative. The net coal thickness of all coals thicken in the northeast corner near Basin Creek, indicative of a large coal buildup known south of Durango. Coal 4 stringers also increase in thickness in the northeast, but in outcrop are stratigraphically discontinuous or grade into shale. Thick coal seams in the northern part probably pinch out against the Pictured Cliffs Tongue in Basin Creek just north of the study area.

Methane gas seeps in Valencia Canyon and Basin Creek have been recently discovered. A small surface seep was discovered in Indian Creek during this field mapping. A concern for seepage exists within the study area because of the close proximity of the outcrop to shallow production. Methane gas detectors can be positioned on major coal outcrops in the Indian Creek region prior to gas development. The surface maps generated by this project should help future workers find coal outcrops for both exploration and environmental concerns. Natural gas production in this part of the San Juan Basin is exceptional. A high productive fairway known to the petroleum industry outcrops within the study area. Fracture data on the Pictured Cliffs Sandstone and Fruitland Formation sandstones, along with coal cleat data, can be used to interpret locations of higher permeability.

EXECUTIVE SUMMARY

In the fall of 1997, the Colorado Geological Survey supervised the mapping of Fruitland Formation coalbed outcrops on the Southern Ute Indian Reservation. This coalbed methane productive zone crops out along the northern rim of the San Juan Basin as a prominent topographic ridge. Several cross-sections, both strike and dip elongate, were constructed of gas production wells along the outcrop. The logs from wells closest to the outcrop were used in an attempt to correlate productive Fruitland coalbeds to the surface. A geologic map with these coal groups was produced at 1:24,000 scale for the northern half of the study area. The Southern Ute Division of Energy Resources mapped the southern outcrop region in 1996. Coal correlations established from that map were carried through to the northern map. This nomenclature was used to map the coalbeds in the northern part in both surface and subsurface studies. Coals located on outcrop can now be tied to local producing coal intervals. Subsurface data includes a production database, cross-sections, net coal thickness isopach maps, and production index maps. The geologic data can be used for scientific interpretation varying from environmental to coalbed methane production concerns. The maps can enable the user to locate coal outcrops for methane gas seepage, distressed vegetation, and geologic controls of coal production. Correlation of individual coals determined in the subsurface with those mapped in outcrop can help determine whether coal groups contribute to surface seeps known in the area. These correlations may also be used in planning seep mitigation. Monitoring of the Fruitland coal outcrops within the study area can provide important baseline data to future seep studies.

INTRODUCTION

The most productive coalbed methane basin in the United States is the San Juan Basin of southwestern Colorado and New Mexico. The northern rim of the basin crops out within Colorado mostly on the Southern Ute Reservation. The western outcrop refers to the Reservation land where the Cretaceous Fruitland Formation outcrops between the Colorado-New Mexico border and the region southwest of Durango. More than 171.8 billion cubic feet (bcf) of coalbed methane gas was produced in La Plata County, Colorado alone during the first half of 1998 (Colorado Oil and Gas Conservation Commission data, 1998). La Plata County recently became the first county in Colorado to cumulatively produce more than 2 trillion cubic feet of natural gas. Coalbed methane production is mainly from the Fruitland Formation; 89 percent of all gas production in the county comes from that formation.

Population growth in southwestern Colorado has seen a dramatic increase in the last ten years. At the same time, Federal tax breaks have given companies incentive to drill the Fruitland Formation for methane gas. Coal gas seepage into air and water was a natural phenomenon prior to increased

drilling into the Fruitland Formation coals. Whether the drilling and gas production has caused increased seepage is now of concern to the people living in this area. The mid-1990s geologic investigations at the Pine River subdivision gas seeps indicate that similar situations could occur in other parts of the basin. Of special concern to this project are the coalbed methane wells producing in close proximity to the outcrop on the western side of the basin within the boundaries of the Southern Ute Indian Reservation. Gas seeps of hazardous proportions have been reported along this outcrop belt. In 1994 a large seep at Valencia Canyon was detected from faults and fractures very close to production wells. Hydrogen sulfide and methane gas was detected above explosive levels. This report is completed as a follow-up geologic investigation into these seeps, with the objective of determining which subsurface coalbeds are producing gas, and to correlate these productive horizons to coalbeds in outcrop. Outcrop mapping completed by the Colorado Geological Survey (CGS) and the Southern Ute Tribe (SUIT) during the past three years will be interpreted in light of the data and maps generated in this current subsurface study.

LOCATION OF STUDY AREA

The study area for this report includes Sections 4-9, 16-21, of T32N, R11W; Sections 1-3, 10-15, 22-24, of T32N, R12W; the northwest quarter of T33N, R10W; all of T33N, R11W and T34N, R10W; and the southeastern quarter of T34N, R11W (Figure 1). The subsurface study area consists of 114 square miles, extending north 18 miles from the Colorado-New Mexico border to the northern boundary of the Southern Ute Indian Reservation (between latitudes 37° 00'N and 37° 15'N). The area is approximately 4 miles in width, encompassing the Fruitland Formation and underlying Pictured Cliffs Sandstone outcrop and the natural gas wells within approximately two miles of the outcrop.

