Geologic Model of the Purgatoire River Watershed within the Raton Basin, Colorado

PREPARED FOR:

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May 2011

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Acknowledgements

The Colorado Geological Survey submitted a grant application on January 30, 2008 to the Colorado Water Conservation Board (CWCB) Severance Tax Trust Fund Operational Account for funding to execute this study. The application was approved and CWCB entered into an interagency agreement with CGS on October 27, 2009. We would like to thank Mr. Steve Miller of the CWCB for his support, input, and assistance in finalizing the scope of work for this project and management of the fiscal and contractual matters.

The Colorado Geological Survey was fortunate to hire Mr. Rob Jaecks on a temporary basis to assist on this project. Rob was invaluable in compiling, analyzing, and presenting a variety of geologic and hydrologic data. Colorado Geological Survey permanent staff also provided critical assistance and work products particularly in the application of GIS software. Mr. Chris Carroll, coal geologist for the CGS, provided the original PETRA database and coal bed correlations and picked the top and bottom contact of the Raton Formation in 700 wells for this study. Mrs. Karen Morgan assisted in producing elevation profiles for the cross-sections. Mr. Larry Scott assisted with graphical services, producing final figure and display graphics from preliminary work products.

We wish to acknowledge the previous work done in this same area by Ken Watts of the U. S. Geological Survey. In 2006, Ken published Scientific Investigations Report 2006-5129 that provided an improved definition of the hydrostratigraphic framework of the Raton, Vermejo, and Trinidad aquifers in Las Animas County, Colorado. His work included contour maps of the generalized altitude of the tops and bottoms of these same formations. The control points for his mapping included water well information from the Division of Water Resources and oil and gas well information from the Colorado Oil & Gas Conservation Commission. Ken utilized geologic information from scout cards of 1,305 CBM wells and applied geostatistical (kriging) computer contouring methods to produce structure contour maps. His map products were also made available electronically as spatial data through the web (http://water.usgs.gov/lookup/getgislist). The geologic formation structure contour maps presented in this report have much in common with the work produced by Ken Watts, e.g. data sources, data manipulation, software application, and resultant products. This overlap was not intentional. The scope of work for the CGS project was initially much broader and subsequent derivative analysis using the formation surfaces was anticipated. That original scope of work,

however, was modified as the State Engineer initiated rule-making on produced water. While we were aware of Ken's work and performed some preliminary quality control based on his mapping, we collected, analyzed, modified, and presented the data used in our study completely independent of any work that preceded our study. The differences between the common products produced by Ken Watts and those presented herein are:

- Focus on hydrostratigraphic framework versus the geologic model, i.e. consideration of hydrostratigraphic units versus discrete geologic formations. This may not be that significant as the top of Raton, Vermejo, and Trinidad aquifers as described by Watts appears to be the same as their respective geologic formations;
- CGS was able to benefit from the more detailed mapping, which we digitized and geo-referenced, resulting in greater positional accuracy of surface geologic formation contacts;
- The difference in the study timeframes also resulted in a greater number of oil and gas well control points for the CGS study;
- Final CGS structure contours were modified and manipulated by hand using professional judgment, whereas Watts' utilized computer software for contour generation, smoothing, and editing; and
- The CGS structure contour maps were limited to the Purgatoire River watershed and produced at a higher resolution with a contour interval of 100 feet.

1.0 INTRODUCTION AND PURPOSE

The coal resources of the Raton Basin of southeastern Colorado have been critical to the development and economy of this region since the late 1800s (Figure 1.1). When large-scale, commercial coal mining ceased in the mid 1990s, a new extractive industry, production of coalbed methane (CBM) started to boom. The production of natural gas (CBM) from coal seams in the Vermejo and Raton Formations in Las Animas County increased from 28 billion cubic feet (BCF) in 1999 to over 126 BCF in 2008 (Colorado Oil & Gas Conservation Commission). Groundwater coproduced by CBM wells in Las Animas County also increased dramatically from 22.9 million barrels in 1999 to a peak of 119 million barrels in 2007 (Colorado Oil & Gas Conservation Commission). The coal-bearing geologic formations critical to these industries are also part of the aquifers upon which residents rely for water supply. The mineral and water resources of the basin have and continue to play an integral part in the development and economy of the region. Furthering our understanding of the geologic formations that comprise these resources affords the best opportunity to effectively manage and protect them.

In 2009, the Colorado Water Conservation Board funded a severance tax grant request by the Colorado Geological Survey to study these resources. The purpose of this geologic investigation was to provide additional information and develop a geologic model to depict the stratigraphic and structural relationships of the coal-bearing formations in the Purgatoire River watershed of Las Animas County, Colorado (study area). The vast majority (nearly 90%) of the CBM production in the Colorado portion of the Raton Basin has been concentrated within the Purgatoire River watershed of Las Animas County. This study was undertaken because of the recent interest in and need to protect and manage both the mineral and water resources within these relatively shallow formations, and is facilitated by a large amount of recent subsurface data available from over 3,500 geophysical well logs acquired from CBM wells over the past fifteen years. The analysis and interpretations provided herein were made by integrating available surface and subsurface geologic data in a GIS environment to construct structural and stratigraphic cross-sections; develop maps depicting the structural surfaces of the Pierre Shale, Trinidad Sandstone, Vermejo, and Raton Formations; identify coal zones, and assemble a new digital composite surface geologic map from previous geologic investigations in the area. These formation surfaces, in digital format, provide for future geospatial analysis and model integration.

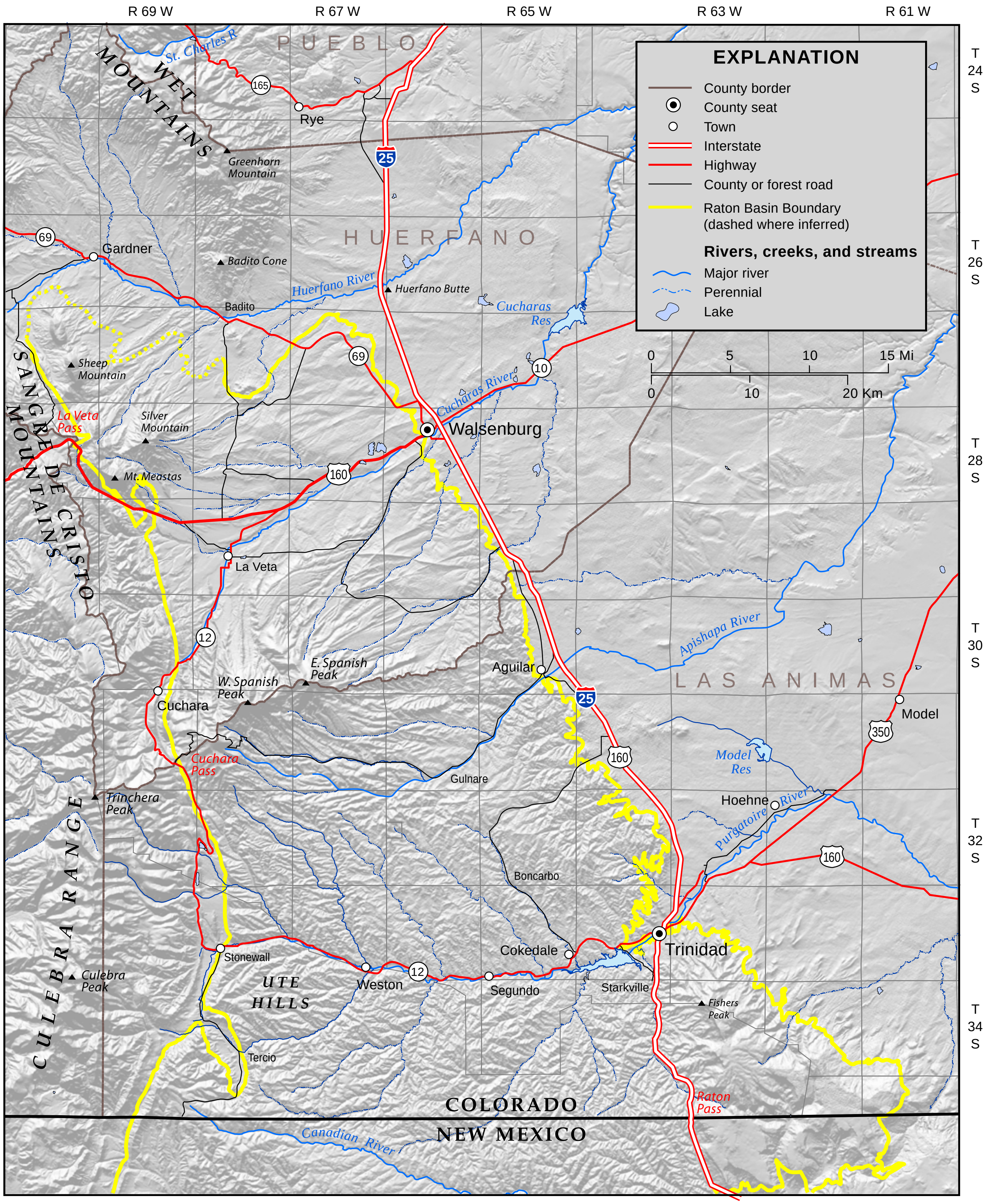


Figure 1.1 Geographic Reference Map for the Raton Basin and its Major Drainage Systems

2.0 REGIONAL AND GEOLOGIC SETTING OF THE RATON BASIN

The Raton Basin of southern Colorado and northeastern New Mexico is the southernmost of several coal-bearing basins along the eastern margin of the Rocky Mountains. The region contains an estimated 2.7 billion tons of bituminous coal reserves (Geldon, 1989). While active commercial coal mining in the Colorado portion of the basin ceased when the Allen mine closed in 1984, the region has become one of Colorado's major producers of coalbed methane since the mid 1990s. Total gas production in 2008 within the Colorado portion of the basin was 148.6 billion cubic feet of gas; the majority of which was produced in Las Animas County (126 BCF) (Colorado Oil & Gas Conservation Commission, 2009). The USGS (2005) has estimated that 1.6 trillion cubic feet of gas reserves remain undiscovered from Raton and Vermejo Formation coals within the basin.

