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This mapping project was funded jointly by the Colorado Oil and Gas Conservation Commission and the Colorado Geological Survey

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
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FOREWORD

The purpose of this project is to describe the geologic mapping and coal bed resources along a 23-mile outcrop of the Fruitland Formation in western Archuleta County, Colorado. This area is part of the northeastern rim of the San Juan Basin. CGS geologist Chris Carroll, and consulting geologists Dr. David Gonzales, Dr. Gary Gianniny, Dr. Karen Houck, and field assistants Tor Stetson-Lee and Emilee Skyles completed the field work on this project during the summer of 2008. The sedimentary bedrock and quaternary unit descriptions, geologic setting, and coal resource sections of this report were written by Mr. Carroll. Dr. Gonzales completed the sections on fractures and structural geology. Dr. Gianniny, Dr. Houck, Mr. Stetson-Lee, and Ms. Skyles contributed the measured section compilation.

This mapping project was jointly funded by the Colorado Oil and Gas Conservation Commission and the Colorado Geological Survey. The Colorado Geological Survey created this map with funds drawn from the Colorado Department of Natural Resources Severance Tax Operational Funds, which are obtained from the Severance Tax paid on the production of natural gas, oil, coal, and metals in Colorado.

Vince Matthews

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ABSTRACT

The western part of Archuleta County, Colorado is a new frontier for coalbed methane (cbm) in the northern San Juan Basin. Detailed coal bed stratigraphy is important to both exploration and environmental compliance efforts in this area. The Colorado Oil and Gas Conservation Commission (COGCC), the U.S. Bureau of Land Management (BLM), and the U.S. Forest Service (USFS) oversee most of the prospective land for mineral development in this area. The environmental and regulatory concerns are also very important to the citizens of Archuleta County. Past considerations of methane gas seeps, coal fires, and groundwater withdrawal from the Fruitland Formation cbm play in nearby La Plata County are a major concern here as well.

The COGCC contracted with the Colorado Geological Survey (CGS) to create a new geologic map along 23 miles of Fruitland Formation outcrop to depict detailed exposures of coal east of the La Plata/Archuleta County line (see Index Map in the list of plates). The 1:24,000-scale map shows formation contacts between the Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, Kirtland Shale, and the Animas Formation. Four derivative plates at 1:12,000-scale show detailed coal bed occurrences within the Fruitland outcrop (Plates 1-4). Previous geologic maps by the US Geological Survey in this area combined the Fruitland Formation and Kirtland Shale as one unit and in some cases combined these units with the Pictured Cliffs Sandstone. The Fruitland/Kirtland contact, coal bed outcrops, and clinker had never been mapped in this area before. The new maps (Plates 1-4) depict Upper Cretaceous and Paleocene geology, correlate coal beds, and show distressed vegetation, coal cleat orientation and spacing, surface distribution of clinker, and regional fracture patterns.

Coal beds were mapped in the field using an integrated data set consisting of GPS data collection points, measured sections, and aerial photography. The map was constructed digitally in GIS using ESRI ArcMap and ERDAS computer imagery. Stratigraphic sections were measured in the field and later drafted and compiled digitally. These measured sections are displayed individually and combined in an outcrop long cross-section created using PETRA software. Correlation of coal beds is shown in the cross-sections. These data were then tied to subsurface correlations in an attempt to correlate subsurface coal beds with surface exposures. Fluvial sandstones intercalated with siltstone, shale, and coal beds were correlated to determine the extent of each coal bed facies.

Detailed coal correlations show a complex relationship between brackish-water, back-shore sediments intertonguing with the regressive-marine Pictured Cliffs Sandstone and the basal Fruitland Formation coal beds. At least two main sequences of coal mires were distinguished interfingering with Pictured Cliffs shoreface sandstones. The en-echelon

geometry of time-transgressive stratigraphy between the Pictured Cliffs and the basal Fruitland coals are demonstrated in Cabezon Canyon where the two formations intertongue. Fresh-water Fruitland Formation coal beds up to four feet thick (C_0 coal zone) in Cabezon Canyon were found to be stratigraphically 50 ft below the top of the Pictured Cliffs Sandstone locally.

New cbm drilling in this area will reveal how productive Archuleta County may be for gas development. The northwest trend of the Fruitland outcrop in this area is unique to the San Juan Basin as this area has an outcrop parallel to the Cretaceous paleo-shoreline. The Fruitland Formation /Pictured Cliffs Sandstone outcrop trends northwest in this part of the San Juan Basin, thus the Pictured Cliffs outcrop generally reveals laterally contiguous sheet sands that trend for miles, especially along the Piedra River. The strikes of Fruitland coal face cleats are nearly parallel to the outcrop indicating low permeability at right angles to coal bed outcrops. No apparent gas seeps were encountered in the study area, and recent studies by LT Environmental corroborate this finding. Gas seeps usually develop along low topographic areas of the Fruitland outcrop: therefore Beaver Creek, Squaw Creek, Fosset Gulch, Piedra River, Stollsteimer Creek, Deep Canyon, and Cabezon Canyon areas will be closely monitored by COGCC as part of the annual gas seep survey of the Fruitland Formation outcrop conducted by oil and gas companies operating in Archuleta County.

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A sincere thanks to the following individuals who assisted in the completion of this project: Mark Bauer (Mark A. Bauer Consulting) set the digital stereo models in ERDAS© Imagine Stereo Analyst© for ArcView©; Larry Scott (CGS) provided assistance with annotated photographs and scanning aerial photography for the digital model; and Matt Morgan, CGS, assisted with the GIS cartographic model link to ESRI ArcMap. Erin Capra (Innovative Technology) assisted with the construction of the stratigraphic cross-sections.

Access to private land was graciously arranged and provided by the land owners in Cabezon Canyon, northern Peterson Gulch, northern Fosset Gulch, and in Beaver Creek. Additional thanks go to James Cappa, formerly with the CGS, for providing the original study plan for this map and to Steven Lindblom, COGCC, for his time and generous contributions to making this project possible.

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INTRODUCTION

The Upper Cretaceous Fruitland Formation is a prolific coal and coalbed methane (cbm) resource. In the Colorado part of the San Juan Basin, Fruitland coal beds have yielded 1.55 million short tons of coal, and over 1.38 trillion cubic feet (tcf) of coalbed methane (cbm) gas (CGS, 2009). These resources have been extensively explored in La Plata County. In neighboring Archuleta County, where coal beds occur along the northwest-trending Fruitland outcrop, coalbed methane has not yet been produced. Rough terrain, low productivity, deeper reservoirs and access on the National Forest have combined to limit drilling in this area (Hoppe, 1992). Drilling and pipeline infrastructures are now being developed for exploration and producing gas in this part of the basin. An environmental impact statement (EIS) for the development of Federal leases was approved in late 2007, allowing for coal beds in the Fruitland Formation to be tested by drilling (BLM, 2006).

In 2008, the Colorado Oil and Gas Conservation Commission (COGCC) asked the CGS to map 23 miles of Fruitland outcrop east of the La Plata/Archuleta County Line. The project was designed to provide more detailed information relative to coal bed occurrences, distressed vegetation, coal clinker or burned coal areas, and geologic contacts between the Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, Kirtland Shale, and the Animas Formation. The geologic map (see Index Map) was designed to assist regulators by collecting baseline data for Fruitland Formation coal bed outcrops.

PREVIOUS INVESTIGATIONS

In the 1940s and 1950s, the U.S. Geological Survey (USGS) mapped the coal resources of the coal field near Durango with a series of 1:62,000 to 1:63,360 scale maps. One of the first maps was OM-81 by Wood and others (1948), "Geology of the southern part of Archuleta County, Colorado". This publication was the most detailed geologic work on the Upper Cretaceous stratigraphy in the area and covered the southern part of the current map area. This 1948 map (at a scale of 1:63,360) shows the Lewis Shale, Pictured Cliffs Sandstone, and the Animas Formation as separate map units. The Fruitland Formation and the Kirtland Shale, however, were combined into a unit labeled 'Kf'. These units were not mapped throughout this area because they were not easily distinguishable at the reconnaissance level of mapping. Fruitland coal beds were also not mapped.

Barnes (1953) mapped the area between Ignacio and Pagosa Springs at 1:63,360 as part of the work by the U.S. Geological Survey (Map OM-138). This map, "Geology of the Ignacio and Pagosa Springs quadrangles," covers the northwest part of our study area near Beaver Creek and Yellowjacket Pass and shows the Kirtland Shale and Fruitland Formation contact and other mappable Cretaceous units such as the Farmington Sandstone Member of the Kirtland Shale. It does not map coal outcrops, but it does show six measured coal sections within the area of the 2008 mapping study that were used in the measured section included in this report. Together these two maps constituted the best available mapping before the 2008 field mapping. In 1953, the Animas Formation was considered completely within the Cretaceous, and was mapped as ‘Ka’. The 1:250,000 scale geologic map of this area (Steven and others, 1974) incorporates geologic data from both OM-138 and OM-81; all three of these maps were used as scanned references for our digital geologic mapping process.