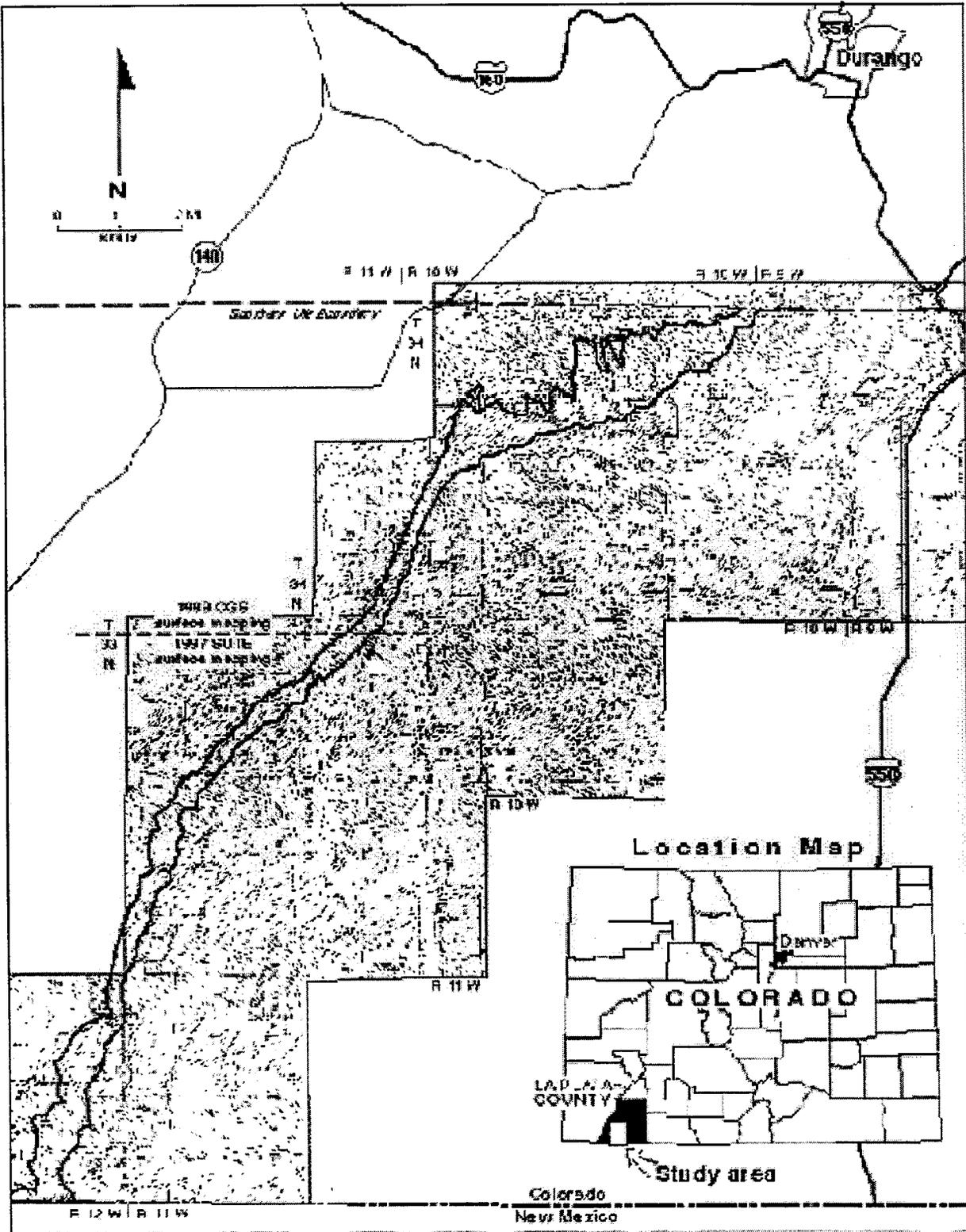


Figure 1. Location map of study area

The northern part of the study area is aligned in a southwest-northeast orientation, and the southern part is aligned north-south. This is due to a bend in the outcrop noted in upper Indian Creek. The surface mapping was divided into two parts, the northern and southern portions. The CGS mapped the Fruitland Formation outcrop between the northern Reservation boundary and the T.33 N./T.34 N. boundary. Geologists from the Southern Ute Division of Energy mapped the coal outcrops south of that line to the New Mexico border.

PREVIOUS WORK

Coal resource workers from the U.S. Geological Survey have completed most of the geologic mapping in the literature. The CGS surface map was the first within the northern part of the study area since Barnes and others, 1954. Barnes' map was accurate but not as detailed as the CGS mapping. Barbara Wickman of the SUIT Division of Energy Resources mapped the surface coals in the southern part of the study area in 1996. This same area was also mapped by the USGS (Robinson-Roberts and Updegrave, 1991). Coalbed methane interests brought more subsurface workers to this part of the San Juan Basin including Fassett and Hines (1971), Kelso and others (1980), Molenaar (1977), and Sandberg (1990). Several publications by the Bureau of Economic Geology, University of Texas at Austin on coalbed methane development are instrumental in the understanding of the stratigraphy and structural settings. Several coal cleat and fracture studies (Tremain and Whitehead, 1991) have been completed in the area recently. The U.S. Geological Survey recently completed two studies in the area; Condon (1995) completed a surface map and fracture study of the Fruitland Formation outcrop near Valencia Canyon, and in 1997 mapped surface geology and fractures at Basin Creek just north of the study area.

REGIONAL GEOLOGY

The Upper Cretaceous stratigraphy of the San Juan Basin is one of time-transgressive lithofacies. The Fruitland Formation is a coal-bearing and distributary channel sandstone unit deposited landward of the Pictured Cliffs shoreline sandstone. In outcrop south of Durango the two formations intertongue for several miles. The Pictured Cliffs tongue can be seen in the north side of Basin Creek but was not observed on Basin Mountain within the Reservation boundary. The contact between the two formations is placed at the top of the last massive sandstone, usually bounded by thick coal. Small, localized sandstone bodies of Pictured Cliffs Sandstone were found to increase in thickness rapidly in areas, indicating times of subsidence in the basin. The thick section of Fruitland Formation near the New Mexico border is close to the basin depocenter. At one locality west of Bridge Timber Mountain, 30 feet (9.14m) of stratigraphic section was seen to correlate Fruitland Coal 1 straight into Pictured Cliffs Sandstone shoreface sands (see 1:12,000 data point map, data pt.87). The sandstone forms a small pavement and cliff-face. This Pictured Cliffs Sandstone buildup can be seen in three dimensions as it grades into Fruitland Coal 1. Pictured Cliffs Sandstone forms the beach platform on which the basal Fruitland coal is deposited. Throughout the study area this relationship is present. The upper Fruitland Formation is marked by abundant distributary channel sandstones. The contact with the overlying Kirtland Shale is difficult and arbitrary at best. The distinct lack of coal, brown channel sandstone, and a thicker shale sequence marks the Lower Kirtland Shale.