The Raton Basin covers an area of about 2,200 square miles extending from southern Colfax County, New Mexico, northward into Huerfano County, Colorado (Figure 2.1). It is bounded by the Sangre de Cristo Mountains and Culebra Range to the west, the south edge of the Wet Mountains to the north, the Apishapa Arch to the northeast, the Las Animas Uplift to the east, and the Sierra Grande uplift to the south and southeast. The basin is an elongate asymmetric syncline that extends 80 miles north to south and as much as 50 miles east to west. The axial trace of the basin is represented by the La Veta syncline resulting in a steep eastward dip of the sedimentary rocks on the west limb (20-90 degrees), adjacent to the Sangre de Cristo Mountains, and a gentler westward dip (2-10 degrees) on the east limb (Tyler and others, 1991; Tremain, 1980). Sedimentary rocks along the western edge of the basin are extensively deformed by steeply dipping thrust faults and several major folds (Hemborg, 1998). Normal faulting within the basin generally displaces strata less than 50 feet (Rice and Finn, 1996). The deepest part of the basin is located approximately 15 miles southwest of Walsenburg. Total sediment thickness is 15,000-25,000 feet on the western side of the basin and 10,000 feet on the eastern side (Tremain, 1980).

The Raton structural basin was part of the larger Rocky Mountain foreland basin and contains sedimentary rocks as old as Devonian overlying Precambrian basement (Tremain, 1980). While the Raton Basin has a complex structural and stratigraphic history, its geologic formations are typical of the southern Rocky Mountains (Figure 2.2). A geologic map of the basin, based on Johnson's (1969) geologic map of the Trinidad quadrangle, is presented as Figure 2.3. During the Upper Cretaceous

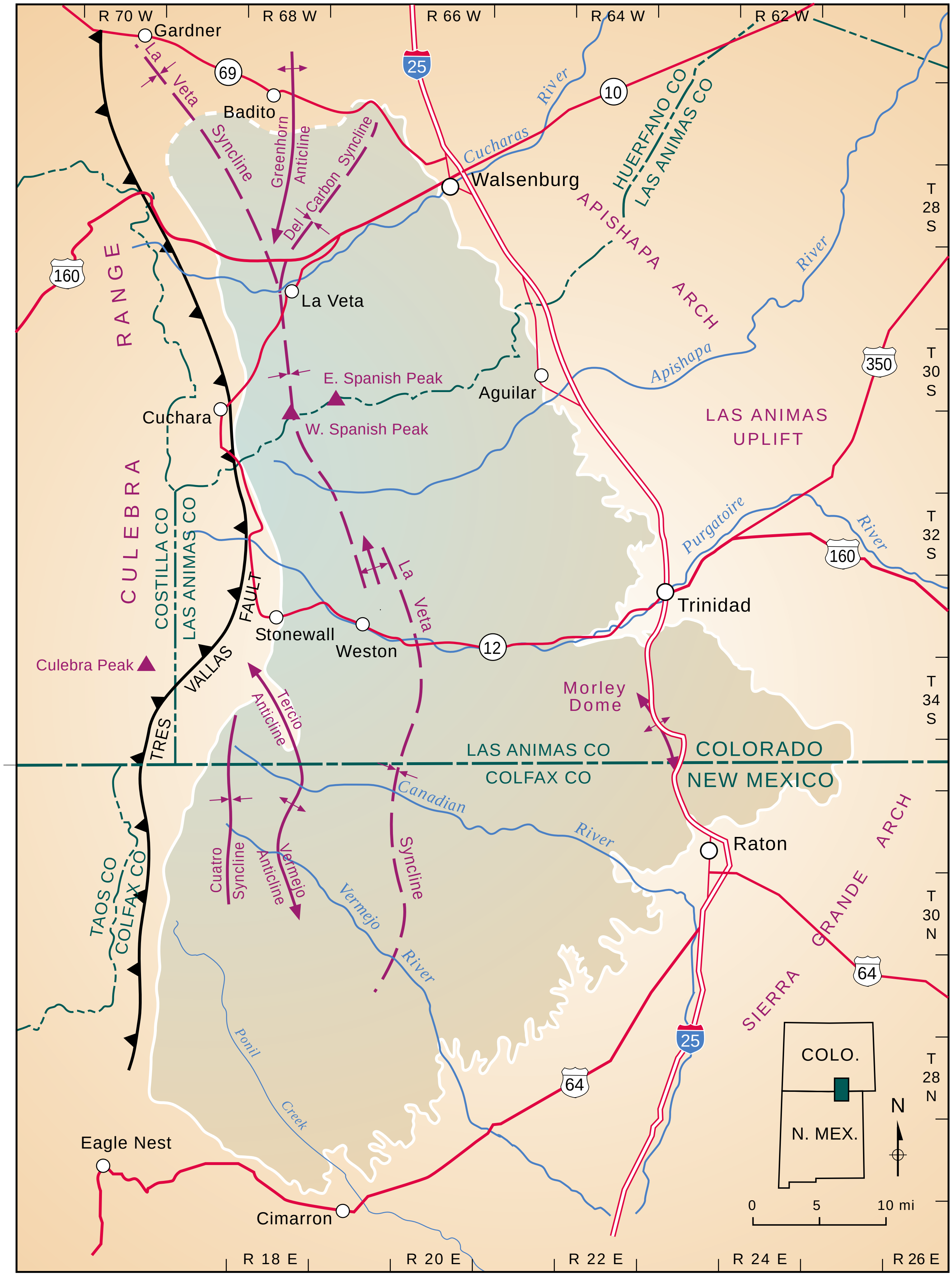


Figure 2.1 Location of the Raton Basin in Colorado and New Mexico Showing Structural Features

ERA	PERIOD / EPOCH	FORMATION	THICKNESS (FT)	LITHOLOGY
CENOZOIC	Recent		0—30	Alluvium, basalt flows
CENOZOIC	Miocene	Devils Hole Formation	25–1,300	Light-gray conglomeratic tuff and conglomerate
CENOZOIC	Oligocene	Farisita Formation	0–1,200	Buff conglomerate and sandstone
CENOZOIC	Eocene	Huerfano Formation	0–2,000	Variegated maroon shale and red, gray, and tan claystone
CENOZOIC	Eocene	Cuchara Formation	0–5,000	Red, pink, and white sandstone, and red, gray, and tan claystone
CENOZOIC	Paleocene	Poison Canyon Formation	0–2,500	Buff arkosic conglomerate and sandstone, yellow siltstone, and shale
CENOZOIC	Paleocene	Raton Formation	0–2,000	Light-gray to buff sandstone, dark-gray siltstone, shale, and coal; conglomerate at base
MESOZOIC	Upper Cretaceous	Raton Formation		
MESOZOIC	Upper Cretaceous	Vermejo Formation	0–380	Dark-gray silty and coaly shale, buff to gray carbonaceous siltstone, and sandstone beds; coal
MESOZOIC	Upper Cretaceous	Trinidad Sandstone	0–260	Light-gray to buff sandstone
MESOZOIC	Upper Cretaceous	Pierre Shale	1,300–2,300	Dark-gray fissile shale and siltstone
MESOZOIC	Upper Cretaceous	Niobrara Group: Smokey Hill Marl	560–850	Yellow chalk, marine gray shale and thin white limestone; and light-gray limestone at base
MESOZOIC	Upper Cretaceous	Niobrara Group: Fort Hayes Limestone	0–55	
MESOZOIC	Upper Cretaceous	Benton Group: Codell Sandstone	0–30	Brownish sandstone, dark-gray shale, gray limestone and gray shale
MESOZOIC	Upper Cretaceous	Benton Group: Carlile Shale	165–225	
MESOZOIC	Upper Cretaceous	Benton Group: Greenhorn Limestone	30–80	
MESOZOIC	Upper Cretaceous	Benton Group: Graneros Shale	185–400	
MESOZOIC	Lower Cretaceous	Dakota Sandstone	100–200	Buff sandstone, buff conglomerate sandstone, and dark-gray shale
MESOZOIC	Lower Cretaceous	Purgatoire Formation	100–150	
MESOZOIC	Jurassic	Morrison Formation	150–400	Variegated maroon shale, gray limestone, red siltstone, gypsum, and gray sandstone
MESOZOIC	Jurassic	Ralston Creek Formation	30–100	
MESOZOIC	Jurassic	Entrada Sandstone	40–100	
MESOZOIC	Triassic	Dockum Group	0–1,200	Red sandstone, calcareous shales, and thin limestones
PALEOZOIC UNDIVIDED			5,000–10,000	Variegated shales, arkose, conglomerates, and thin marine limestone

(After Tremain, 1980)

Figure 2.2 Stratigraphic Sequence of the Mesozoic and Younger Aged Geologic Units in the Raton Basin