Another USGS map of more recent vintage is the “Geologic and Structure Contour Map of the Southern Ute Indian Reservation and Adjacent Areas, southwest Colorado and northwest New Mexico”, Miscellaneous Investigations Series Map I-1958, at a scale of 1:100,000 (Condon, 1990). This map shows the Kirtland Shale and Fruitland Formation as a combined unit termed ‘Kfk’. This 1990 map showed the Animas Formation as Tertiary with the map unit labeled ‘Ta’. The map in this report shows the Animas Formation as Tertiary and also labels this rock unit ‘Ta’.

Between 1999-2000, the COGCC, CGS, and other participants engaged in a project called “3M”; this project involved mapping coals and monitoring and modeling groundwater in the Fruitland Formation in La Plata County north of the Southern Ute Reservation (Wray, 2000). The 3M study also included monitoring of formation pressures and gas concentrations in COGCC wells near the outcrop. The 3M study mapped detailed geologic relations such as Fruitland and Pictured Cliffs tongues, methane gas seeps, and detailed coal bed stratigraphy. Results of that study are located on the COGCC library website under San Juan Basin studies http://cogcc.state.co.us/ (COGCC, 2001; Wray, 2000). Geologic mapping conducted as part of the 3M study included 26 miles of Fruitland Formation outcrops starting near Ridges Basin southwest of Durango to the Archuleta County line near US-160.

In 2008, CGS began mapping this study in Archuleta County starting where the 3M study ended at the county line near the Shamrock Mine (See Index Map and Geologic Map Plate 1). This map includes the Fruitland Formation from the Shamrock Mine in the northwest corner of the study area and ending at the Southern Ute Reservation boundary line 23 miles to the southeast. This project included measuring stratigraphic sections and mapping individual coal beds. Results of this study are included on this CD. This study and the 3M study are both listed on the COGCC library website under San Juan Basin studies http://cogcc.state.co.us/ (COGCC, 2001).

In 2006, the BLM and the USFS compiled an Environmental Impact Statement (EIS) in the area focused on coalbed-methane development north of the Southern Ute Indian Tribe (SUIT) reservation line in both La Plata and Archuleta counties. The resulting three volume EIS outlines several alternatives for proposed coalbed methane development in this area. Alternative 7 is the BLM/USFS preferred alternative, which enables the six current lease-holding oil companies to develop their cbm leases in this area over the next

40 years. The EIS recommends the establishment of a 1.5-mile-wide buffer zone down dip from the Fruitland Formation outcrop in the Fosset Gulch Federal Unit in Archuleta County. Coal bed-methane development within the Fruitland buffer zone may proceed in a 'step-wise' manner that will be monitored by COGCC (2009) for discrete environmental impact performance.

As Fruitland Formation cbm production is expected to expand from west to east across the northern San Juan Basin, a need for additional large-scale, detailed mapping of the Fruitland Formation, including coal beds, was recognized in Archuleta County. Our current geologic map will assist the COGCC in establishing the exact location of the Fruitland Formation/Pictured Cliffs Sandstone contact for measuring the 1.5-mile down dip buffer.

GEOLOGIC SETTING AND DEPOSITIONAL ENVIRONMENTS OF THE UPPER CRETACEOUS UNITS

Upper Cretaceous rocks in the San Juan Basin are time-transgressive and were deposited as a series of intertonguing marine and nonmarine strata on the western shoreline of the epicontinental Western Interior Seaway (Fassett, 2000; Warwick, 2005). The lowest stratigraphic unit mapped, the Lewis Shale, was deposited as an offshore marine shale facies within the seaway (Reeside, 1924). The Huerfanito Bentonite Bed in the Lewis Shale is one of several volcanic ash beds upon which stratigraphic timelines in the San Juan Basin are based (Fassett and Steiner, 1997). The youngest Upper Cretaceous rocks are exposed near Chimney Rock, where the Huerfanito Bed is estimated to be 1,100 ft underlying the Pictured Cliffs Sandstone (Fassett and Hinds, 1971). The regressive marine sandstone was deposited on the edge of the seaway as it retreated northeastward over time. This shoreface sandstone marks the edge of the marine/non-marine interface between Lewis Shale sea floor deposits and the continental fresh-water deposits of the Fruitland Formation.

The Pictured Cliffs Sandstone is late Campanian in age, ranging from 75.76 Ma in the southwest part of the San Juan Basin to 73.04 Ma in the northeast part of the basin (Fassett, 2000; Lucas and others, 2006). The top of the Pictured Cliffs Sandstone marks the boundary between marine and non-marine environments (Steven and others, 1974) (Figure 1). The strandline of Pictured Cliffs Sandstone orientation shifted from northwest to east-west, to northwest again as it regressed northeastward across the present San Juan Basin area. The Pictured Cliffs Sandstone rises 1,300 ft stratigraphically northeastward across the San Juan Basin (Fassett, 2000). Coal beds of the overlying Fruitland Formation were deposited in an environment of back-shore swamps interrupted by distributary river systems trending northeastward, landward of the northwest-trending shoreline. Fruitland coal beds are 2.72 m.y. younger in the Chimney Rock area than in the southwest part of the basin; the youngest Fruitland coal beds in the basin are in coal group C_6 of this report.

Figure 1. Contact of Fruitland Formation C1 coal overlying Pictured Cliffs Sandstone pavement

Deposition of the Fruitland coal beds was closely related to the regression of the Western Interior Seaway (Fassett and Hinds, 1971; Fassett, 2000). A Campanian age was first assigned to the Fruitland Formation and associated Cretaceous strata based on the identification of palynomorphs identified from Fruitland samples from the Gasbuggy core in the northeast part of the basin. Later correlation of the Fruitland strata with coeval Western Interior ammonite zones in the Lewis Shale (Cobban, 1973; Fassett, 1985) allowed for a more accurate dating of Fruitland strata. Finally, Fassett and Steiner (1997) published a series of $^{40}Ar/^{39}Ar$ analyses for sanidine crystals from altered volcanic ash beds in the Fruitland that dated the formation at 73-75 Ma. These Fruitland Formation age dates are similar to, but slightly younger than the Pictured Cliffs Sandstone. Depositional environments for Fruitland coals were influenced by the relative position of the Pictured Cliffs shoreline and the rate of shoreline movement (Hoffman and others, 1992; Fassett, 2000). Thickness, quantity, ash, and sulfur content of coal preserved in the Fruitland rock record is influenced by the position relative to the shoreline and the rate of shoreline shift. Moisture content and Btu values are influenced by these controls as well as the degree of coalification. Uplift of the San Juan Mountains has also influenced the coal quality because of the heat flow derived from massive intrusive bodies in the nearby La Plata Mountains.

COAL QUALITY AND QUANTITY OF THE FRUITLAND FORMATION

Fruitland coal in the San Juan Basin is generally low sulfur (average less than 1 percent per pound) and high ash (probably averaging about 30 percent) (Kelso and others, 1980; Ayers and Kaiser, 1994). Moisture content is variable, ranging from 5 to 10 percent at shallow depths near the outcrop to less than three percent in the deeper parts of the basin (Fassett, 2000). Fixed carbon percentages range from 40 to 80 percent in the basin. Fassett (2000) further characterized the north-central part of the San Juan Basin as a low-volatile bituminous rank. Coal rank generally increases from the southwest to northeast across the basin.

Average Heat Value (Btu/lb)	Ash range (%)	Volatile Matter range (%)	Fixed Carbon range (%)	Moisture range (%)	Sulfur range (%)
12,651	**11.53 - 13.39**	**34.2 - 36.25**	**47.62 - 50.71**	**2.39 - 4.79**	**0.6 - 0.86**

Table 1. Heat value and coal quality of Fruitland Formation coals from five historic coal mines in the study area. All analyses reported as-received, air-dried, moisture and ash free. *Source: Carroll and Bauer* (2002).

Mining of Fruitland coals within the project area occurred between 1923 and 1985 at ten mines or prospects (Carroll and Bauer, 2002). Of the 1.38 million short tons of coal mined, 89 percent of the total was mined at the Chimney Rock Mine in the 1980s. This mine was the most prolific producer of coal from the Fruitland Formation in Colorado. Coal quality data reported from five of these ten mines are averaged in Table 1. Fassett (2000) reported that the Fruitland coal tonnage for all of Archuleta County totals 9.8 billion short tons, and the Chimney Rock quadrangle contains 1.1 billion short tons of total coal resource (Sandberg, 1990).