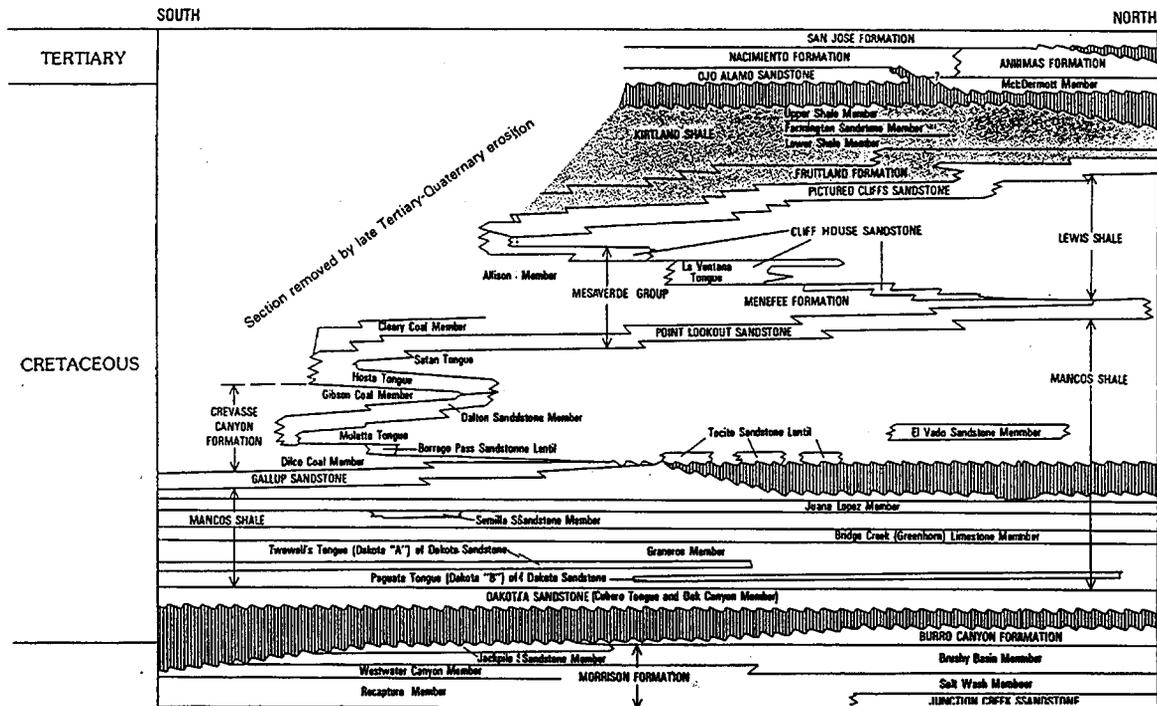


Figure 2. Stratigraphic nomenclature of San Juan Basin (after Molenaar, 1977)

RESULTS AND DISCUSSION

SUBSURFACE CORRELATIONS

METHODOLOGY

Data acquisition of electric logs for the study area was compiled. The database comprises 268 wells recorded on MJ Systems microfiche and 23 U.S. Geological Survey (USGS) core holes with density logs from a report by Roberts (1989). Gamma ray and density log curve characteristics were used to make coal determinations. As the sandstone and shale sequences vary dramatically between individual coals, the only reliable correlation tools are the coal log curves. Low density and low natural gamma identify coal. These well logs were used to make detailed coal correlations, structure and net coal isopach maps, and a series of stratigraphic cross-sections. Since the sandstone and shale sequences surrounding the individual coals can vary dramatically in thickness and log character, the correlations themselves depend completely on the density and gamma ray log character of the individual coals.

Previous workers have used various terminologies for the coalbed nomenclature. Amoco Production Company uses a color scheme for these coals. The U.S. Geological Survey uses a

general terminology of Basal, Intermediate, and Upper coal sequences of the Fruitland Formation north of the study area in Basin Creek. The Texas Bureau of Economic Geology uses a color scheme similar to Amoco's but with more detail. As the recent outcrop mapping within the study area uses the terminology of B. Wickman, a geologist for the Southern Ute Indian Tribe, this usage was also applied to the current subsurface study. The coal terminology consists of whole and decimal numbers, starting at depth and increasing numerically upwards. For this project, the SUIT terminology has been modified to reflect the relationships within each large coal grouping.

The nomenclature begins with the first basal coal group above the Pictured Cliffs Sandstone, termed Coal 1, with individual gamma ray and density log coals labeled with alphabetical subterms. As these subcoals split, additional numerals and/or letters can be added to the name string to indicate the subgroups and main groups to which they belong. For instance, the subcoals included within Coal 1 are 1a, 1b-1 and 1b-2/1b-3. The tonstein at the top of Coal 1 appears to have been eroded away as observed in the well logs, and thus the top of the Pictured Cliffs Sandstone was used as a datum in all of the cross-sections. The assumption here is that time-transgressive sequences are negligible or small within the study area.

In the southern part of the study area a middle coal sequence is present. This coal package splits into three parts towards the northeast. These subcoals may be interpreted as separate coals 2a, 2b, and 2c, with associated further sub-subcoals. As Wickman has already named these subcoals Coal 2, Coal 2.5 and Coal 3, this study retains the Wickman terminology. Coal 2 is the lowest coal within the middle coal group. Above Coal 2 is a thin marker coal with very consistent character and has been labeled Coal 2.5. The coal above Coal 2.5 is Coal 3, which is also consistent in character throughout the study area. The upper coal group consists of small stringers of coal, of mainly localized extent. Two of these were identified by Wickman in the USGS core holes and named Coal 3.5 and Coal 4. These terms have been retained in this study, but these coals are not as widespread or readily identifiable as coals of the other groups. Since these higher coals cannot be continuously followed in outcrop throughout the Indian Creek area, Coal 3.6 nomenclature is used northeast of there on the map. No other coals from this grouping have been named in this study, as they were not reliably identified other than locally. Stray higher coals were not named as Coal 4+ stringers. Several coal stringers were noted in the upper Fruitland but are generally discontinuous and not laterally correlative. These coals are probably correlative with coalbeds associated with the Pictured Cliffs Tongue north of the study area. All of the maps were hand-contoured, and the best GeoGraphix-generated fit to hand contouring was chosen for use in this study.

COAL CORRELATIONS

(See Spreadsheet, Appendix A, and Cross-Sections, Appendix B)

The correlation sequences are most complete and consistent in the southwestern part of the study area because well control is very dense near the outcrop. Well control in the southwest averages two wells per section. In well logs further northeast thicker units of sandstone and shale separate the subcoals. Wells with useable logs are further apart and not as close to the outcrop. Well control there averages one well per section.

COAL GROUP 1

1a: This basal-most coal consists of a potential sequence of five thin lobes, bounded by the top of the Pictured Cliffs Sandstone and the base of the Coal 1-b sequence. No single well has been observed to contain all five of these lobes, and most contain one or two lobes. It was not possible in this study to identify individual lobes of coal within this sequence for correlation differentiation or for the cross-sections. (See Arco 17-2, Cross-Section B-B'; Union Texas 17, Cross-Section A-A'). In the USGS core holes and in wells where the subcoal is seen as a thick lobe, the density log characteristics for Coal 1a are very clear; with a blocky part at the top of the lobe, and a thinner density spike at the base. (See Arco 18-2, Cross-Section B-B'; Palo 24-1, Cross-Section A-A'; Palo 23-1, Cross-Section D-D'). This lowest coal was observed in outcrop to interfinger with the Pictured Cliffs Sandstone only one time, a short, 100-yard long area near Bridge Timber Mountain.