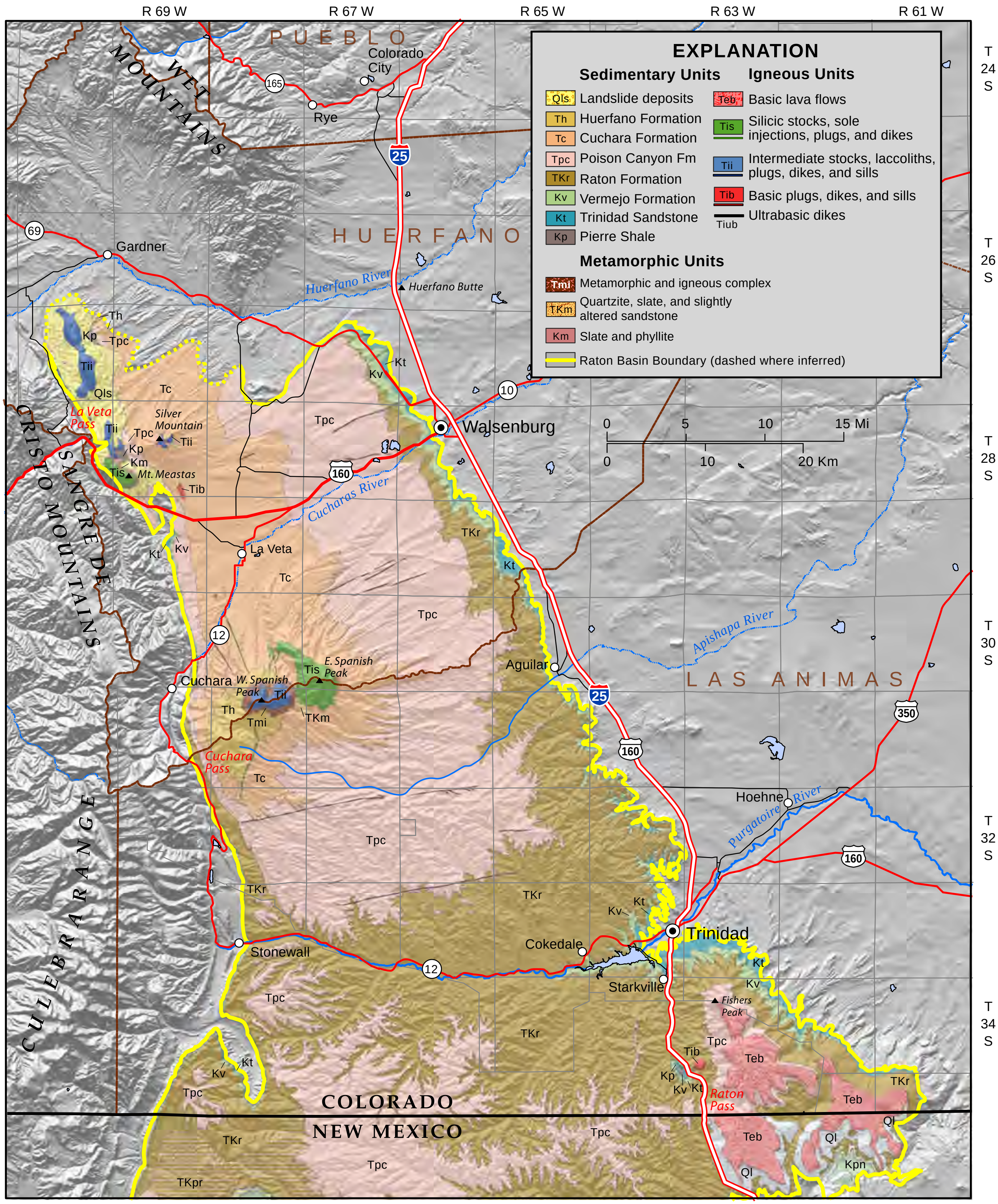


Figure 2.3 Geologic Map of the Raton Basin

period, the position of the Western Interior Seaway dictated the depositional environment: marine, shoreface, or continental (Figure 2.4). The Raton Basin contains a nearly complete Cretaceous and Tertiary stratigraphic sequence of sedimentary rocks that include the coal-bearing Vermejo and Raton Formations (Close and Dutcher, 1990a). The marine Pierre Shale was conformably deposited on the Smoky Hill Member of the Niobrara Formation during late Cretaceous. The upper 200 to 300 feet of the Pierre Shale becomes sandy and forms a gradual transition zone that intertongues with the Trinidad Sandstone marine shoreface. The upper Pierre Shale transition zone marks the final regression of the Western Interior Seaway in the Raton Basin. The Trinidad Sandstone is a ledge-forming sandstone depositionally correlative with the Pictured Cliffs Sandstone in the San Juan Basin and the Fox Hills Sandstone of the Denver Basin.


Figure 2.4 Western Interior Seaway and approximate position of the Raton Basin (modified from Blakey, 2010)

The upper Trinidad intertongues with and is overlain by the coal-bearing Vermejo Formation (Tremain, 1980). The nearshore, fluvial-deltaic deposits of the Vermejo contain the best developed and most laterally extensive coal beds in the basin. The late Cretaceous to Paleocene Raton Formation, which is also coal-bearing, overlies the Vermejo. Syndepositional clastic sediments shed off the rising Sangre de Cristo Mountains were deposited near the mountain front as the Raton basal conglomerate and mark the erosional contact between the Raton Formation and the underlying Vermejo Formation (Stevens and others, 1992). The Tertiary Poison Canyon Formation, consisting of continental sediments deposited as the Laramide uplift continued, unconformably overlies the Raton Formation. Up to 10,000 feet of Tertiary sediments were originally deposited in the basin, but erosion has removed much of them (Hemborg, 1998). In the northern part of the basin, the Poison Canyon Formation is overlain by clastic floodplain deposits of the Cuchara, Huerfano, and Farisita Formations. Subsequent uplift and erosion removed most of the Middle Tertiary and younger sediments and partially exhumed the Upper Cretaceous Vermejo and Raton Formations (Stevens and others, 1992). Quaternary alluvial deposits of limited extent and thickness have been deposited along the present stream and river drainages.

Young igneous rocks (Late Oligocene to mid Miocene) form the Spanish Peaks stocks and radial dikes in the northern portion of the basin along the Huerfano and Las Animas county line. Igneous intrusive rocks of mafic to intermediate composition were emplaced as stocks, laccoliths, plugs, dikes, and sills throughout the coal-bearing Vermejo and Raton Formations (Johnson, 1961). The dikes produced limited alterations when intruded within coal-bearing rocks. Sills on the other hand commonly intruded coal seams and altered, assimilated, and destroyed the original coal. A study of the intrusive rocks in the basin was not an objective of this report.

The Raton Basin is delineated by the outcrop of the Trinidad Sandstone, which encompasses an area of approximately 1,320 square miles in Colorado (Figure 1.1). Much of the coal region of the Raton Basin in Colorado coincides with the Park Plateau section of the Great Plains physiographic province (Fenneman, 1931). The Park Plateau is deeply incised by two of the three major drainages in the basin, the Purgatoire and Apishapa Rivers and their tributaries (Figure 1.1). The Cucharas River, north of the Spanish Peaks, drains the northern portion of the basin. Topography ranges from fairly flat along the Cucharas River west of Walsenburg to very steep and rugged in the vicinity of the Spanish Peaks. The lowest elevation is just over 6,000 feet, along the Purgatoire River west of Trinidad, while the highest elevation occurs at West Spanish Peak (13,626 feet). Most of the Park Plateau area ranges in elevation from 6,400 to 8,400 feet.

3.0 UPPER CRETACEOUS AND LOWER PALEOCENE GEOLOGY

A more detailed description of the Upper Cretaceous and Paleogene geologic units is presented below. A stratigraphic chart, presented as Figure 3.1, summarizes the physical characteristics of the Upper Cretaceous and younger sequence. A new digital composite geologic map (Plate 1) was compiled from multiple mapping programs to portray the basin's geology and structure at the greatest level of detail available. The sources of the surface geologic mapping and limitations of the composite map are discussed in Section 4.0, Data Sources and Methodology.

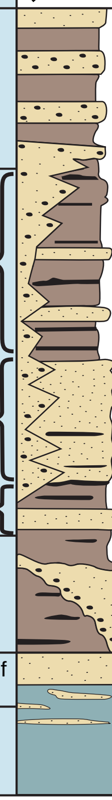
Pierre Shale

The upper Cretaceous marine Pierre Shale was deposited in the Western Interior Seaway and what was to become the Laramide age Raton structural basin. The Pierre Shale thickens northwestward from about 1,800-1,900 feet thick in eastern Colfax County, New Mexico to about 2,000-2,300 feet thick in the vicinity of the Spanish Peaks and Walsenburg, Colorado (Wood, Johnson, and Dixon, 1957). It consists of dark gray to black non-calcareous shale with thin zones of calcareous and iron carbonate concretions (Johnson and Wood, 1956). The upper 200 to 300 feet of the Pierre Shale, containing light gray siltstone and fine sandstone interbedded with darker shale, has been called the "transition zone" by Lee (1917). The sandstone beds become more numerous and increase in thickness higher in the transition zone as it grades into the base of the blocky, massive-bedded Trinidad Sandstone. Some authors (Lee, 1917; Johnson and Wood, 1956; Woodward, 1984; and others) include the "transition zone" in the Pierre Shale and place the top of the Pierre Shale at the top of the transition zone. Other authors (Hills, 1899; Matuszczak, 1969; Stevens and others, 1992) include the transition zone as the lower part of the Trinidad and place the top of the Pierre at the base of the transition zone. For this study, the transition zone is considered part of the Pierre Shale and the base of the Trinidad Sandstone is selected as the formation contact, as this is a more consistent pick on geophysical logs.