The Fruitland coal mined in the study area can be characterized as a high Btu, moderate ash, and moderately low sulfur bituminous coal (Table 1). The Colorado Geological Survey characterized coal in the Fruitland Formation on the Southern Ute Indian Reservation as ‘high- to medium-volatile’ bituminous (Kelso and Rushworth, 1982), and has the potential to be a high-volatile A bituminous coking coal, if not for its high ash content (Kelso and others, 1979; Goolsby and others, 1979).

Several mine openings were discovered during the field investigation. Names for local mines from historic coal mine data were assigned to these openings based on relative information about the locations for those mines. According to the BLM/FS EIS (2006), cbm development and production now has precedence over coal mining. Because there are no active coal mines in the study area, cbm development will be allowed to proceed for about 40 years before future mining of Fruitland coal beds will be allowed.

COALBED METHANE

Over the last three decades, coal seams of the Fruitland Formation in the San Juan Basin have produced 11.4 trillion cubic feet of gas as of October 2004 (COGCC, 2009), making the basin the world leader in cbm production. Currently, these coal beds are producing a trillion cubic ft of gas per year. However, only 29 gas wells have been drilled, or are proposed, in this study area as of 2010. Elm Ridge Resources, Inc., and Petrox Resources, Inc., are the majority lease holders for the Fruitland cbm play in this area. Other oil and gas operators in the area include EXOK, Inc., William Perlman, and BP America Production Co. These companies are experienced at directional drilling and plan to use that method beneath the environmentally sensitive HD Hills area. Preliminary directional subsurface information indicates some coal beds near the Piedra River are greater than 2,000 ft in length (COGCC, 2009).

In late 2008, the COGCC drilled six groundwater monitoring wells at three locations near to, and down dip from, the Fruitland Formation outcrop. The State plans to monitor water levels and formation pressures as new cbm drilling develops in Archuleta County. These wells are located in pairs near the outcrop at Wagon Gulch, Fosset Gulch, and the Chimney Rock coal mine (see map plates for locations). Coal samples from these wells were analyzed by Weatherford Laboratories of Arvada, Colorado for proximate and ultimate analyses, heat content, and coal desorption and adsorption (see Table 2).

Additional testing by the CGS with Wyoming Laboratories was conducted later from other coal intervals from the same cores for proximate, ultimate, heating value and trace elemental chemistry. Results from all testing shows that the Fruitland coal in western Archuleta County is characterized as a high-volatile A bituminous coal averaging 11,200 Btu/lb, but with some heat values over 13,000 Btu/lb locally, and exceedingly low mercury and arsenic contents. All lab results are included in Appendix A. The complete Weatherford report is available from the COGCC website.

API #	Well Name	Core Sample Depth	Proximate Analysis	Ultimate Analysis	Desorption	Adsorption	Trace element chemistry
05-007-06267	Wagon Gulch MW 34-5-4 #1	Not sampled					
05-007-06266	Wagon Gulch MW 34-5-4 #2	754-816 ft	Yes	Yes	Yes	Yes	Yes
05-007-06264	Fosset Gulch MS 34-5-14 #1	Not sampled					
05-007-06265	Fosset Gulch MS 34-5-14 #2	480-532 ft	Yes	Yes	Yes	Yes	Yes
05-007-06271	HWY 151 34-4-30 MW #1	228-274 ft	Yes	Yes	Yes	Yes	Yes
05-007-06270	HWY 151 34-4-30 MW #2	Not sampled					

Table 2. List of coal cores and sample analyses performed for COGCC monitor wells. Results are presented in report appendices.

GEOLOGIC MAPPING AND METHODOLOGY

The main focus of this mapping was to identify the upper and lower contacts of the Fruitland Formation and collect regional fracture information. David Gonzales (Fort Lewis College) mapped the geologic contacts in a continuous direction from the northwest to the southeast. Gary Gianniny, Tor Stetson-Lee (Fort Lewis College) and Karen Houck (UC Denver) measured sections, spaced every mile, along the outcrop (Figure 2). Chris Carroll and Emilee Skyles mapped the coal beds within the Fruitland Formation and collected coal cleat data.

Field data and notes include geologic attitudes (>200 data points), coal cleat measurements (52 data points), joint measurements (37 data points), and mafic dike trends (3 data points). These data were assembled in a GIS data file using location information gathered by GPS. Photographs of sites within the study area and aerial photographs acquired during a reconnaissance flight were also located and are provided as GIS data points including descriptive information and image file paths for hyper-linking capability. These field data were used to create a map of the geology and coal bed stratigraphy in the area.

Figure 2: Completing a measured section at the head of Archuleta Canyon (Karen Houck and Tor Stetson-Lee pictured).

COAL BED NOMENCLATURE

Coal beds in the Fruitland Formation were assigned a name based upon their height above the Pictured Cliffs Sandstone as shown in Table 2. Coal beds within the Fruitland Tongue in Cabezon Canyon are labeled C_0. Basal Fruitland coal beds located within 33 ft (10 m) of the top of the Pictured Cliffs Sandstone are labeled C_1. These coals were correlated regionally with all of the basal coals between the measured sections and assigned coal group designations Group 1, Group 2, or Group 2.5 (see cross-section plates 5a and 5b). Correlation of the measured sections (MS) shows how C_4 coal group coals in MS A1 correlate with C_1 group coals in MS A22 from northwest to southeast.

Formation	**3M Section 25**	**MS A1-A3**	**MS A4-A6**	**MS A7-A9**	**MS A10-12**	**MS A14-16**	**MS A17-19**	**MS A20-22**	**Height above Kpc**	**Coal Bed Name**
Kk										
Kf uppermost							Group 4		165-197 ft	C_6
Kf						Group 4	Group 3.7	Group 3.7	132-164 ft	C_5
Kf				Group 4	Group 4	Group 3.6	Group 3.6	Group 3.6	100-131 ft	C_4
Kf	Interval 5	Group 3	Group 3	Group 3	Group 3.5	Group 3.5	Group 2.8	Group 2.8	67-99 ft	C_3
Kf	Interval 4	Group 2		Group 2.5	Group 2.5	Group 2.7	Group 2.7	Group 2.7	34-66 ft	C_2
Kf basal coal	Interval 3	Group 1	Group 2	Group 2	Group 2	Group 2.5	Group 2.5	Group 2.5	0-33 ft	C_1
Kft						Group 2.4				C_0
Kpc										

Table 3. Correlation chart showing laterally equivalent coal groups, Archuleta County, Colorado. Coal group names are used in cross-sections and relative coal bed names are used in map attribute files. For example, C_1 coal bed in measured section A22 represents coal group 2.5, but C_1 coal bed in measured section A1 represents coal group 1, laterally non-equivalent.

MEASURED SECTIONS

Precise measurement of coal bed thicknesses and stratigraphic positions were obtained by measuring numerous sections by Jacob staff in the Fruitland Formation. Gary Gianniny led the team to measure sections approximately every mile along the outcrop. Field work was conducted by Gianniny, Karen Houck, Tor Stetson-Lee, and Emilee Skyles. This effort resulted in the collection of 22 measured sections. Karen Houck oversaw three new sections in Archuleta Creek. Gary Gianniny measured 13 new sections and used two sections in the Chimney Rock area from previous geologic work completed in 2001. A 1,000-acre parcel of private land south of Beaver Creek (Plate 1) could not be accessed in 2008, so four sections measured by Harley Barnes of the USGS (Barnes, 1953) were re-drafted and re-correlated for this study. New geologic information regarding coal bed continuity in length and variations in thickness was gathered from all of the measured sections along the outcrop. Overall correlations show an eastward progradation of sediments within the Pictured Cliffs Sandstone and Kirtland Shale, and an eastward thinning of the Fruitland Formation. Measured section A8 shows the greatest Fruitland Formation thickness of 195 ft (59.5 m) while MS A1 at the Shamrock Mine in the northwest part of the study area has the most net coal (45 ft, 13.7 m). Coal beds and the Fruitland Formation overall are thinnest in the Archuleta Creek area on the east side of the study area.

The lengths of coal beds between measured sections one mile apart are subjective and open to interpretation. Some authors have correlated coal beds for short distances (Fassett and others, 1997) at Pine Valley Ranches, whereas others have correlated coals for miles (Wray, 2000). Fassett (2000) has discussed the extent of the coal beds and their correlations in detail throughout the San Juan Basin. In Archuleta County, coal beds can only be correlated for a few thousands of feet because outcrops of the Fruitland Formation are mostly parallel with the paleoshoreline, and the continuity of back-shore swamps was interrupted by streams cutting through the swamps at right angles as they flowed to the sea (J.E. Fassett, personal communication, 2009).