1b: This coal subgroup consists of two log identifiable coals, 1b-1 and 1b-2/1b-3. It cannot be distinguished in the field.

1b-1: This coal is usually directly below Coal 1b-2/1b-3. In the southwestern part of the study area, it is observed to be directly above Coal 1a, (See Arco 18-2, Cross-Section B-B'). It grades to shale in some areas (See Bowen-Edwards Indian Creek 14-2, Cross-Section A-A'), and in others is separated by shale and sandstone beds from either or both bounding coals (See Palo 34-1-R and Palo 24-1, Cross-Section A-A'). In the USGS core holes, and in many of the other wells, the density log characteristic is clear, with a roundness of curve resulting from a slightly lower density at the base than at the top of this coal (See Bowen-Edwards Deer Canyon 16-1, Cross-Section D-D'; Bowen-Edwards McCulloch 29-2, Cross-Section F-F').

1b-2/1b-3: This is a double coal sequence, which cannot be subdivided, as the top part does not exhibit sufficient separation from the main basal coal. The gamma ray character is very consistent for this coal, and as this coal is widespread, its consistency makes it an excellent marker (See all wells in Cross-Section B-B'). A definitive tonstein, where present, forms the upper boundary of Coal 1 Group (See Arco 17-2, Cross-Section B-B'). Unfortunately, it is not always present, probably due to post-depositional erosion.

COAL GROUP 2:

2.0 This coal is the least consistent of all the lower Fruitland Formation coals. This coal consists of two thin coal lobes with a thicker coal lobe between them (See Palo 34-1-R, Cross-Section A-A'). In some instances the upper thin coal lobe is separated from the lower lobes (See Bowen-Edwards McCulloch 21-1, Cross-Section A-A'). In other instances, the lower lobe is separated from the upper two lobes by a sandstone and shale sequence of varying thicknesses (See Meridian #202 and Union Texas Petroleum #15, Cross-Section B-B'). In some wells it is directly above the Coal 1 tonstein (See Meridian #202, Cross-Section B-B'). In the northeastern part of the study area, the entire Coal 2 sequence is separated from Coal 2.5, and is directly above the Coal 1 tonstein (See Cross-Section G-G', northeast part of Cross-Section A-A').

2.5: This thin double coal lens is consistent in log curve character and also is widespread in occurrence across the study area (See USGS Core hole #6, Cross-Section B-B'; Bowen-Edwards Sawmill McCulloch 22-3, Cross-Section G-G'). It is a very reliable marker coal, and although not

grouped with Coal 2 and Coal 3 by the Southern Utes outside of the southwestern part of the study area, Coal 2.5 is important in determining coal correlations where sandstone/shale inter-coal sequences and shale-out of individual coals are complicated.

COAL GROUP 3:

This coal consists of two thin coal lenses with a thick coal sequence between them (See Bowen-Edwards Valencia Canyon 29-1, Cross-Section C-C'). The lower coal lens is not always well-separated from the base of the thick coal, and sometimes is totally absorbed into the thick lens. The upper coal spike is always present, but discussion below of Coals 3.5 and 4 indicate an ambiguity. In some instances, the lower spike is separated from the thick coal lens, and is grouped with Coal 2.5 (See Bowen-Edwards Deer Canyon 16-1, Cross-Section D-D'). What makes Coal 3 a very good marker, though, is the fact that the thick middle coal and upper thin coal do not show separation throughout the study area.

COALS 3.5 AND 4+ STRINGERS: These two coals were originally correlated from the USGS core holes by Wickman (See USGS Corehole #16, Cross-Section C-C'). Beyond the southwestern area, the correlation of these coals is difficult. Variable changes in log character, addition or loss of thin coal lenses, and the varying amount of sandstone and shale separating them from the individual lenses within each subcoal (See Palo Eldridge 1-25, Cross-Section D-D') are ambiguous. To the northeast, Coal 3.5 thickens and merges with other more discontinuous coals. The upper Fruitland coals even merge and correlate with Coal 3 (See Bowen-Edwards Indian Creek Wheeler 22-2, McKenzie 36-1, Cross-Section G-G'). In some instances, Coal 4+ stringers can be correlated in wells where there is no clear correlation for Coal 3.5. In these wells, however, it is observed that there is an additional coal lobe on top of Coal 3, which could correspond to Coal 3.5 (See Meridian #202, Cross-Section B-B'). As it is not identifiable by log character with Coal 3.5, it has been categorized as part of Coal 3 throughout this study. Due to the lack of consistency of log character and the restricted geographic occurrence of these coals, they are definitely not reliable markers. They are interpreted as generally discontinuous. Coal 4 group should not be considered correlative across the entire study area.

FAULTING

The existence of faulting is difficult to examine in the subsurface. Many local faults are high-angle and do not repeat bedding in logs. Missing section in well logs within the formation is usually attributed to lithologic variations as opposed to structural reasons. Although there are indications that faults with small throw are probably present throughout this area, these faults are not identifiable on the well logs. Many faults are small compaction features. A few small compaction faults were found in the field but were not very long (less than 30 feet, or 9.14m). One fault that was identified in the field (Roberts and Uptegrove, 1991) is supported by USGS Core hole #8, which lacks much of Coal 1, presumably faulted. This fault appears to have an estimated 20 feet (6.1m) of displacement. Generally, no major faults were found in outcrop. Long linear features are suspected as faults, such as 44 Canyon or West and East Gap, but field evidence is lacking.

ISOPACH MAPS AND STRUCTURAL IMPLICATIONS

(See Appendix C and Appendix D and Appendix E)

Structure maps and net coal isopach maps were generated based on the detailed coal correlations. Five structure maps were completed, on the tops of Coal 1a, Coal 1b, Coal 2.5, Coal 3, and Coal 4. Five net coal isopach maps were completed, using the intervals of Coal 1a, Coal 1b (1b-1 and 1b-2/1b-3 together), Coal 2 (2 and 2.5 together), Coal 3, and Coal 4 (3.5 and 4 together).