Trinidad Sandstone

The Trinidad Sandstone, ranging in thickness from 0 to 260 feet, is a light gray to buff, locally arkosic sandstone with a few thin beds of tan or gray silty shales. Its depositional environment is a prograding marine shoreface. Billingsley (1978) and Monzolillo (1976), divide the Trinidad into an upper fluvial zone and a lower, delta-front sandstone. Lee (1917) included the lower delta-front sandstones of Billingsley in the Pierre Shale.

AGE		FORMATION NAME	GENERAL DESCRIPTION	LITHOLOGY	APPROX. THICKNESS IN FEET
TERTIARY	PALEOCENE	POISON CANYON FORMATION	SANDSTONE–Coarse to conglomeratic beds 13–50 feet thick. Interbeds of soft, yellow-weathering clayey sandstone. Thickens to the west at expense of underlying Raton Formation		0–2,500
TERTIARY	PALEOCENE	RATON FORMATION	Formation intertongues with Poison Canyon Formation to the west UPPER COAL ZONE–Very fine grained sandstone, siltstone, and mudstone with carbonaceous shale and thick coal beds		*600–1,100* 0–2,000
TERTIARY	PALEOCENE	RATON FORMATION	BARREN SERIES–Mostly very fine to fine grained sandstone with minor mudstone, siltstone, with carbonaceous shale and thin coal beds		*180–600* ←K/T Boundary
MESOZOIC	UPPER CRETACEOUS	RATON FORMATION	LOWER COAL ZONE–Same as upper coal zone; coal beds mostly thin and discontinuous. Conglomeratic sandstone at base; locally absent		*150–300*
MESOZOIC	UPPER CRETACEOUS	VERMEJO FORMATION	SANDSTONE–Fine to medium grained with mudstone, carbonaceous shale, and extensive, thick coal beds. Local sills		0–380
MESOZOIC	UPPER CRETACEOUS	TRINIDAD SANDSTONE	SANDSTONE--Fine to medium grained; contains casts of *Ophiomorpha*		0–260
MESOZOIC	UPPER CRETACEOUS	PIERRE SHALE	SHALE--Silty in upper 300 ft. Grades up to fine grained sandstone. Contains limestone concretions		1,300-2,300



Adapted from Flores and Bader (1999), Tyler and others (1991), and Tremain (1980).

Figure 3.1 Detailed Stratigraphic Chart of the Upper Cretaceous and Younger Units in the Raton Basin

Stevens and others (1992) divide the Trinidad into three separate units. The basal unit consists of distal offshore bar deposits of a lower delta front environment that include alternating lenses of very fine-grained sand and shale. The middle unit is a fine-grained sand deposit of the lower delta front. The upper part of the Trinidad is a fining upward, medium to fine-grained delta front deposit that intertongues with and is conformably overlain by the coal-bearing Vermejo Formation. The contact is marked by a thick, coal-bearing sequence in most regions of the basin.

Vermejo Formation

The Vermejo Formation is a 0 to 550 foot thick delta plain deposit consisting of sandstones interbedded with siltstones, shales, and coal. The Vermejo was deposited conformably on the Trinidad Sandstone and includes channel, lagoon, coastal swamp, and delta plain deposits (Stevens and others, 1992). Peat beds which would later form the extensive coal deposits of the Vermejo formed in poorly drained swamps in the delta plain. These coals are the thickest and most laterally extensive coal beds in the Raton Basin. Individual coal seams in the Vermejo Formation range from a few inches to a maximum 14 feet thick. In aggregate, total coal thickness typically ranges from 5 to 35 feet (EPA, 2004). The formation forms gentle slopes or valley floors between sandstones of the underlying Trinidad and overlying Raton Formations. Tremain (1980) presents a detailed characterization of the individual deposits of the Vermejo Formation. The contact between the Vermejo and the overlying Raton Formation is locally characterized by a proximal conglomerate sourced from erosion during uplift of the Sangre de Cristo Mountains. The outcrop area of the Vermejo Formation, as presented on Plate 1, is limited to the edges of the basin, the Morley Dome, and areas down cut by the Purgatoire River west of Trinidad.

Raton Formation

The Raton Formation is a 0 to 1,925 foot thick continental alluvial plain deposit consisting of siltstones, sandstones, shales, coal beds, and a basal conglomerate. This lithology is a complex series of channel, overbank, and swamp deposits representing a fluvial meander belt. The Raton Formation contains one of the world's best preserved Cretaceous/Tertiary (K/T) time boundaries (Orth and others, 1981; Pillmore and Flores, 1987). Tschudy and others (1984) and Pillmore and Flores (1984) placed the K/T boundary (Figure 3.2) near the top of the lower coal-rich interval below the sandstone dominated barren series. The Raton Formation is exposed over much of the basin (Plate 1). Because of extensive erosion, particularly in the eastern part of the basin, much of the upper coal zone is no longer present (Stevens and others, 1992).

Figure 3.2 The K/T boundary in Longs Canyon. The boundary is represented by the light colored thin clay layer directly below the massive sandstone bed.

Lee (1917) divided the Raton Formation into a basal conglomeratic interval, a lower coal rich zone (LCZ), a barren sandstone dominated series, and an upper coal-rich zone (UCZ). The basal conglomerate, where present, is as much as 50 feet thick and consists of interbedded pebble conglomerate and granule, quartzose sandstone (Pillmore and Flores, 1987). The lower coal rich zone ranges from 100 to 250 feet thick and is composed of interbedded coal, carbonaceous shale, mudstone, siltstone, and sandstone. The barren series ranges in thickness from 180 to 600 feet. It is dominated by fine-grained sandstones with minor mudstone and siltstone layers and occasional coal beds. The upper coal-rich interval ranges from 600 to 1,100 feet thick, and consists of interbedded sandstone, mudstone, siltstone, coal, and carbonaceous shale (Flores and Bader, 1999). Lee's (1917) divisions for the Raton Formation are used in this report as they more clearly identify the coal zones within the Raton Formation.

In the 1950s, the USGS conducted detailed coal investigations in this region. Wood and others (1951, 1957) have divided the Raton Formation into three members (upper, middle, and lower) based on the stratigraphic position of persistent zones of sandstone observed in outcrop. Those authors describe the Raton members as follows: "The rocks that make up any member of the Raton are neither individually nor collectively distinguishable from any other rocks in the formation. The members may be recognized only by their relative position in the formation and not by distinctive lithologies." Their mapping and classification is included in the revised, composite geologic map (Plate 1) though the three members of the Raton Formation have been collapsed into a single unit due to their non-distinct descriptions.

Harbour and Dixon (1959) have divided the Raton into three general informal units: "a basal conglomerate, a middle coal-bearing unit, and an upper transition zone". The authors indicate that "the units were not mapped separately because of the thinness of the basal conglomerate and the indefinite nature of the boundary between the middle and upper units". The geologic map of Harbour and Dixon was incorporated into the northeast portion of the composite map (Plate 1) but does not identify the informal Raton units in that area. We offer this discussion on the nomenclature and classification of the Raton Formation in an attempt to correlate and clarify historic uses.

Most of the Raton Formation coals formed in well drained, small, shallow flood basins cut by crevasse splay and channel sands. The resulting thin, discontinuous coal seams range from inches to 10 feet thick with total aggregate coal deposits ranging from 10 to 140 feet (Stevens and others, 1992). The coal seams are characteristically lenticular with lateral continuity of 500 to 1,000 feet (Clarke and Turner, 2002). Although the Raton Formation contains more coal in aggregate than the Vermejo, individual seams are thinner and less continuous, and they are distributed over 1,200 feet of vertical section. Between 5 and 15 individual coal seams produce coalbed methane for wells in the basin as does the methane charged Raton conglomerate (Hemborg, 1996; Carlton, 2006). The Raton Formation grades westward into, and in the north is unconformably overlain by, the conglomeratic Poison Canyon Formation.

Poison Canyon Formation

The Poison Canyon Formation is a 0 to 2,500 foot thick Paleocene age deposit consisting of poorly sorted conglomerates and sandstones interbedded with shales and mudstones. The formation was first described by R.C. Hills in 1891 at Poison Canyon in Huerfano County, Colorado. Because of the similar lithology of the Poison Canyon and Raton formations, it is often difficult to identify the contact boundary. Typically, the base of the lowest sandstone containing unweathered feldspar grains is chosen as the boundary (Tremain, 1980). The Poison Canyon Formation is exposed over much of the northern portion of the basin. This formation is overlain by clastic floodplain deposits of the Cuchara, Huerfano, and Farisita formations. The Cuchara Formation unconformably overlies the Poison Canyon and consists of up to 5,000 feet of massive sandstone interbedded with shale.

Alluvial Deposits

Pleistocene age pediment alluvium, shed from the rising mountains to the west, occurs as erosional remnants overlying the Cuchara and Poison Canyon Formations in the upper Apishapa River valley. Wood and others (1956) determined that these deposits are generally less than 10 feet thick, but may occur up to 40 feet thick.

Holocene stream alluvium exists in the valleys of the Purgatoire and Apishapa Rivers and their tributaries. In the Purgatoire River valley, these deposits range from 12-41 feet in thickness (Geldon, 1989). The composition of the stream alluvium takes on the characteristics of the outcropping formation in the area; that is, sand and gravel dominate where canyons are cut into the Poison Canyon and Cuchara Formations, and silt and clay where the Raton or Vermejo Formations dominate. Consequently, identification of alluvial deposits in the field is difficult as bedrock is often exposed in river bank cuts and the differentiation between weathered bedrock and silt dominated alluvium is tenuous.