The average net coal thickness throughout 23 miles of outcrop is 27.5 ft. This average was obtained from the 14 measured sections of the full thickness of the Fruitland Formation. Fassett (2000) and Sandberg (1988a, 1988b) show Fruitland Formation net coal thicknesses decreasing eastward in Archuleta County from more than 50 ft at the La Plata County line to 0 ft where the Fruitland outcrop crosses the Colorado-New Mexico State line. The greatest thicknesses of net Fruitland coal found in this study occurred in MS A1 near the Shamrock Mine with 44.88 ft total net coal, and at MS A8 with 35.85 ft at Squaw Gulch and Wagon Gulch near US Hwy 160. This is less than the total coal measured in the COGCC Squaw Gulch well drilled in November 2008 that had over 45 ft of net coal. The Fruitland Formation net coal thickness in Archuleta Creek is only 18 ft.

Molluscan bivalves were found in MS A16 through MS A19 near Cabezon Canyon (Figure 3). These bivalves were found in mudstones overlying the C_2 coal zone. These fossils suggest brackish to freshwater environments for Fruitland coal beds. These freshwater bivalves were found to be *Edmontonian* in age, spanning the Campanian/Maastrichtian boundary (Hartman, 1993). All individual measured sections are included as Appendix B in the Measured Sections folder included with the digital publication. Correlated measured sections are shown in Cross-Section Plates 5A and 5B.

Figure 3: Picture of molluscan bivalves found just above C2 coal near Cabezon Canyon.

GENERAL GEOLOGIC STRUCTURE

The 80-mile-long Hogback Monocline is the most prominent geologic structure in the area. This Laramide feature flanks the entire rim of the San Juan Basin in Colorado. The strike of the monocline bends abruptly in the vicinity of the La Plata/Archuleta County line as it is influenced by the younger Archuleta Anticlinorium near Pagosa Springs. The structural San Juan Basin began forming after deposition of the Tertiary Ojo Alamo Formation (Fassett, 1985), and uplift began before or during deposition of the upper Animas Formation. The outcrop pattern of Upper Cretaceous strata is influenced by river incision and erosion since the Laramide uplift.

One small anticline was noted in the study area near Heath's Haven. This small flexural fold is observed in the Pictured Cliffs Sandstone pavement north of Stollsteimer Creek and in the Fruitland Formation and Kirtland Shale south of the creek near MS A17, marked by southeast dipping bedding. Several faults mapped by Condon (1990) at Yellowjacket Guard Station were not observed in this study.

FRACTURE STUDIES AND COAL CLEAT MEASUREMENTS

Natural fracture trends in the Pictured Cliffs Sandstone, Fruitland Formation, Kirtland Shale, and Animas Formation within the map area were measured during this investigation by David Gonzales and Chris Carroll. These measurements were made to determine the trends and relationships of the joint sets and to gain insight into the fracture history in the area. In addition to rock joint measurements, joint patterns in coal seams were also measured and documented. A previous study of the fractures in the northern San Juan basin that includes the study area was published by Condon (1989).

It is critical to understand the character and trends of fractures in the region because these fracture networks provide the conduits, primarily in coal beds, for the possible migration of methane, hydrogen sulfide, and groundwater from the subsurface to the outcrop (Tremain and Whitehead, 1991). Coalbed methane will be extracted from the Fruitland Formation near the outcrop, or possibly 1.5 miles from the outcrop, in the northern San Juan Basin in Archuleta County. The fracture data presented in this report are intended to provide baseline information to evaluate potential migration pathways of gases and fluids.

This study presents 703 joint measurements made at 56 locations within the study area. The number of measurements made at individual sites varied from two to over one hundred. Figure 4 is a Rose diagram of all joint measurements showing the strong northwest trend of J1 fractures.

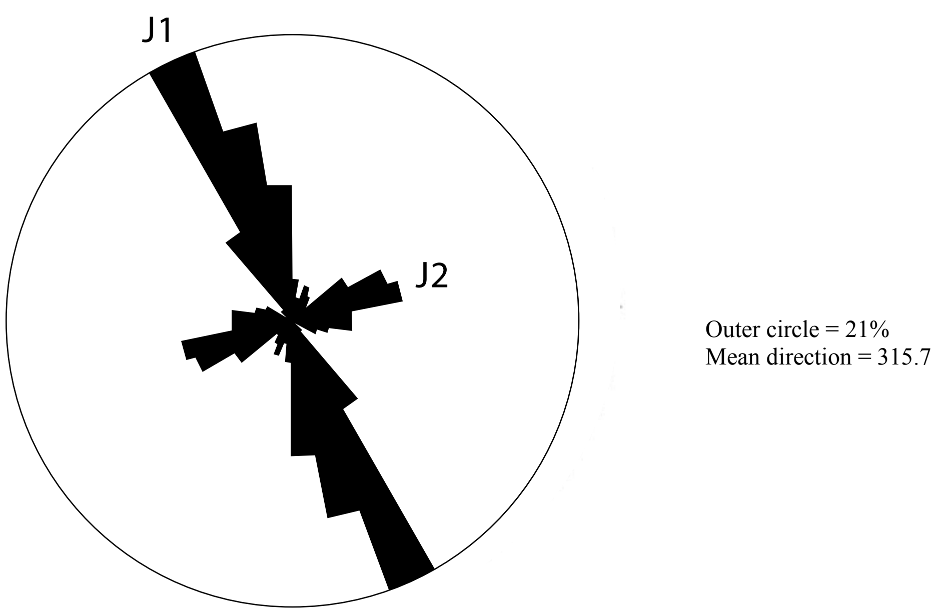

Figure 4: Rose diagram plot of all fracture data collected.

Joint trends were documented in the Pictured Cliffs Sandstone, Fruitland Formation, Kirtland Shale, and the Animas Formation at four locations in the study area in an attempt to understand controls on joint patterns in different rock types. These joint trend studies were conducted at Yellowjacket Pass, Fosset Gulch, near the abandoned Chimney Rock Coal Mine, and at Cabezon Creek (see plates). Measurements were made at these locations with the assistance of students enrolled in the Fort Lewis College Field Geology course in the summer of 2008.

Outcrop measurements included the general characteristics of joints such as length, spacing, sinuosity, mineral infilling, and slip features. The character and spacing of the joints measured varied for different rock types, but for the most part, parameters for joint sets were similar. The joints examined were mostly planar to slightly curviplanar. In few localities the joints had a strong curvature or were sinuous and branching. The dominant joint sets (J1) were mostly planar to curviplanar and had exposed lengths up to tens of feet. The J2 joint sets were also mostly planar with exposed lengths up to several feet. The apertures of all joints varied on average from less than 0.25 inches to 0.5 inches, but in some instances joint apertures were as much as several inches. Most joint surfaces were coated and stained with a veneer of iron and manganese oxide minerals, and were generally open and not filled by secondary mineralization except for rare veins and coatings of calcite and gypsum. Joint density varied greatly for different rock types. The highest densities of joints were observed in Animas Formation sandstone beds where an area of 50 square feet might contain as many as 100 distinct joints.

Two dominant joint sets (J1 and J2) were documented during this study. The oldest and most extensive sets of joints (J1) have an overall azimuth of ~330°. The dips of J1 joints are either vertical or dip steeply northeast or southwest. The J2 joint sets have an overall trend of ~70° with vertical to steep northwest and southeast dips. Although there are dominant trends within the data set, there is considerable scatter within both the J1 and J2 trends.

Fracture data collected in Archuleta County by the USGS (Condon, 1989) shows four populations of joints (J1-J4). Their trends of joint sets measured were N25W (J1), N62E (J2), N70E (J3), and N4E (J4). The J1 and J2 trends of Condon (1989) are similar to those measured in this investigation. Condon (1989) also reported that J1 and J2 joints were mostly steeply dipping, and our observations confirmed that, however we found some locations where dips are less than 50°. We did not recognize extensive development of the J3 and J4 joints sets noted by Condon (1989) who indicated that these sets are uncommon, poorly developed, and appear to connect J1 and J2 joints in map view. Some of the joint trends that we measured that fell outside the dominant J1 and J2 trends may belong to the J3 and J4 joint sets of Condon (1989), however we did not notice clear intersecting relations with J1 and J2 joints. It is possible that J3 and J4 do not represent distinct events of joint development but instead formed in response to local deviation of stress fields due to anisotropy in the rock units.

The J1 and J2 joint sets documented in this study are nearly orthogonal and mostly define a crude ladder pattern, although some cross-cutting relationships were observed. The majority of the joint surfaces examined did not show evidence of movement such as displacement, slicken sides, or polished surfaces. Most of the joints documented were open-mode 1, tensile-mode cracks that either developed during simple extension at right angles to the minimum principal stress field (Condon, 1989), or perhaps related to reactivation of basement structures without significant displacement.

Rose diagram plots of joints measured in the Animas Formation, Kirtland Shale, Fruitland Formation, and Pictured Cliffs Sandstone at Yellowjacket Pass, Fosset Gulch, the abandoned Chimney Rock Coal Mine, and Cabezon Canyon are shown in figures 5 through 8. The plots indicate that joint trends are highly variable in different geologic units at each location. Furthermore, for a given geologic unit joint trends vary between the four locations. These data indicate that rock type had a strong influence on the development and trends of the joints, and demonstrates the local scatter within the dominant regional trends. A number of factors may have influenced joint development at the different sites including variations in rock properties, pre-existing anisotropies, and variations in regional versus local strain fields.