Generally, the structure maps reflect a structural trend parallel to the outcrop, with the steeply dipping hingeline area extending 1.5-2 miles from the outcrop. The dips vary from 15-30 degrees in the area of the hingeline and outcrop, decreasing beyond the hingeline very abruptly to 1 or 2 degrees in the subsurface. The structure maps of Coals 1a and 1b exhibit several areas where the coals grade into shale, some of these areas being quite large. In the map of Coal 1a, these areas are due to nondeposition around pre-existing positive features. In the map of Coal 1b there are two areas of coal grading to shale, which may be areas of post-depositional scour. In the Indian Creek region Coals 2.5 and 3.0 have more stratigraphic separation to the northeast. Generally, Coal 3.5 is discontinuous in distances over one mile. The map of Coal 4 also reflects postulated positive and scour features. Because structure maps were not generated for all of the individually correlated coals, the cross-sections indicate where there are additional shale gradation changes (postulated positive scour features).

Net coal isopach maps reflect the erosional or positive features by either thinning or gradational changes (shaleout) of the net coal, respectively. There are no identifiable, widespread, consistent thickness trends; i.e., single channel traces; and no identifiable correspondence with the high-production areas. Each map reflects a different location for, and pattern of, thickness variation.

The isopach map of Coal 1a indicates the thickest coals exist in the extreme southwest and in the middle parts of the study area, both close to the outcrop. The map of Coal 1b indicates the thickest coals across the middle of the study area and in the northeast, with an area of thinner coals in the extreme northeast. The isopach map of Coal 2 group (2 + 2.5) indicates the thickest coals exist in the middle of the study area, close to the outcrop, with subsidiary, slightly thinner coals, to the northeast.

Coal 3 isopach map indicates the thickest coals in the extreme south of the study area, and in the southern part of the extreme northeastern study area. Although there is no obvious regional trend, the closed thin areas are generally aligned in a northeast-southwest direction. The map of Coal 4 (3.5 + 4) indicates that the net coal thickens gradually from southwest to northeast. The closed thick areas generally are aligned in a northeast-southwest direction, but there is a belt trending northwest-southeast interrupting this lineation just south of the middle part of the study area. This trend is in line with a regional correlation that the Fruitland coals thicken north of the study area toward Durango because of Pictured Cliffs Sandstone buildup and interfingering formations (Ayers and Ambrose, 1994).

Production Map:

The production bubble map indicates a very rough correspondence between the Coal 4 group net coal isopach map lineation interruption area and the higher production figures. In comparing the total net coal isopachs for all of the coals (closed thick areas), a rough correspondence between the

area where all five coals overlap and the highest production (southeast quarter of T.33 N., R 11 W.). There is no pattern of prograding thicknesses through time reflected in this map. All of the coals overlap in thickness near Valencia Canyon. This area is the only place that has overlapping of all coals.

CROSS-SECTION DETAILS

(See Appendix B)

Seven cross-sections were constructed for this project. One strike-parallel Cross-Section A-A' extends northeast-southwest, and six shorter ones extending northwest-southeast from the subsurface toward the outcrop. The depositional strike or Pictured Cliffs strandplain is northwest-southeast, parallel to the shorter cross-sections. The depositional dip is southwest to northeast, parallel to the major cross-section.

Since the focus of the project was detailed correlations, the cross-section wells are equally spaced instead of reflecting actual distances between the wells. The distances between wells are indicated by footages on the cross-sections. As previously noted, the coals are consistent in character and grouping in the southwest, and evidence indicates more variability in coal grouping and log curve character towards the northeast.

Cross-Section B-B':

In the southwest, Coal 1 contains all three coal lobes grouped together. Coal 2, Coal 2.5 and Coal 3 are also grouped together. Further from the outcrop, the lower lobe of Coal 2 is present, but is separated from the upper two lobes by a sandstone and shale sequence. This lower lobe is also directly above the Coal 1 tonstein. Coals 3.5 and 4 are not readily identifiable this far southwest.

Cross-Section C-C':

In this cross-section, northeast of Cross-Section B-B', Coal 1a shales out around a postulated positive feature. Coal 1b-2/1b-3 shales out around a postulated scour feature. Coal 2 starts to exhibit separation between the lower lobe and the thick middle and upper lobes further from the outcrop. Coal 2.5 is separated from Coal 2 and Coal 3 near the outcrop, and rejoins the other coals to form a cohesive Intermediate Coal Group further from the outcrop. Coal 3 exhibits similar separations as Coal 2.5. Coals 3.5 and 4 are present and identifiable, but inconsistent in thickness and log curve character, as well as amount of sandstone/shale separation.

Cross-Section D-D':

Coal 1a tracks closely with Coal 1b-1. Coal 1b-2/1b-3 is scoured away near the core hole, and exhibits separation from Coals 1a and 1b-1 further from the outcrop. Coal 2 is separated from Coals 2.5 and 3 near the outcrop, but further to the southeast, Coals 2 and 2.5 are grouped, and separated from Coal 3. Coals 3.5 and 4 track with each other and with Coal 3 fairly closely.

Cross-Section E-E':

In this cross-section, northeast of Cross-Section D-D', Coal 1a groups with Coal 1b near the outcrop, but tends to separate from Coal 1b to the southeast. Coal 1b grades to shale at a positive feature. The top part of Coal 2 and Coal 2.5 are grouped together, but beyond the USGS core

hole, the lower lobe of Coal 2 is separated from the middle and upper lobes, and is located just above the Coal 1 tonstein. Coal 3 remains separated from Coals 2 and 2.5, but tracks fairly well with Coals 3.5 and 4. The sandstone and shale sequences separating Coals 3, 3.5 and 4 thin from the outcrop until they are a single group, then Coal 4 is separated from the others at the southeastern end of the cross-section.

Cross-Section F-F':

Coal 1a entirely grades to shale within the positive feature. Coals 1b-1, 1b-2/1b-3, and Coals 2 and 2.5 all track closely to each other. Coal 3 remains separated from the coals below. Coals 3.5 and 3.0 are adjacent at the northwest end, and separate widely towards the southeast. Where identifiably present, Coal 4 stringers closely resemble Coal 3.5.

Cross-Section G-G':

In this cross-section, northeast of Cross-Section F-F', Coal 1a entirely grades to shale within the positive feature. Coals 1b-1 and 1b-2/1b-3 track closely with each other and also with Coal 2, which is just above the Coal 1 tonstein. There is a shale out of Coal 2 towards the southeastern end of the cross-section. Coal 2.5 is separated from both Coals 2 and 3 except in a single well in the middle of the cross-section. Coals 3.5 and 4 track closely where both are identifiably present, and are separated from Coal 3 except for the southeastern end of the cross-section, at which point there is no separation between Coals 3, 3.5 and 4.