4.0 STUDY AREA, DATA SOURCES, AND METHODOLOGIES

Our study area coincides with that portion of the Purgatoire River watershed that lies within the Raton Basin of Las Animas County, Colorado. Nearly 90% of the total CBM production in the Colorado portion of the basin has come from within this study area (Fig. 4.1). Development of coal bed methane resources within the Colorado portion of the Raton Basin during the past 15 years (1995-2010) has provided a dense array of wells with modern geophysical logs. Prior to 1995 there were only 221 wells drilled in the study area, by the end of 2009 that number increased to 3,505. These closely spaced well log data sets have afforded the opportunity to develop a geologic model depicting the area's subsurface structure and stratigraphic variability in greater detail than was previously available. The distribution of CBM wells and outline of the study area are shown on Figure 4.1.

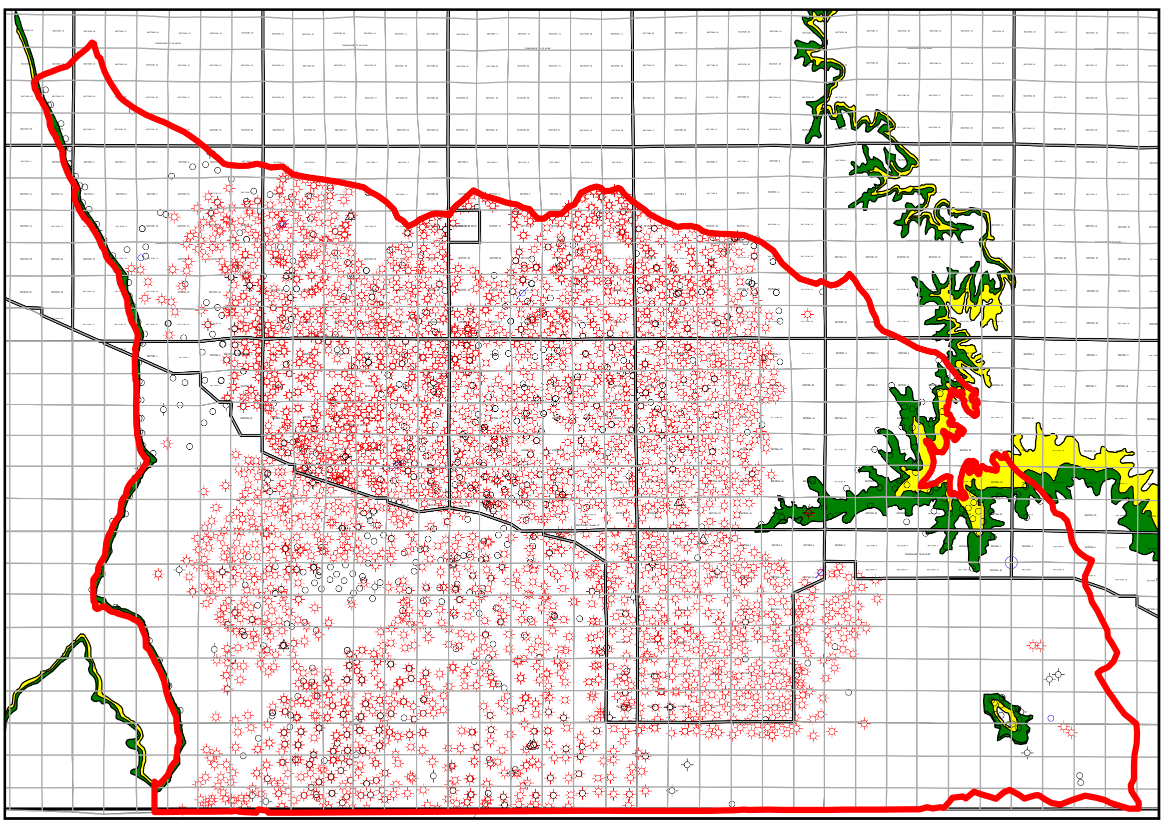


Figure 4.1 Distribution of wells in the Purgatoire River watershed study area (red outline)

4.1 Data Sources

4.1.1 Surface Geologic Data

Gathering of geologic information in the Raton Basin began well before the region was acquired by the United States in 1845. The coal resources were great assets for the development that was to come. In the 1950s, a series of investigations by USGS geologists G.H. Wood and R.B. Johnson with geologic assistant G.H. Dixon focused on the geology and coal resources of the area (Wood and others, 1951, Johnson and Stephens, 1954a, 1954b, Wood and others, 1956, Wood and others, 1957, Johnson, 1958, Harbour and Dixon, 1959). Coal represented the dominant economic resource, but their investigations also evaluated oil and gas possibilities. A series of five, 1:31,680 scale maps were produced: 1) the Stonewall-Tercio area, 2) the Walsenburg area, 3) the La Veta Area, 4) the Gulnare area, and 5) the Starkville-Weston area. Since these investigators focused on the coal resources of the basin and mapped the geology on single–lens aerial photographs at scales of 1:20,000 and 1:24,000, we adopted their work products as the most detailed available for our purposes. Consequently, the four geologic maps pertinent to the study area were georeferenced and digitized from the published paper plates. The digital vector data include geologic formation contacts, strikes and dips, intrusive igneous rock contacts, faults, structural axis, and coal beds.

To compile the composite geologic map, used in this study, of the Purgatoire River watershed in the Colorado portion of the Raton Basin, CGS used the 1950s map series and augmented areas not covered with the 1:250,000 scale geologic map of the Trinidad Quadrangle produced by Johnson (1969). A complete list of the data sources used to compile the composite geologic map, presented as Plate 1, is provided in the following table (Table 1).

Table 1
Data Sources for Composite Geologic Map (Plate 1)

Authors	Date	Title	Publication	Scale
Wood, et al	1951	Geology and Coal Resources of the Stonewall-Tercio area, Las Animas County, Colorado	USGS Coal Investigations Map C-4	1:31,680
Wood, et al	1957	Geology and Coal Resources of the Starkville-Weston and Las Animas Counties Colorado	USGS Bulletin 1051	1:31,680
Wood, et al	1956	Geology and Coal Resources of the Gulnare, Cuchara Pass, and Stonewall Area, Huerfano and Las Animas counties, Colorado	USGS Coal Investigations Map C-26	1:31,680
Harbour and Dixon	1959	Coal Resources of the Trinidad-Aguilar Area, Las Animas and Huerfano counties, Colorado	USGS Survey Bulletin 1072-G	1:31,680
Johnson	1969	Geologic Map of the Trinidad Quadrangle, south-central Colorado	USGS Misc. Geological Investigation Map I-558	1:250,000

4.1.2 Subsurface Data Sources and Formation Tops

Final well locations were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) well database in an effort to provide the most accurate location for each control point. Specific well and geologic information including: well name, location, elevation, depth, formation tops, and completion and test information were obtained from the PI/Dwights PLUS® well data base and imported into IHS Petra® Version 3.2.2.1. software for data management and interpretation. Geophysical well logs were imported into the project as registered and scaled raster images from MJ Systems. The abundance of modern geophysical logs (gamma ray, resistivity, bulk density, density and neutron porosity, and photo-electric) allowed us to determine the individual lithologies (coal, sand, silts or shales) in the Raton and Vermejo Formations. Cross-sections and sub-surface maps were developed, as work in progress, using Petra® for visualization of the geological and petrophysical data.

Well control points and formation top depths were exported out of the IHS Petra® database and related to the COGCC well database using API number, as the common reference, in order to link the COGCC well location coordinates with the geologic information stored in the Petra® project. Ground surface elevations at each well control point were generated in GIS (ESRI ArcMap 9.3.1) from the 10-meter resolution National Elevation Dataset (NED) digital elevation model (DEM). Lastly, formation top elevations were calculated using the DEM-derived ground surface elevations at each well control point. These formation top elevation control points were then used in contouring the structural surfaces.

To maintain consistency with current exploration and production operations in the basin, formation tops and data used to construct the cross-sections and structure contour maps were based on the interpretations/conventions used by the oil and gas operators as reported to the COGCC. These data were validated for consistency of the formation pick by contouring the data. Specific points or wells which produced an anomalous deviation in the contoured surface, were identified as an "outlier" point. These were subsequently verified by correlating the top in question with the geophysical log(s) interpretation for the well. Formation tops were adjusted to conform to the industry picks, as necessary, and the database updated. Questionable formation picks that could not be resolved by validation methods (i.e. remained anomalous) were not used for development of geologic surfaces or cross-sections.

4.2 Methodologies

Both surface (USGS geologic mapping at various scales) and subsurface (COGCC and PI/Dwights PLUS® well data bases and geophysical logs) were integrated for this project to produce the maps, contoured surfaces, and cross-sections presented. The source material's age, scale, analog to digital conversion, and manual data entry all have the potential to impart errors in the data. Though a methodical and scientific approach was used to analyze and present these data, it is important that the reader understand the methodologies and limitations of the data and products presented herein.