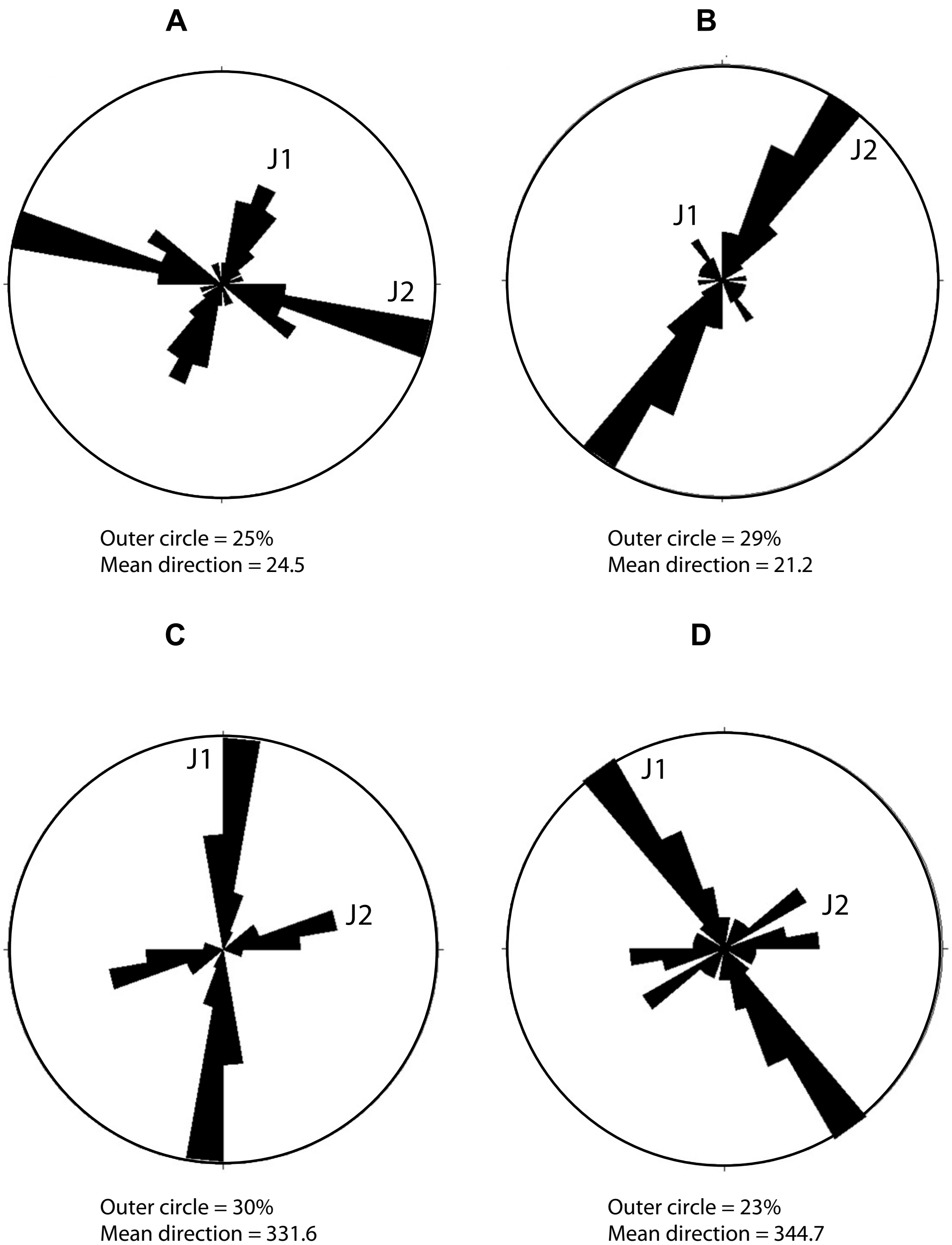

Figure 5: Yellowjacket Pass fractures. Data shows variability of fracture patterns by formation as measured in the Animas Formation (A), Kirtland Shale (B), Fruitland Formation (C), and Pictured Cliffs Sandstone (D).

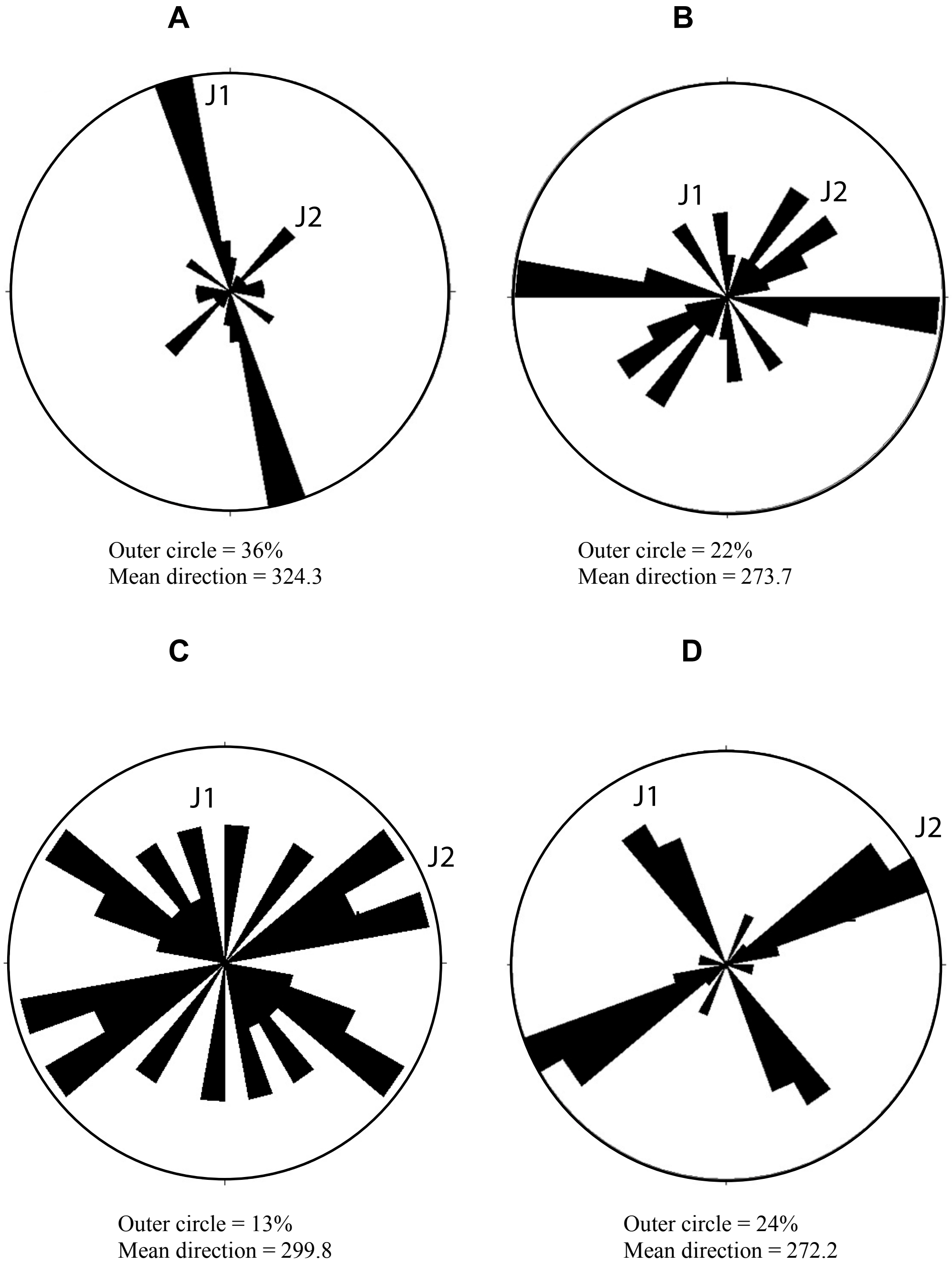

Figure 6: Fosset Gulch fractures. Data shows variability of fracture patterns by formation as measured in the Animas Formation (A), Kirtland Shale (B), Fruitland Formation (C), and Pictured Cliffs Sandstone (D).