Depositional Dip Cross-Section A-A':

Coal 1a is present throughout the southwestern half of the cross-section, until it grades into shale in the northeast. Where both are present, Coals 1b-1 and 1b-2/1b-3 track very closely, except close to the positive feature causing gradational changes of Coal 1b-2/1b-3, at which point Coal 1b-1 tracks very closely with Coal 1a. Coal 1b-1 grades into shale in the northeast. In the southwest, the lower coal lobe of Coal 2 is just above the Coal 1 tonstein, but the separation between the Coal 2 lobes thins near the middle of the cross-section. In the northeastern part of the study area, Coal 2 is just above the Coal 1 tonstein. In the southwestern part of the study area, the upper lobes of Coal 2, Coal 2.5, and Coal 3 remain tightly grouped. Varying thickness of sandstone and shale splits coal 3. In two wells in the middle of the study area, Coal 2 is separated from Coal 2.5 as well. Coals 3.5 and 4 track fairly closely where both are identifiably present. The amount of sandstone and shale thickness separating these two coals from Coal 3 vary widely, and the numbers of coal lobes and their thicknesses within these two coals also vary greatly.

SURFACE MAPPING

The CGS mapped the northern half of the study area in 1997-1998. The concentration for this map was to locate coal outcrops in the Basin Mountain and Bridge Timber Mountain area approximately 10 miles southwest of Durango, Colorado (Figure 1). Barnes and others first mapped detailed coal outcrops in 1954. Those maps show three coals along the West Side of Bridge Timber Mountain and only one or two coal outcrops along Basin Mountain. Mapping coalbeds in the dip slope south of Basin Mountain is difficult because the erosional topography has incised drainages that cut through the Fruitland Formation at oblique angles.



Photo 1. Pictured Cliffs Sandstone outcrops near West Gap.

The coalbeds outcrop as long, linear features that trend up and down the canyon walls for miles. Due to this unique topographic profile, the field map was drawn to show the large-scale extent of the coal outcrop. Coalbeds tend to appear thin along the cross-section face of Bridge Timber Mountain but appear thicker in dip slope along Basin Mountain (see 1:24,000 scale geologic map in the appendices).

METHODOLOGY

The field map was created by locating coals on aerial photographic imagery at a scale of 1:17,560. Coal outcrops were located on the photographs using a stereo board and traced in ink. Upon completion of the field work the stereo images were set on a Kern PG-2 Plotter at the U.S. Geological Survey Plotter Lab in Lakewood, Colorado. Coal outcrop lines were transferred to both the digital and cartographic base maps. The map was then digitized and printed at 1:24,000 scale final product. The 1:12,000 scale geologic map file was too large for reproduction. A data point and gas well map of the northern study area was produced at 1:12,000. Both maps are provided here as attached appendices.

CLINKERS

Baked and fused rock, or coal clinker, was noted throughout the study area. B. Wickman described several clinker beds and coal fires near Cinder Buttes near the Colorado-New Mexico border. Clinkers were noted on the surface map. Clinkers dominate the outcrop in several locations in upper Indian Creek. Clinkers are located within the Coal 1 and 2 groups north of Bridge Timber Mountain, along West and East Gap, and on the ridges around Box



Photo 2. Coal 2 conjugate face cleats. Pine Canyon.

and Blackwater Canyons. Baked and fused rocks surrounding the coal cover coal outcrops. For the most part, the clinker beds are located on the higher topographic areas of steep portions of the northern outcrop. At one location at the top of Blackwater Canyon clinker beds on the outcrop topographically high. This clinker bed changes to unburned coal one-half mile down the canyon, perhaps implying that lightning strikes may be a cause. Significant clinker beds are indicated on the surface map.

CLEAT AND FRACTURE DATA

Along the northern rim of the San Juan Basin, there are two prominent sets of fractures within the Pictured Cliffs Sandstone. Laubach and Tremain (1990) and Tremain and Whitehead (1991) suggest that fracture swarms in outcrop trend in the west-northwest strike direction. Areas of dense fracture swarms tend to influence the coal bed cleat density, and hence have better permeability. Face and butt cleats are well developed in Fruitland coals. They are orthogonal, with the face cleats oriented north-south. Within the study area one main face cleat (north-south) and one orthogonal butt cleat (east-west) was prominent. However, in two locations an occurrence of conjugate face cleating was observed. Two face cleats are oriented N2W and N 20E (Coal 2 group) in Pine

Canyon near the northeast corner of the study area. This relationship was also noted in the headwaters of 44 Canyon within Coal 1 group.



Photo 3. Coal 2 outcrop in Pine Canyon.

Field observation shows that prominent J1 joints are not always aligned between Fruitland and Pictured Cliffs sandstone bodies. In fact, J1 joints are consistently 5 to 7 degrees different between the two units. Fracture swarms may show alignment of fault zones with enhanced permeability. A fracture swarm within the Pictured Cliffs Sandstone was found in the NE NE Sec 26, T.34 N. R.11W. At data points 69 and 70 the Pictured Cliffs Sandstone is exposed along the west side of Bridge Timber Mountain as a continuously erosion-resistant outcrop that forms large pavement exposures. The outcrop between these two data points is a zone of fractures that are long, parallel features of J1 joints. This fracture swarm is quite distinct with several 100 feet (30.49m) long fractures spaced only inches apart. Some fractures are more than 100 feet long, continuous with the outcrop. These fractures are in part topographic with the outcrop, but generally trend azimuth 350 with the regional J1 orientation.

The USGS also recently mapped in the Basin Creek area, T.34 N. R.10 W. Secs.1 and 2. The Pictured Cliffs Sandstone and Fruitland Formation outcrop just north of the Reservation in a low drainage point susceptible to seeps. Fracture data there also shows long fractures in the Pictured Cliffs Sandstone, some up to 100 feet (30.49m) long. J1 joints sets in Pictured Cliffs Sandstone are oriented at 332 degrees. J1 joints in Fruitland Formation sandstones are 358 degrees. Coal cleats

are basically north-south for the main cleat and east-west for the butt type. This is consistent throughout the study area. The U.S. Bureau of Land Management recently placed surface monitoring equipment in this location to record background levels of methane gas. The gas monitoring program will continue south onto the Indian Creek area in the near future.

METHANE SEEPS AND DISTRESSED VEGETATION

A minor seep was located during the CGS field investigation in 1998. Coal Group 3 in Blackwater Canyon, datapoint 163, is the suspected source of the seep. It is small, with only a few bubbles noted in May 1998. It has a pungent smell within an ephemeral pond. SUIT personnel observed the seep and suspect that it is an older, naturally occurring seep. Evidence for this is the lack of hydrogen sulfide, the slow rate of bubbling, and lack of recent vegetation disturbance. Anecdotal evidence from local ranchers indicates that several of these types of seeps exist in many of the canyons north of Indian Creek. Methane gas equipment detected only a small amount of methane gas and no hydrogen sulfide. One-half mile east of this point on Coal beds 3 and 3.6 distressed vegetation occurs. A cluster of eight 'recently' dead junipers is noticeable. The source of this disturbance is unclear. Occasional dead trees were noted throughout the map area but occurrences appear to be random. No large-scale ponderosa pine tree distress was noted in the northern part of the study area.