4.2.1 Surface Formation Contacts

The structural position and contacts between the Pierre Shale, Trinidad Sandstone, Vermejo, and Raton formations are observed in outcrop on the west and east margins of the basin as upturned beds displaced during the Laramide orogeny. Strike and dip measurements for formation bedding on the west and east boundaries of the basin were obtained from geologic mapping published by Wood and others (1956 and 1957) and Harbour and Dixon, 1959. The contact between the Raton Formation and the overlaying Poison Canyon Formation, within the basin interior, provides outcrop data that affords additional control points for the geologic model. These surface data sets were incorporated with subsurface interpretations, made from geophysical logs, to define the geometry and structural orientation of the formations, i.e. a geologic model. Additionally, using the digital GIS vector data from the mapped geology of the area, control points were created at a spacing of 1,000 meters along geologic contacts for use in contouring the formation tops. Ground surface elevations from the USGS 10-meter DEM were generated in GIS (ESRI ArcMap 9.3.1) and used to represent the elevation of the formation top at each surface contact control point.

4.2.2 Subsurface Formation Contacts

The data presented in this study attempts to conform to the general industry formation picks as listed in the PI/Dwights PLUS® data base rather than promote new interpretations of the coal-bearing formations. The published industry subsurface formation contacts were identified and verified through interpretation of geophysical well logs and lithologic descriptions. The boundary between each unit or formation may be recognized by the change in character of the response of the geophysical logging tools as it passes from one lithologic type or package to another. The correlation of formation tops and zones from well to well were based on the geophysical log response of various logging tools used to survey the borehole. Where a formation top was not available a pick was interpolated based on adjacent control points.

The logging tools frequently run in Raton Basin wells include gamma ray, gamma-gamma density or bulk density, and porosity (density and neutron). The gamma ray log was used in this study for the identification of formation contacts and sand/shale determination. The bulk density log was used to identify coal zones and as additional confirmation of formation contacts.

The top of the Pierre Shale was assigned at the top of the Pierre transition zone, where sandstones predominate. The top of the massive Trinidad Sandstone is placed at the top of the uppermost sandstone unit, where there is an abrupt change from sandstone to shale or coal. The top of the Vermejo Formation is picked at the base of the Raton Formation basal conglomeratic sands which may be from 2 to 70 feet above the last coal in the Vermejo. A type log indicating these stratigraphic relationships and formation contacts for the Pierre Shale, Trinidad Sandstone, and Vermejo Formations is presented on Figure 4.2.

The oil and gas industry typically uses the top of the uppermost coal in the Raton Formation as the formation top. This convention may be appropriate for mapping coals, but it does not represent the true geologic top of the formation. The industry's convention is further complicated by the presence of coal seams in the lower portion of the overlying Poison Canyon Formation. Further, the upper coal seams identified on logs may not be correlative well to well because of discontinuity and differential erosion. To address these inconsistencies, we picked the top of the Raton Formation on geophysical logs at the base of a 10 foot shaley sand interval that corresponds with the mapped surface contact between the Raton and Poison Canyon formations. The Raton top was only picked in those areas where the formation is overlain by the Poison Canyon Formation and the interval was logged (Plate 1). In the remainder of the study area, the Raton is an erosional surface. A type log for the Raton Formation, showing the upper and lower coal zones and the barren zone (over two different wells), is presented on Figure 4.3.

4.2.3 Cross Section Development

Six structural cross-sections were constructed, at locations as shown on Figure 4.4, using geophysical logs, surface geological mapping, and published measured sections. Three cross-sections

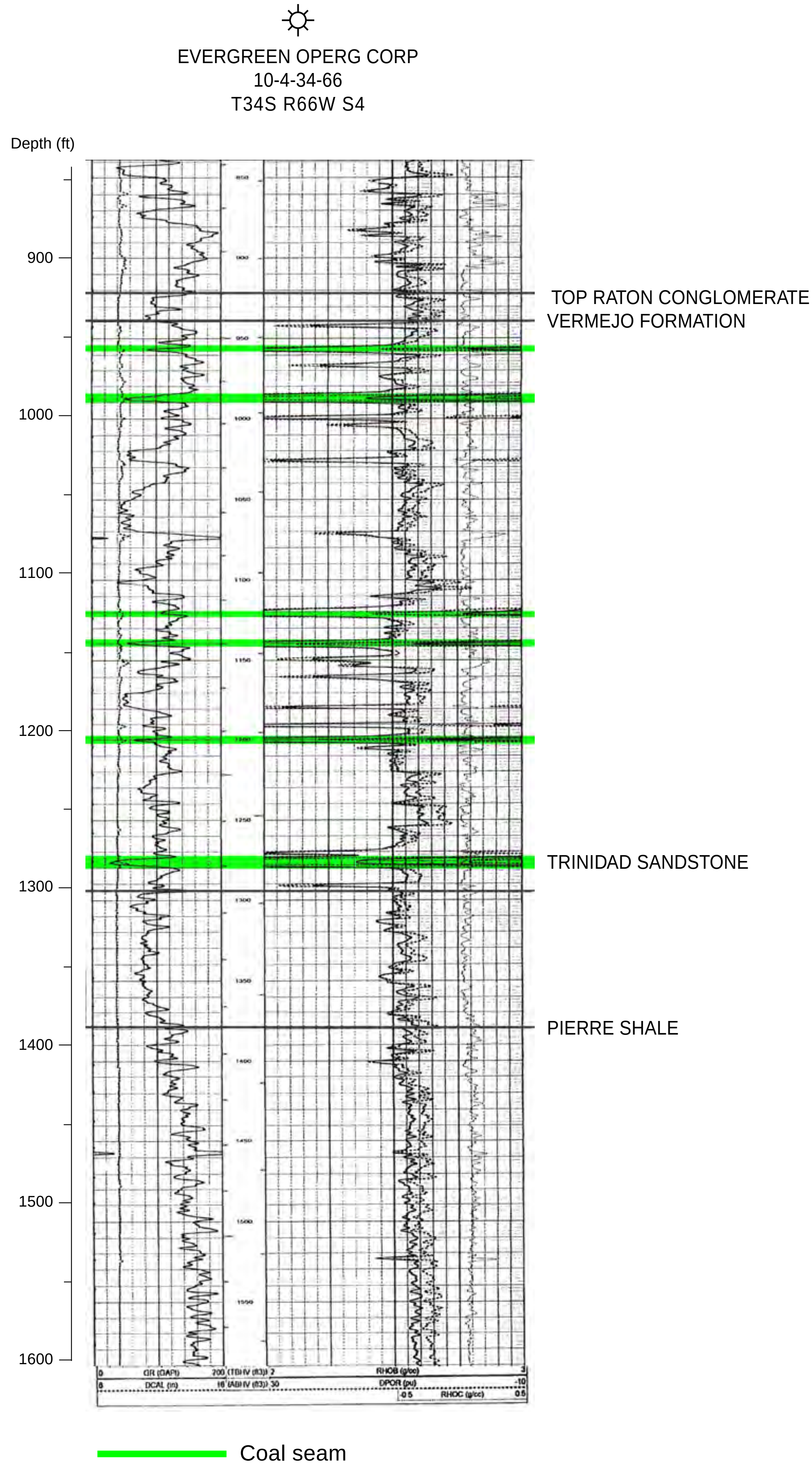


Figure 4.2 Type Geophysical Log for the Vermejo Formation Coal Seams

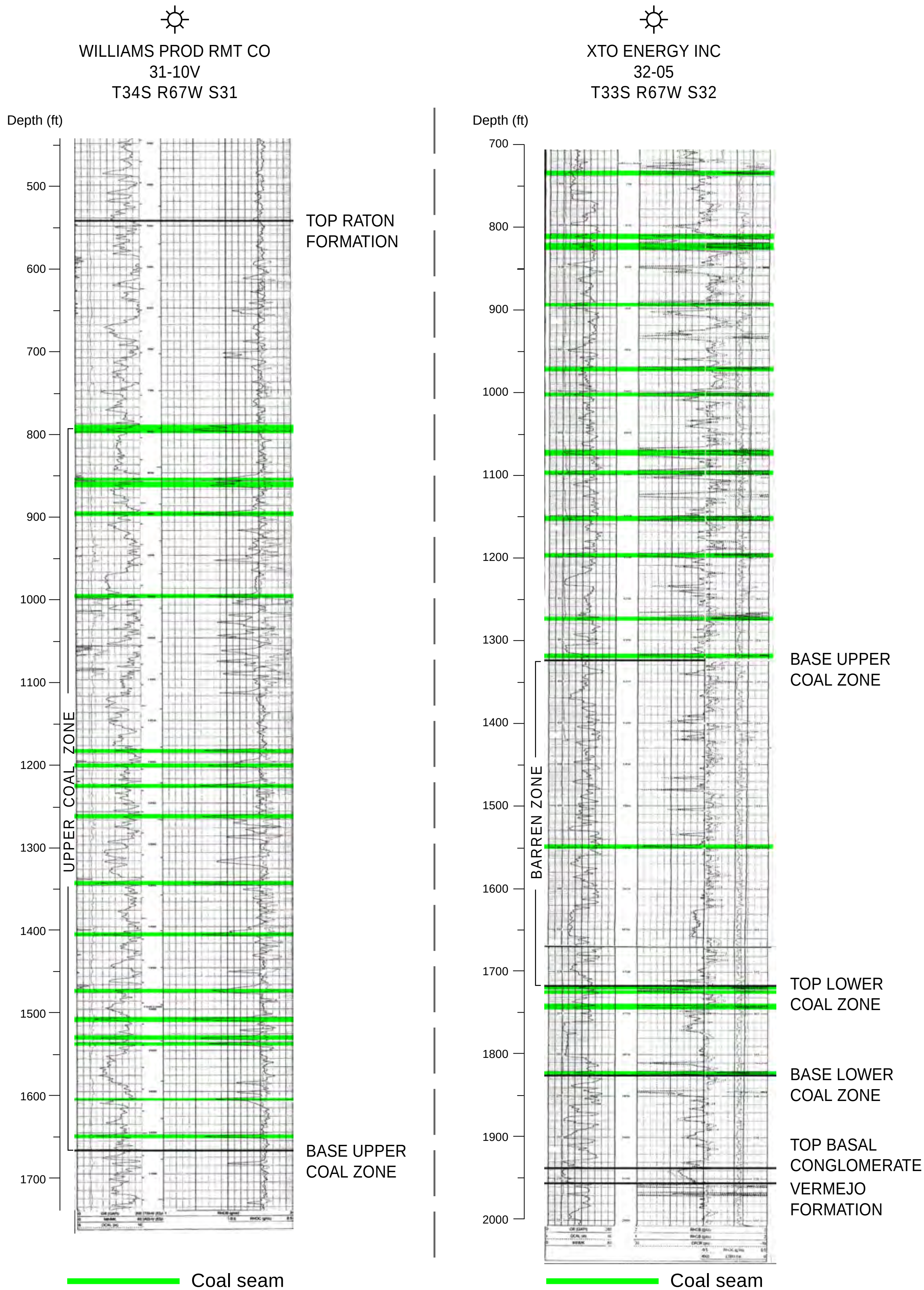


Figure 4.3 Type Geophysical Log for the Raton Formation Coal Zones from Separate Wells