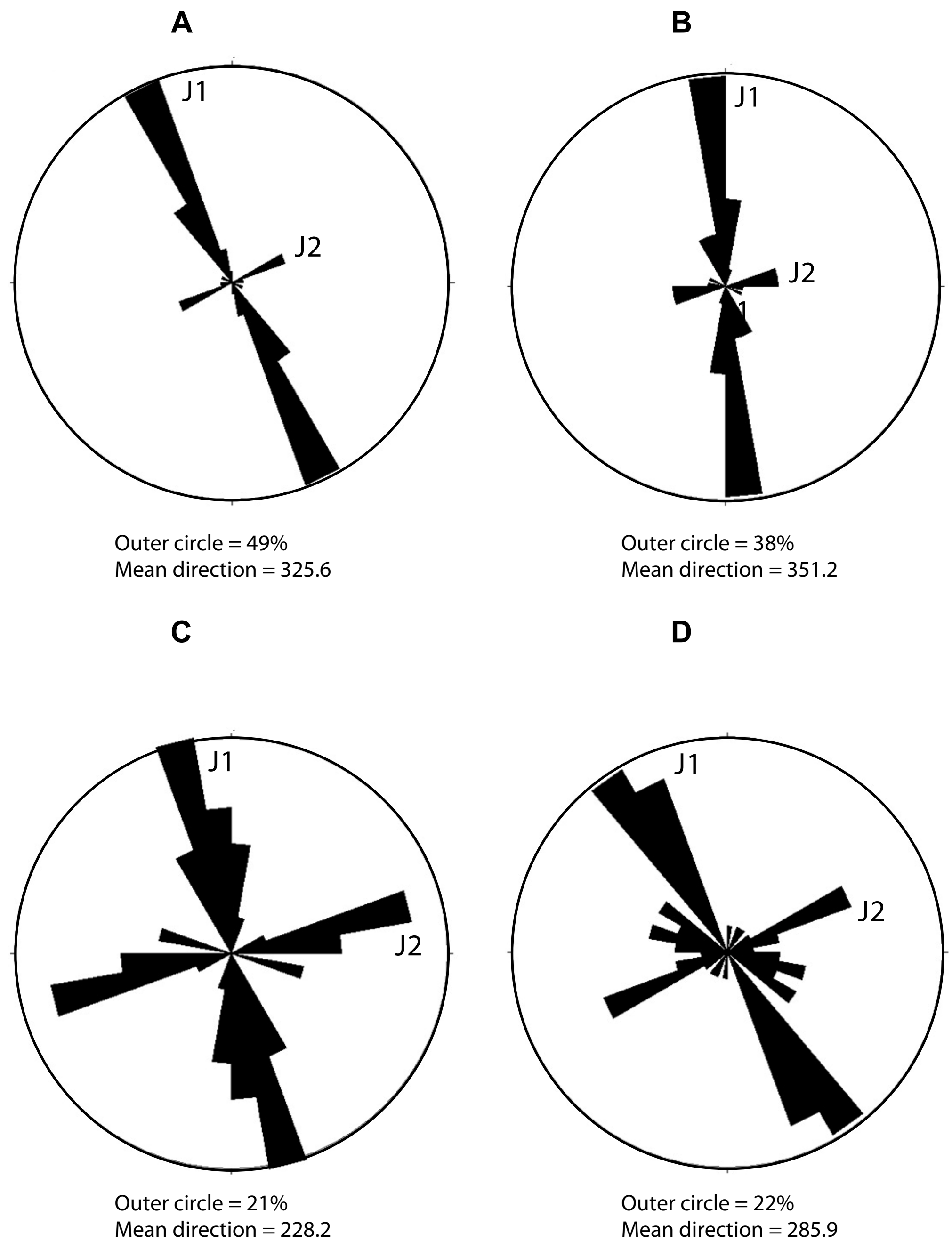

Figure 7: Chimney Rock coal mine fractures. Data shows variability of fracture patterns by formation as measured in the Animas Formation (A), Kirtland Shale (B), Fruitland Formation (C), and Pictured Cliffs Sandstone (D).

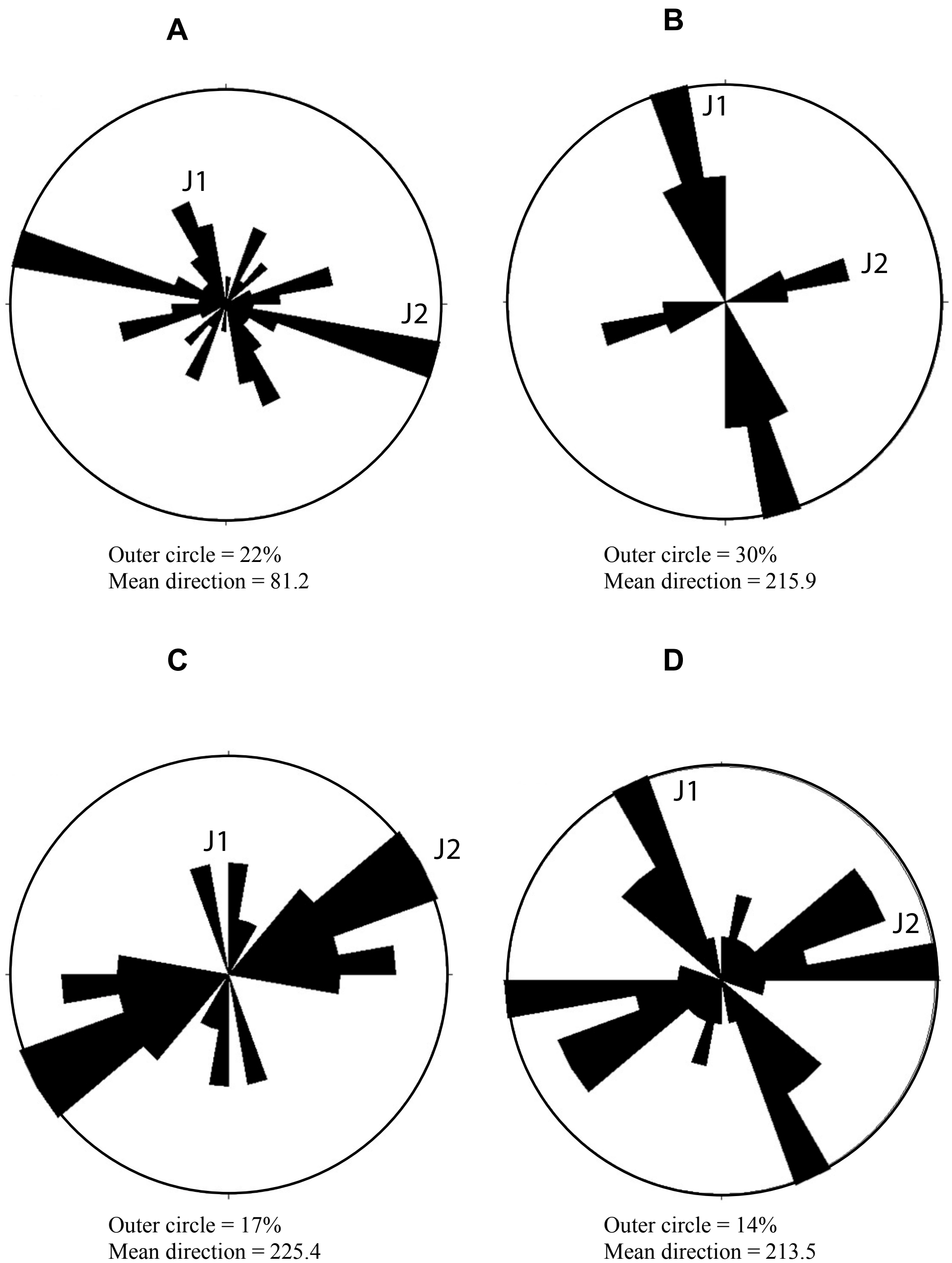

Figure 8: Cabezon Creek fractures. Data shows variability of fracture patterns by formation as measured in the Animas Formation (A), Kirtland Shale (B), Fruitland Formation (C), and Pictured Cliffs Sandstone (D).

Fracture densities are also important to fluid flow. Cox and others (2001) measured fractures in the upper part of the Pictured Cliffs Sandstone in this area. They concluded that although the upper bench of the unit is massively bedded, its primary permeability is low. The outcrop of this bench shows fractures without a random pattern, and fractures can be a secondary permeability feature that increases system or reservoir permeability. However fracture densities were low for this unit and the dominant permeability consisted of intergranular permeability unique to localized micro-fractures.

Causes for the fracture patterns in all formations observed here are not well understood. The fact that most of the joints are tensile fractures and do not show evidence of movement suggests that they formed perpendicular to the minimum principal compressive stress (σ_3). Condon (1989) proposed several different scenarios to create the joint patterns but favored a mechanism involving multiple episodes of northwest-directed compressional tectonics (horizontal σ_3) to generate J1, followed by uplift and unloading that re-oriented the stress field to create J2.

A plot of 204 trends shown on published maps (Wood, Kelley, and MacAlpin, 1948; Condon, 1989, and 1990) for mafic dikes exposed in the area gives an azimuth trend of ~24°. The trends of these dikes indicate NW-SE extension in the area during the mid-Tertiary that was accompanied by emplacement of mafic magmas and development of a series of NW-SE trending folds in the area around Pagosa Springs. The dominant trends of faults on these maps are mostly between 330° and 350° with dips northeast and southwest. This trend is similar to that of J1 joints. Subordinate fault trends are N-S, E-W, and from 20° to 50°. Cross-cutting relationships of the dikes and faults indicate that some of them may have developed at the same time, but in most instances dikes post-date the NW-trending faults (Gonzales, 2009).