In 1995 R. Baughman of the Southern Ute Division of Energy Resources discovered a seep in Valencia Canyon, T.33 N. R.11 W, Sec. 20. It is an area of outcrop on which distressed and dead vegetation exists with a strong odor of hydrogen sulfide. Methane gas and hydrogen sulfide were detected in the outcrop above hazardous and explosive levels. Ten water-producing CBM wells were shut-in nearby. A consortium of operators drilled four slant holes down dip into the coal outcrop to vent off the methane. The area was closed to entry during the 1997 field work so a site inspection was not possible. S. Condon of the U.S. Geological Survey conducted a fracture and field study of the outcrop nearest the Valencia Canyon production. B. Wickman of the SUIT for her surface mapping used his map of the area.

SURFACE TO SUBSURFACE CORRELATIONS

The surface map shows coal group mapping only. Individual detail mapping of tonsteins, shales, and sandstone beds in outcrop is difficult to correlate to the subsurface.



Photo 4. Coal 3 near north end of Bridge Timber Mountain with tonsteins.

All of the wells used to make cross-sections in Indian Creek are more than one mile apart. Coal correlations in the field were labeled to local well logs because the wells are located in Indian Creek just at the base of the Fruitland outcrop. Coal outcrops nearest the wells were given nomenclature terminology first, but following those coalbeds through the steep topography was difficult. Hence, the best coal outcrops are located in steep hillsides of drainage valleys. Detailed coal designation from the cross-sections wells was not possible to distinguish in outcrop. Stratigraphic height of coalbeds above the Pictured Cliffs Sandstone was extensively used to correlate nearby wells.

It is not possible to correlate individual coalbeds to known production, although coal groupings can. In Blackwater Canyon the methane seep is attributed to the Coal 3 group. All of the lower coalbeds are clinker exposure there. Coal outcrops in low-lying areas near Indian Creek are particularly susceptible.

Coalbeds along the outcrop can be correlated to producing Fruitland coals by stratigraphic position. Using logs from wells nearest the outcrop, all productive units are exposed well throughout the study area. Most of the coal exposures in the southern part of the study area are correlated directly to producing units in the subsurface. Those coal exposures in Indian Creek are also linked to wells penetrating Fruitland coalbeds. The production map shows that the northern part of the study area is not as productive as the southern area. Monitoring of the Fruitland outcrop on Basin Mountain can provide important baseline data to future seep studies.

PRODUCTION DATA

The production database is included as Appendix A. Of the 366 wells located within the study area, 23 are USGS coreholes, and 343 are oil and gas wells. Cumulative production data from the 268 coalbed methane wells is included. Several wells are large producers of coalbed methane, with ten wells over 5 bcf gas cumulative production each, just within the last eight years. Analysis of that data shows that within the study area, one well (Meridian Southern Ute), T.33 N. R.11 W Sec.33 has a cumulative Fruitland coalbed methane production of greater than 10 bcf, producing from all five main Fruitland coals. A summary of the highest coalbed methane wells in the study area is included as Table 1.

The production bubble map (Appendix E) shows that the largest production is near Valencia Canyon. Coals 3.5 and 4 are particularly thick here. An overlay of all the coal isopach maps shows that all five main coal groups are located represented in this area. This may be the thickest total net coal area within the study area. Valencia Canyon is an area of shallow drilling. Ten of the top 20 shallowest wells in the study area (excluding the USGS coreholes) are located in Valencia Canyon.

These wells range in total depth from 377 feet (115m) to 1404 feet (428m). If a correlation exists between production and gas seeps, it occurs at locations of shallow drilling, close proximity to the recharge zone of the outcrop, or at outcrop locations that have coalbeds topographically cut by streams and rivers. The Indian Creek area may be susceptible to this because of the large incision of stream valleys, and the shallow production. The deepest Fruitland Formation production in the study area is near the New Mexico border. Most of the Fruitland Formation production is from wells shallower than 4,000 feet (1219m).

The individual coalbeds can be analyzed by thickness as well. Coalbed 1a is thickest along the Colorado-New Mexico border at 11 feet (3.35m) thick. This is positionally concurrent with the deepest part of the basin. Coalbed 1b1 net thickness is greatest at Bridge Timber Mountain, T.34 N. R.11.W, where it is 10 feet (3.05m) thick. No production from Bridge Timber Mountain wells is reported (as of September 1997 data). The best production from wells with 10 feet (3.05m) of Coal 1b1 are located in Valencia Canyon. The thickest coal 1b2/1b3 sequence is 10 feet thick in three wells in Indian Creek (T.34 N. R.10 W. Secs.16, 22, and 24). These coals were readily observed in outcrop and formed the basis for historic coal exploration around the Peabody well in upper Indian Creek.

Operator	Lease name	Well Number	Section	Township	Range	Prod Firm	TD (ft)	Up Perf	Low Perf	Cum MCF	1997 MCF
MERIDIAN	SO UTE	302	33	N033	W011	FRUIT COAL	2936	2630	2935	10936766	3615554
BOWEN- EDWD	VALNCIA CN	SU32-1	32	N033	W011	FRUIT COAL	2136			8271658	2071943
EMERALD	VALNCIA CN	SU32-4	32	N033	W011	FRUIT COAL	2045			7644684	
AMAX O&G	SO UTE	5-5	5	N032	W011	FRUIT COAL	2299			6618429	1803566
SO'LND ROY	SO UTE	300	33	N033	W011	FRUIT COAL	2520	2244	2518	6132451	2199514
MCKENZIE	WALKER	2-16	16	N032	W011	FRUIT COAL	2790	2526	2685	5909744	1895039
MERIDIAN	UTE 33-11	351	35	N033	W011	FRUIT COAL	3048	2787	3045	5764490	1715056
BOWEN- EDWD	VALNCIA CN	SU29-1	29	N033	W011	FRUIT COAL	2110			5691773	1368502
EMERALD	VALNCIA CN	SU29-4	29	N033	W011	FRUIT COAL	1865	1556	1851	5587961	1481998
EMERALD	VALNCIA CN	SU32-3	32	N033	W011	FRUIT COAL	1552			5569710	
MERIDIAN	SO UTE	304	27	N033	W011	FRUIT COAL	2774			5446283	1646466
LADD PET	SO UTE	3-6	6	N032	W011	FRUIT COAL	1560			5332713	949137
PALO PET	SO UTE 36	1	36	N033	W011	FRUIT COAL	3088			5207663	873926