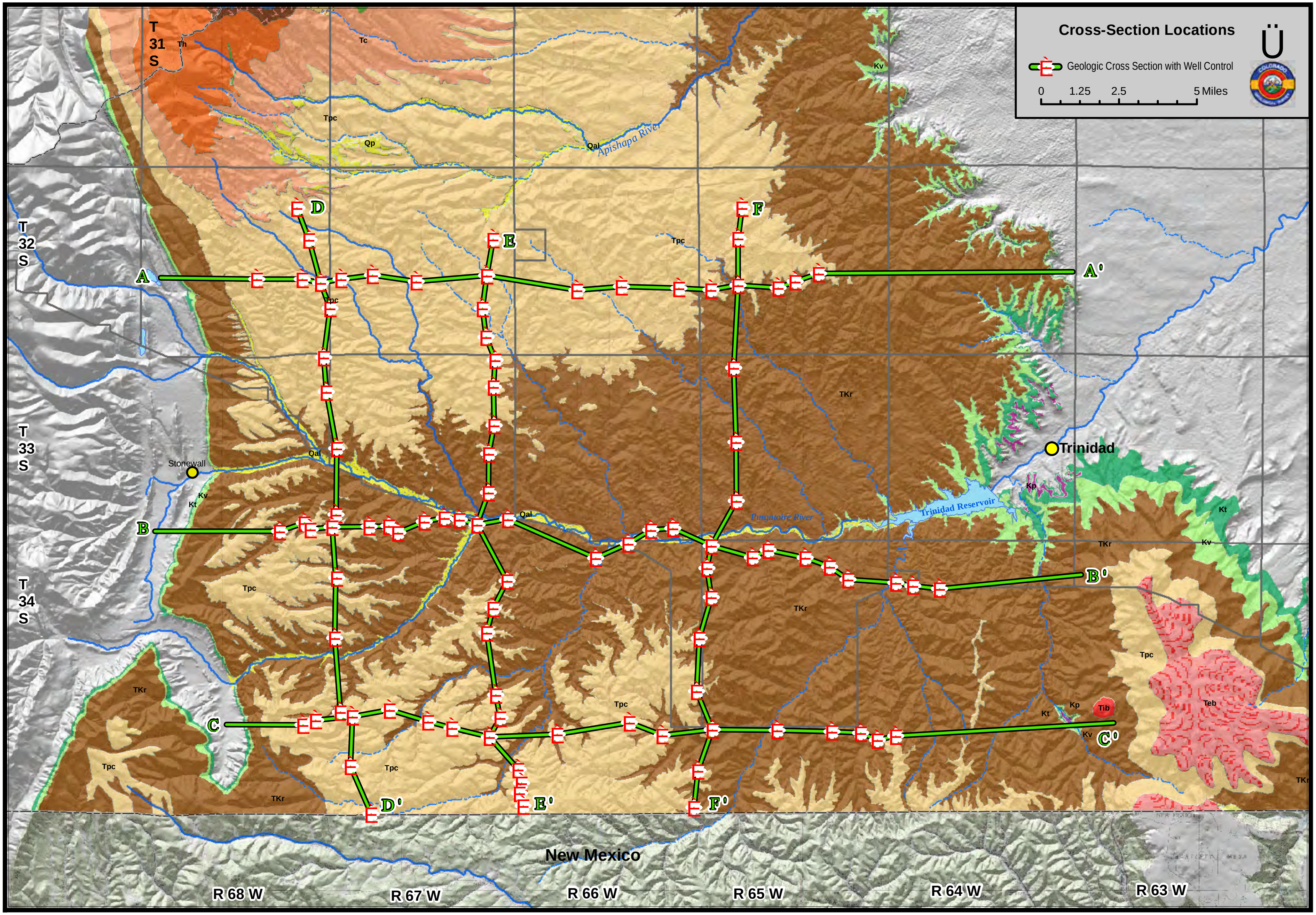


Figure 4.4 Location of Structural Cross-Sections with Well Control Points

(A-A’, B-B’, and C-C’, Plate 2), were developed in a west to east orientation perpendicular to the basin’s structural axis and include control from formation outcrops and published dip measurements on the western basin margin. Three additional sections (D-D’, E-E’, and F-F’, Plate 3) were constructed in a north to south direction crossing or “tying” the west-east sections at well locations to insure continuity between all cross-sections across the study area. The section locations were chosen to provide a representation of the structural geometry of the basin as well as portraying the stratigraphic relationships of the fluvial deltaic sediments along both depositional strike and dip. The lines of section were adjusted to include control points on the basin margins and to utilize wells which had complete well logs in the formations of interest. The sections were constructed with a ten times vertical exaggeration to provide a detail presentation of the structural and stratigraphic relationship of the formations. In addition, the same cross-sections are shown with no vertical exaggeration to provide a true perspective of the structural geometry.

The three east-west cross-sections, A-A’, B-B’, C-C’, are also presented as stratigraphic sections with the datum set at the top of the Vermejo Formation (Plate 8). These stratigraphic cross-sections are constructed with a vertical scale of 1-inch equal 600 feet and with equal spacing between well locations (no horizontal scale) to display visually the discontinuity and heterogeneous distribution of coals and sands in the Vermejo and Raton Formations. Interpretive details of the structural and stratigraphic cross-sections are discussed in Section 5.

Coal and sandstone lithologic units were identified based on geophysical log response. Coal beds in the Vermejo and Raton formations were identified from bulk density logs, where available. Most coals have a density of approximately 0.7 to 1.8 grams/cm^3 (Wood and others, 1983). The density tool has a vertical bed resolution of 18 inches and cannot accurately define units of less thickness. Coals were identified as beds with a density of 1.8 grams/cm^3 or less and at least two feet or greater in thickness. Sandstone beds in the Vermejo and Raton Formations were identified from the gamma ray log. Two gamma ray baselines were defined: 1) a shale baseline representing 100% shale (high gamma ray response) and, 2) a sandstone baseline representing approximately 100% sandstone (low gamma ray response). A gamma ray response equal to or less than 50% of the value between the sandstone and shale baselines was considered to be sandstone. The baselines were modified as the stratigraphic intervals changed and variations in lithology caused the baselines to shift higher or lower.

4.2.4 Development of Digital Geologic Surfaces

The structural surfaces of the top of the Pierre Shale (Plate 4), Trinidad Sandstone (Plate 5), Vermejo Formation (Plate 6), and Raton Formation (Plate 7) were contoured using subsurface contact control points obtained from interpretation of well and borehole log databases and surface contact control points derived from surface geologic mapping. The structure contours surfaces were first generated in ArcGIS using the "natural neighbors" point interpolation method (ESRI, ArcGIS 9.3.1, 3D Analyst) to create a raster representing the elevation surface of the top of each formation. The raster surface was then contoured (ESRI, ArcGIS 9.3.1, 3D Analyst). This output was manually assessed and adjusted based on professional judgment and geologic interpretation.

The control point datasets for the Trinidad Sandstone and Vermejo Formation had the greatest population and geographic distribution. As a result, these two units were contoured first to provide the most accurate structural representation of the basin. The Pierre and Raton were then contoured taking into consideration the over- and underlying surfaces of the Trinidad and Vermejo.

The Trinidad Sandstone is relatively thin in the study area (200 feet or less) and due to the steep bedding dips along the western margins of the study area, there is a high potential for the contours from the underlying Pierre Shale to cross due to the contour interval (100 feet). To avoid such conflicts, the top Pierre Shale surface was initially created by digitally adding the Trinidad Sandstone isopach, calculated at control points, to the top Trinidad surface using the Raster Calculator method (ESRI, ArcGIS 9.3.1, Spatial Analyst). In this case, control points containing an elevation for the top of both the Trinidad and Pierre were used to calculate Trinidad thickness at each point. Additionally, bedding attitude (dip angle) and apparent thickness measurements at the outcrop were used to estimate the true thickness of the unit near outcrop areas where the dip is steep. The structural surface of the top of the Pierre generated by this method was manually assessed and adjusted, to reflect actual Pierre log picks, based on professional judgment and geologic interpretation.