Condon (1989) argued that the variability of orientations in J1 and J2 joints were not consistent with two distinct periods of extension, but rather episodic and changing principal compressive stress (σ_1) fields. Gonzales (2009) proposed that J1 fractures and NW-SE trending faults in the area are related to an early period of regional compression during the late Cretaceous to early Tertiary. This period of deformation is also reflected by a series of folds in southwestern Colorado (e.g., Hogback monocline). In the middle Tertiary NE-SW the compressive stress field appears to have shifted to NE-SW and was accompanied by NW-SE extension and emplacement of mafic dikes and related joints. The relationship of J2 within these regional events is uncertain, but might reflect rotation of the compressive field that generated the NE-SW trending dikes and joints. Development of the different joint sets in the region may have been influenced in part by later reactivation of basement structures.

Coal cleat orientations were measured at 44 stations in the study area. Primary coal cleat (face cleat) and butt cleat were measured at each station. In the study area, the coal face cleat strikes (or trends) within the Fruitland Formation are approximately 325° (N35W), with an average dip of 82° northeast. Butt cleat was measured at 25 stations with an average strike of N52E and a dip of 84° southeast. A few through-going regional fractures or J1 joint sets were observed near the abandoned Chimney Rock coal mine superimposed over the coal cleat in the coals. Condon (1989) also measured coal cleat in this area and determined that Fruitland coal beds have main or primary cleat trends that parallel the J1 and J2 fracture sets.

The main face cleat direction (325°) is significantly rotated west of the main face cleat direction in La Plata County, which averages 353° azimuth for the Fruitland coals in eastern La Plata County on the Ludwig Mountain quadrangle (Carroll and others, 1998). The face cleat orientations do not vary among any of the C_1-C_6 coal beds. The basal coals were usually thicker and more laterally contiguous. The upper Fruitland coal beds tend to be thinner, less contiguous, and of poorer rank, grading to carbonaceous shale and containing less cleat development.

Coal face-cleat trends usually determine the main direction for fluid flow. Groundwater production from coalbed aquifers occurs during production of coalbed methane wells. Water production reduces the pressure in the reservoir allowing methane to desorb from the coal beds and flow through the cleat system (Papadopulos and Associates, 2006; Cox and others, 2001). In western Archuleta County the main coal cleat direction is northwest-southeast, or parallel to the direction of the Fruitland outcrop along the rim of the San Juan Basin.

STRATIGRAPHIC COAL MAPPING AND CORRELATIONS

Using the measured sections collected along the outcrop, individual coal beds were correlated between sections. Field relations between the map and the measured sections gave a high probability of correlation for many of the thicker coal units. Coals were grouped by height above Pictured Cliff Sandstone, and then numbered by group. A cross-section along the outcrop was constructed using IHS PETRA software. PETRA is a relational database used in the petroleum industry for stratigraphic interpretations and contour mapping. Each measured section was entered as a vertical data point into PETRA, using the actual location of the top of the Pictured Cliffs Sandstone as the point location. The database contains stratigraphic top and bottom interval information for each coal bed from the measured sections. Using the cross-section module in PETRA the measured sections were correlated and displayed with correlations between the coals (see Cross-section Plates 5a and 5b). An arbitrary datum was selected for correlation purposes in the upper Group 2 coals that trend throughout the entire study area.

The coal beds mapped on each plate are also vectorized for GIS interpretations. Using ESRI ArcGIS 9.3 geostatistical functions, it is determined that the Fruitland coal beds in the study area have an average length of 1,457 ft and an average thickness of 4.49 ft on the surface (Table 4). The average coal bed thickness ranges from 2.13 ft thick for C_5 coals to 5.76 ft thick for C_1 coals. Average lengths of coal beds range from 363 ft for the C_6 coals to 2,596 ft for the C_1 coals. Note that thinner coal beds are not used much in the data because they are not as easily observed. Generally coal beds decrease in length and thickness higher in the section.

Depositionally, thicker coal beds developed during times of shoreline stability when the swamp was forming and vertical build-up of the backshore behind geographic shoreline stability of the Pictured Cliffs Sandstone (Fassett, 1988; Fassett, 2000). The longitudinal length of those coal beds indicates a long axis in the direction parallel to the shoreline, or northwest-southeast for this study. The outcrop study here is located nearly parallel to the interpreted paleoshoreline of the Pictured Cliffs Sandstone depositional setting, or northwest-southeast. Therefore, the very long lengths of continuous coal observed in this study may be attributed to the outcrop being parallel to this shoreline, and hence, the longitudinal direction of the outcrop.

Coal Bed Name (based on height above Kpc)	**Average Thickness (ft)**	**Maximum Thickness (ft)**	**Minimum Thickness (ft)**	**Average Length (ft)**	**Average Thickness *Shape Length (weighted representative value)**	**Number Samples (N)**
C_0	2.25	5	0.1	1,792	796	4
C_1	5.76	20	0.1	2,596	450	49
C_2	4.49	12	0.1	1,197	266	56
C_3	4.48	22.2	0.1	1,038	231	41
C_4	3.78	14.4	0.1	833	220	34
C_5	2.13	6	0.1	647	303	4
C_6	2.54	4.4	0.1	363	142	5
Total/Average All Coal Beds	**4.49**	**22.2**	**0.1**	**1,457**	**324**	**196**

Table 4. Statistical variations for coal bed thickness and length as calculated from mapped coal beds in the study area. Values tend to favor thicker coal beds because they outcrop more readily than thin coal beds.

GEOLOGIC MAP PLATE 1: BEAVER CREEK TO YELLOWJACKET PASS

(Map plates are numbered from west to east)

Most Fruitland outcrops in the San Juan Basin have a thick basal coal bed at the contact with the Pictured Cliffs Sandstone. This is not the case with the Map Plate 1 area and is a notable exception. The most recognizable similarity between the 3M study and the current study is the presence of a major Fruitland coal bed between 90 and 120 ft above the top of the Pictured Cliffs Sandstone. This coal was mined at the Shamrock Mine, and a measured section in the 3M study shows that bed. This coal correlates to the C_4 coals located 110 to 130 ft above the Pictured Cliffs Sandstone that continues from section A1 to A9 in Archuleta County (see Cross-section plate 5A). As correlated by the USGS (Barnes, 1953), a coal bed at this elevation was mined at the Columbine, Triple S, and Shamrock #2 mines; this coal bed has a maximum thickness of 15 ft at MS A1 near the Shamrock Mine. This same bed was correlated in the 3M study westward from the Shamrock Mine as an 11 ft mineable coal bed within ‘Interval 4’ and ‘Interval 5’.

Correlation of this coal bed from the Shamrock Mine to the Triple 'S' Mine is straightforward, but access across private land east of the Triple 'S' Mine was not possible in 2008, thus correlations in this area rely solely on USGS measured sections from 1953 (Barnes, 1953). Another C_4 coal bed at relatively the same distance above the top of the Pictured Cliffs (roughly 110 to 120 ft) is observed south of the Columbine Mine (north of Yellowjacket Pass) from MS A5 to MS A8; this bed has a maximum thickness of 17 ft. The C_4 coal bed is not present in MS A9.

Lower Fruitland coals are thinner and less continuous near the Shamrock Mine. This is unusual in the San Juan Basin because the basal Fruitland coals are almost always the thickest and most continuous (Fassett, 2000). In this area, the C_1 basal Fruitland coal beds have a large net coal thickness, but multiple non-coal partings are present between the coal beds. These discontinuous coal beds do not correlate well between measured sections. C_1 coals range in thickness from 0.2 ft to 3 ft between MS A1 and MS A4.

GEOLOGIC MAP PLATE 2: WAGON GULCH AND YELLOWJACKET GUARD STATION TO NORTHERN PETERSON GULCH

Southeast of Wagon Gulch, Fruitland coals thin to less than 30 ft net coal thickness (Figure 9). The Fruitland outcrop trends northwest and is parallel to the face-cleat direction here. South of Yellowjacket Guard Station, the Fruitland outcrop bends slightly to the west, but in the north part of Peterson Gulch it changes back to a northwest trend. The Pictured Cliffs Sandstone at the Yellowjacket Guard Station is very thin to almost non-existent in a westward direction where US 160 crosses the formation. This may imply faulting but no faults were found.

Figure 9: Lateral accretion surfaces in middle Fruitland Formation along highway US 160 road cut. Sandstone bed forms highlighted. Outcrop is parallel to the paleoshoreline.