The Coal 2 net isopach map shows the greatest thickness in 44 Canyon, T.33 N. R.11 W., Secs. 15 and 30. Coal package 2 is 17 feet (5.18m) thick there. This was observed in outcrop where the exposure was in the cross-section face of the hill, but the outcrop in dip slope was obscure. The Coal 3.0 net isopach thickness is greatest at the border with New Mexico also 17 feet (5.18m) thick. This thickness was also recorded for a well in Indian Creek at T.34 N. R.10 W. Sec. 11. Coal package 3.5 is thickest just east of Bridge Timber Mountain at 11 feet (3.35m). This is from a well in T.34 N. R.10 W. Sec.29. Coal package 4 is thickest at T.34 N. R.10 W. Secs. 12 and 14 in Indian Creek. The outcrop thickness of this coal was not seen. The unit is 14 feet (4.27m) thick on logs, but in outcrop it is a shaly coal with thin stringers of coal up to only one-foot thick.

Correlation of specific gas producing coals to methane seeps is difficult. Most coalbed methane production wells produce simultaneously from several coalbeds. The hydrology of the Fruitland outcrop and monocline is not well known at this time. For example, faults may enhance connection from the subsurface to the outcrop or act as barriers to fluid flow. In some areas such as Indian Creek make coal correlations ambiguous (Wickman, personal comm., 1998). Wells nearest the outcrop tend to produce too much water for economic recovery.

CONCLUSION

There are 7 cross-sections, one extending NE-SW, and six shorter ones extending NW-SE. The depositional strike is NW-SE and the depositional dip is NE-SW. Because of the amount of detail included in these correlations, the 5"/100 feet log was used. The cross-section wells are equally spaced with the distance between wells indicated by the accompanying map. The tonstein at or near the top of Coal 1 group is used as the datum for sections B-B' and G-G.' However, the rest of the cross-sections use the Pictured Cliffs as a datum, even though it is time-transgressive, since the tonstein is eroded in these areas.

The longest section, A-A', extends NE-SW in the depositional dip direction. In the southwest it reflects the intermediate group of Coals 2, 2.5 and 3 as a single package, as do the coreholes. To the northeast this package separates into two and three subgroups, which sometimes consist of 2.5 and 3 together, or 2 and 2.5 together, or sometimes each subgroup is separated from the others. In this interpretation, it appears that Coal 3 subgroup coalesces with Coals 3.5 and 4, while Coal 2 subgroup coalesces with Coal 1. Coal 1 group also has lost individual coals towards the northeast, becoming extremely stringy and in places disappearing almost totally. The shorter cross-sections indicate the same separation and attenuation of coals as they progress towards the northeast.

Detailed correlations of the Fruitland Formation coalbeds indicate that the depositional environment and post-depositional environment caused localized thickness variations in the sandstone and shale sequences separating individual coals. The coals that formed landward of the Pictured Cliffs Sandstone strandline are cut by stream channels and covered by localized floodplain deposits. Post-depositional erosion by braided or meandering streams, mud-filled low spots, and scattered positive features all contribute to areas of non-deposition of coal. These depositional schemes are observed on the well logs and in cross-section.

It is logical to assume that where the individual coals appear to be whole and entire, the effects of complex deposition rather than erosion have caused the random groupings and separations of coals. As this study is oriented essentially parallel to the depositional dip, net coal isopach maps do not reflect any strong trends of thickness in the Coal 1 and Coal 2 sequences in this area. The net isopach maps for Coal 3 and Coals 3.5 and 4 do indicate, by a lineation of thinnest and thickest coal, a northeast-southwest trend.

During deposition of Coal 1, scattered positive features were present, diverting the coal around their flanks. Some of these features, as in Coal 1a time, were quite large. By the time of Coal 1b deposition, the positive features had migrated, implying that sandstone and shale deposition was quite active over short periods of time. By Coal 2 through Coal 3 time far fewer positive features were present, reflected as the continuity of coal present throughout the area. Erosional features are also reflected on the structure maps, indicating some form of fluvial scouring. This was post-depositional, as indicated by the continuity of directional structure contours.

This project resulted in a correlation of individual coals within a complex sedimentary framework.

Further subdivisions can be made within the coals, but the characteristics used for separation are not reliable enough over the size of the project area. Correlation of individual coals determined in the subsurface with those mapped in outcrop can help determine whether coal groups contribute to surface seeps known in the area. These correlations may also be used in planning mitigation of seepage.

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APPENDICES

Appendices Available on Disc

The CD-Rom contains:

SUTT_map.eps-Encapsulated Postscript file of the 1:12,000 scale *Surface Map Showing Data Point Locations and Gas Well Production*. This file can be opened in almost any graphics program such as Adobe Illustrator or Adobe Photoshop.

24k Geology Map-Adobe Acrobat *.PDF file of the *Geologic Map of Fruitland Formation Coalbeds in the Northwestern Outcrop on the Southern Ute Reservation*.

Appendix A-Coal Database. Includes all available well data and USGS core hole data, as well as correlated individual coal data.

Appendix B-Cross-sections A through G. Includes major NE-SW cross-section (cross-section A-A') parallel to stratigraphic dip; and six NW-SE cross-sections (cross-section B-B' through G) parallel to stratigraphic strike. AutoCad *.DXF format, can be opened in any AutoCad compatible program or ArcView with AutoCad extension.

Appendix C-Structural maps of Coal 1a, Coal 1b, Coal 2 (2/2.5), Coal 3, and Coal 4 (3.5/4). AutoCad *.DXF format, can be opened in any AutoCad compatible program or ArcView with AutoCad extension.

Appendix D-Net coal isopach maps of Coal 1a, Coal 1b, Coal 2 (2/2.5), Coal 3, and Coal 4 (3.5/4). AutoCad *.DXF format, can be opened in any AutoCad compatible program or ArcView with AutoCad extension.

Appendix E-Fruitland coal production bubble map and production isopachs. AutoCad *.DXF format, can be opened in any AutoCad compatible program or ArcView with AutoCad extension.

Appendix F-Cross-section index map. Includes previous and current cross-sections within the study area. AutoCad *.DXF format, can be opened in any AutoCad compatible program or ArcView with AutoCad extension.