Between the north end of Peterson Gulch and the junction of US Hwy 160 with the north end of Fosset Gulch Road some very thick dip-slope exposures of coal were noted. The thickest coal bed here is 22 ft thick. These coals are covered in north Peterson Gulch but reappear as thinner beds in Peterson Gulch dip slope exposures. Most of the coal in Peterson Gulch is covered by Quaternary alluvium. The Pictured Cliffs Sandstone forms a dramatic outcrop north and east of Peterson Gulch where it forms a long ridge on the west side of the Piedra River. This outcrop is parallel to the paleoshoreline and individual sandstone beds (shingles) can be traced for miles.

GEOLOGIC MAP PLATE 3: SOUTH END OF PETERSON AND FOSSET GULCH AT PIEDRA RIVER AND CHIMNEY ROCK COAL MINE

At the south end of Peterson Gulch C_2 and C_3 coals thicken and are clearly shown on the map. Much of this coal is covered by clinker. Private land access at the south end of Peterson Gulch was not allowed during the 2008 field season so most of the coal mapping there was from aerial photography only. Thick C_1 and C_2 coals were mapped along both sides of the Piedra River and correlated across the Quaternary alluvium. Geologic contacts for the Fruitland, Kirtland, and Animas formations were interpreted beneath the Piedra River alluvium using three-point geometry based on exposed bedrock attitudes.

A thick section of the Fruitland Formation is present near the Chimney Rock Mine area (Figure 10). Here C_1-C_5 coal beds occur at intervals up to 155 ft above the top of the Pictured Cliffs Sandstone. Stratigraphically, these thicker Fruitland coals are present one to two miles landward and west of Cabezon Canyon where the Pictured Cliffs Sandstone and Fruitland Formation intertongue. These relationships probably reflect peat swamps that occupied the same area for a sustained period of time as the position of the Pictured Cliffs Sandstone shoreline stabilized and backshore peat deposits built up vertically in tandem with the vertical buildup of the adjacent Pictured Cliffs shoreface sands (Fassett, 2000; Fassett and Hinds, 1971). This intertonguing may be stratigraphically connected in a northwest direction to the Fruitland tongue of the 3M study that outcrops in the Rules Hills quadrangle.

Figure 10: Fruitland Formation coal beds truncating at low angles to overlying sandstone near Chimney Rock Coal Mine. Unconformable surface above coal bed units indicates distributary channel switching.

Large clinker polygons cover the map just north of the Chimney Rock Mine in dipslope outcrops. C_1 coals were mapped up to the ridgeline north of the Chimney Rock Mine and may be observed on the ridge as far north as the road leading to the Chimney Rock Archaeological Area. The C_1 coals are of poor quality and rank (subbituminous) with carbonaceous shale common. Minor intertonguing with white Pictured Cliffs Sandstone benches occurs here also at the contact.

An excellent exposure of C_1 and C_2 coals occurs at the mouth of Deep Canyon near US Hwy. 151. An abandoned coal mine opening shows 5 ft of mineable coal with overbank splay deposits in the claystones above. These coal beds are readily traced to the east from this point to Heath's Haven MS-17. The Fruitland Formation is over 159 ft thick here with more than five coal beds exposed.

GEOLOGIC MAP PLATE 4: HEATH'S HAVEN, CABEZON CANYON, AND ARCHULETA CREEK CANYON

This plate shows the Fruitland outcrop trending westward at Cabezon Canyon and then bending to a northwest trend in Archuleta Creek. In this area, there is a Fruitland Formation tongue (Kft) representing a short interval of time during which a shoreline transgression of the Pictured Cliffs Sandstone occurred (Fassett and Hinds, 1971).

The Fruitland Tongue that interfingers with the Pictured Cliffs is documented in Cabezon Canyon where it reaches a maximum thickness of 7.4 ft measured in MS A18, on the west side of Cabezon Canyon. This coal bed is present a mile to the east but pinches out in the western rim of Archuleta Creek where it becomes a sandy coal bed. This bed is 4 ft thick on the east side of Cabezon Canyon.

The Fruitland Formation thins considerably east of Cabezon Canyon. There are no higher level coals (such as C_4 and C_5) east of the Pictured Cliffs Tongue between Cabezon Canyon and the Archuleta Creek canyon. As can be seen on the measured sections, C_4 and C_5 coal zones in MS A18 are 328 ft and 410 ft above the top of the Pictured Cliffs Sandstone. These coal zones completely pinch out into shale zones on MS A19 in the west side canyon of Archuleta Creek, and thus these rock strata are mapped as Kirtland Shale there. East of this point, the Fruitland Formation is less than 130 ft thick.

Large Fruitland pavement outcrops are left as pendants on the east canyon wall of Archuleta Creek. These carbonaceous shale, sandstone, and coal sections are erosional remnants and remain as islands of Fruitland Formation. At one of these pendants, the Tertiary Animas Formation unconformably overlies the Fruitland Formation, with the interpretation that the Kirtland Shale was eroded eastward from the Archuleta Creek area.

METHANE SEEPS

During mapping of the study area geology our team looked for visual signs of active methane gas seeps and distressed vegetation. The surface expression of methane gas seepage may be the result of naturally occurring methane in coal seams, or the inefficient capture of coalbed methane liberated near the outcrop. This was not the major scope of this project, but this information was collected to help locate and study possible seep areas along the Fruitland outcrop. Many localities of distressed vegetation were discovered and placed on the map. The ArcGIS project attribute data contains detailed information about those locations. The BLM/FS Environmental Impact Statement (2006) states that the main problem related to methane seeps includes the potential for methane to contaminate groundwater aquifers and surface water resources used by locals in this area. There is also the potential for gas seeps to harm vegetation and soils, and for hydrogen sulfide gas to accumulate in low-lying areas causing health risks.

Methane seeps from Fruitland coals in low-lying topographic areas such as Cabezon Canyon, Piedra River valley, and at Squaw Creek have the greatest potential for environmental impact in this study area. The BLM/FS EIS states that homes of potentially affected landowners in these areas will be continuously monitored for methane seepage. Several of these homes have been built immediately above the Fruitland Formation. Monitoring of these areas as coal bed-methane development occurs down dip from Fruitland Formation coal bed outcrops will provide much needed data to determine whether or not such development results in increased gas seepage.

The removal of water from coal seams at the outcrop may increase the risk of spontaneous combustion. Cbm development near the outcrop depressurizes the coal seam and may create a condition where oxygen replaces water in the coal seam. The risk of underground coal fires where oxygen is able to reach the dewatered coals enough to sustain combustion should be assessed (BLM/FS EIS, 2006).

There were no significant methane gas seeps observed while conducting this geologic map. H_2S detectors were used while excavating coal for measured sections and coal cleat data, but none were detected. Visual signs of seeps in creeks were not apparent, but seep traces were noted in Cabezon Canyon

In 2007, LT Environmental conducted a gas seep study along 18 miles of Fruitland outcrop on the west side of the study area. This study included an outcrop air monitoring program to assess potential methane gas impacts along the Fruitland outcrop (LT Environmental, 2006; LT Environmental, 2007). This study concluded that methane seepage along the Fruitland Formation outcrop in Archuleta County is very low. Flux rates measured are significantly lower than those measured in La Plata County, CO over the same period. Methane seeps were observed in Squaw Creek, but were determined to be near-surface microbial swamp gas (of biogenic origin) only. No methane seeps were observed in Beaver Creek, Yellowjacket Pass, Little Squaw Creek, Pole Gulch, and Peterson Gulch (LT Environmental, 2006).

SUMMARY

This study provides geologic data for the general public, oil and gas companies, government officials, and regulators. It provides the user with a stratigraphic framework with which to visualize and interpret Fruitland Formation coal beds along the outcrop. This 23-mile stretch of public and private property in Archuleta County is one of the last parts of the San Juan Basin to be mapped at large scale (1:24,000 or larger). These data can now be added to regional stratigraphic and structural maps to fill geologic voids in this part of the San Juan Basin.

The 1:24,000 scale geologic index map shows the formation contacts for all of the Upper Cretaceous units in western Archuleta County, Colorado. Previously published maps combined the Fruitland and Kirtland Shale (and in some places the Pictured Cliffs Sandstone) as one geologic unit. This new map shows all these formation contacts for the first time in this area. The Pictured Cliffs/Fruitland Formation contact can be used by COGCC for regulatory purposes. The Fruitland Formation/Kirtland Shale contact, an irregular and gradational contact, was also mapped for the first time in Archuleta County.

The four geologic plates show detailed coal bed outcrops at a scale of 1:12,000. These maps are useful for regulators and industry alike to locate coalbed methane operations and coal mining purposes in detail. The maps are useful for locating distressed vegetation, coal bed lithology and structural information, and analytical coal data. GIS applications with this CD include an ArcReader map for the non-GIS user to view map by computer, or shapefiles and Arc project for the GIS user. Maps may be printed using Adobe pdf programs.

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