Much of the Raton Formation has been eroded away in the central and eastern portions of the study area (Plate 1). Where the top of the Raton has not been eroded, it is typically at relatively shallow depths. As geophysical logging is commonly not performed in the upper portions of boreholes, much fewer subsurface well control point data for the top of the Raton were available. On the other hand, because the Raton outcrops throughout the basin, the contact between the Raton and overlying Poison Canyon Formation has been mapped in many places, particularly along incised stream and river valleys. Surface contact control points from the mapped surface geology comprise a large fraction of the control point dataset for this unit. Formation contact control points in topographically varied terrains can translate into large elevation errors in the digital conversion process. While recognizing this unavoidable error potential, the structural surface of the top of the Raton was contoured following similar methods as used for the other surfaces. Where the Raton has been eroded in the interior of the basin, the contemporary surface of the top of the Raton is the topographic surface, although this is not the stratigraphic top of the unit. The map representing the current top of Raton surface was constructed using both structural data (where the true stratigraphic top was present) and surface elevation data (where the Raton surface was eroded) to provide greater visual clarity to the contours.

5.0 INTERPRETATION AND RESULTS

A description and interpretation of the structural and stratigraphic cross-sections, and formation surfaces developed during this study are presented below. The results discussed herein are integrated with the geologic relationships identified from previous studies in the basin.

5.1 Structural Relationships of the Geologic Model

The west to east structural cross-sections A, B, and C (Plate 2) illustrate the present asymmetric structural geometry of the basin. Large scale faulting is not apparent on the cross-sections but folds have been inferred from the geometry of formational contacts on the western end of sections A-A' and C-C'. Structure maps of the top of the Pierre Shale (Plate 4), Trinidad Sandstone (Plate 5), and the Vermejo (Plate 6) formations display the details of these surfaces.

Steeply dipping beds on the west side of the basin resulted from intense Laramide faulting and thrusting during the Eocene. West of the study area along the Tres Vallas thrust fault, the Jurassic and Lower Cretaceous formations dip as much as 89 degrees east (Wood and others, 1956). The Raton Formation, at the western extent of the study area, dips about 27^{o} to the east decreasing down dip to one degree within three to four miles of the outcrop. The lowest structural position on the cross-sections follows the axis of the present day La Veta syncline which is also the structural axis of the basin in this area. The position of the syncline axis is well defined on cross-sections A-A' and B-B' but becomes broader towards the south as exhibited on cross-section C-C'. Gentle westerly dipping beds in the central and eastern part of the basin resulted from downwarping, folding and or faulting during the late Eocene (Johnson and Wood, 1956). On the eastern margin of the basin the Raton Formation dips to the west at an average of 8 degrees (Harbour and Dixon, 1957).

Stream erosion has exposed the Pierre Shale, Trinidad Sandstone and Vermejo Formations along Raton Creek, approximately 9 miles south of Trinidad, as a result of uplift of the Morley Dome (fig. 2.1) by Tertiary instrusives. Where exposed in the creek channel, these formations dip 10 degrees to the west (Lee, 1917) as indicated at the east end of cross-section C-C'.

The north to south cross-sections D-D', E-E', and F-F' (Plate 3, fig. 4.4) are sub-parallel to the structural axis of the basin. These cross-sections exhibit monoclinal dip of less than one degree northward toward the deepest portion of the basin, located southwest of Walsenburg, Colorado. Cross-section D-D’ expresses structural roll as the line of section crosses the Ute Hills where D-D’ ties with cross-sections B-B’ and C-C’.

Structure maps of the top of the Pierre Shale, Trinidad Sandstone, Vermejo, and Raton formations are presented on Plates 4 through 7. Both subsurface well control and outcrop contact points are displayed on the structure contour maps. The contour interval is reduced along the basin’s western margin to accommodate labeling and line spacing along the steeper western limb. The structure of each formation demonstrates the asymmetry of the basin with steeply east-dipping beds on the west side of the basin and more gentle west-dipping beds on the eastern margin. The deepest portion of the study area trends north south along the axis of the La Veta syncline (fig.2.1). The axis of the syncline is offset to the west approximately five miles north of Weston, Colorado.

Well control for the top of the Pierre Shale (Plate 4) is much more limited (204 log picks) than for the shallower Trinidad Sandstone and Vermejo Formation. Most wells that do penetrate the Pierre Shale only drill the upper few hundred feet of the formation and typically bottom in the transition zone. Elevation of the top of the Pierre Shale varies from 4,600 feet in the northern portion of the study area to approximately 5,800 feet at the state line along the basin axis. Distinctive structural features include deformation in the Ute Hills area within T34S, R68W, and the Morley Dome (bisected by I-25) in the southeast portion of the study area.

The structural surface for the top of the Trinidad Sandstone was based on 2,391 well log picks plus outcrop contact control (Plate 5). Elevation of the top of the Trinidad Sandstone varies from 4,700 feet in the northern portion of the study area to approximately 5,800 feet at the state line along the basin axis. Due to the increased number of control points, this surface exhibits greater detail than the Pierre Shale. The structural features still portray the asymmetric nature of the basin. The structural deformation in the Ute Hills area, evidenced at the top of the Pierre Shale, is now manifested as an approximate east-west anticline along the western basin margin. The shift in the La Veta Synclinal axis is also evident on this surface, as is the expression of the Morley Dome.

A structure contour map of the top of the Vermejo Formation is presented as Plate 6. Interpretation of this surface utilized 1,918 well log picks in conjunction with outcrop control points.

Plate 6 demonstrates a significant amount of paleo-relief on this surface, implying some degree of erosion prior to deposition of the overlying Raton Formation. The top of the Vermejo Formation is picked at the base of the basal conglomeritic sands within the Raton Formation. The basal conglomerate in the Raton Formation is not ubiquitous throughout the basin and some of the interpreted relief may be due to its absence. The elevation of the top of the Vermejo Formation ranges from 5,100 feet in the basin center of the northern portion of the study area to approximately 6,000 feet at the state line along the basin axis. In the eastern third of the basin, a number of closed highs are interpreted. As in the underlying formations, the Morley Dome and anticline in the Ute Hills area are prominent structural features.

The Raton surface map, Plate 7, was developed from an integration of both subsurface well control and surface geologic mapping. The northwest and southwest portions of the study area contain areas where the Raton is overlain by the Poison Canyon Formation and a true top of Raton can be picked on well logs. In the remainder of the area (central and eastern) the eroded surface of the Raton is a reflection of the surface topography and the drainage system of the Purgatoire River and its tributaries. Where the true structural surface is represented (subcrop extent), the top of the Raton structural surface has a configuration that is similar to the underlying Vermejo. To facilitate the user's comprehension of this surface, the contour lines of the top of the Raton Formation within the subcrop areas have been extended to the outcrop areas where the existing drainages have dissected and eroded the overlying Poison Canyon Formation.

Analysis of preliminary isopach maps developed for the Vermejo and Raton formations indicate that both formations increase in thickness toward the basin center, as is evidenced on the cross-sections. The basin axis represents a north-south area of accommodation where sediment accumulation was greatest. The isopach analysis also suggests that the paleo-axis of the La Veta syncline was westward of the current axis and not offset. The paleo-axis was more aligned with the northern portion of the current La Veta syncline (Fig. 2.1).

5.2 Stratigraphic Relationships of the Geologic Model

A discussion of the stratigraphic relations and lithologic character of the formations identified in this study are presented below. As discussed in Section 4.2.3, lithologies were interpreted from analysis of geophysical log responses at those wells depicted on east-west cross-sections A-A', B-B', and C-C’ (Fig. 4.4). To display the lateral stratigraphic variability within the coal-bearing intervals of the Raton and Vermejo formations stratigraphic cross-sections were created based on the lithologic analysis. These sections utilize the same wells as their corresponding structural cross-sections without application of horizontal scaling (Plate 8). The stratigraphic cross-sections displayed in Plate 8 are flattened (datum equals zero) on the top of the Vermejo Formation, thus removing any misalignments between wells due to surface topography and subsurface structure. As such, we would expect any continuous geologic units to be represented by horizontal or nearly horizontal horizons. This visualization is further enhanced by placing the lithologic log of one well directly adjacent to the next (no horizontal scaling). The three east-west cross-sections in Plate 8 indicate that the Raton Formation coal seams and interbedded shales and sandstones are not laterally continuous beyond several adjacent wells, and that continuity is only slightly better in the Vermejo Formation. The environments of deposition producing this heterogeneity were discussed in Section 3.

<u>Trinidad Sandstone</u>

The Trinidad Sandstone is present over the entire study area and has a range in thickness of 64 to 233 feet from subsurface well control. A thinner section of Trinidad Sandstone (less than 100 feet) trends northwest to southeast through the central portion of the area.

<u>Vermejo Formation</u>

The Vermejo Formation thickens towards the center of the basin. By example, it is 315 feet at the west end of cross-section B-B’, 420 feet thick at the paleo-axis of the La Veta syncline and then thins to 225 feet near the east end of the cross-section. The Vermejo is vertically heterogeneous with interbedded sand, silt, shale, carbonaceous shale, and coal. Sand comprises 9 to 41 % of the formation with an average content of 18 %. Channel sandstones are the thickest type of deposit ranging up to tens of feet thick.

The Vermejo coal zones are more continuous than those of the lower coal zone of the Raton Formation as indicated on the stratigraphic cross-sections (Plate 8). Vermejo coals occur ubiquitously across the study area with few wells encountering little or no coal. The amount of net coal decreases eastward even though the overall percentage of coal in the formation remains constant. This situation is a result of the Vermejo isopach decreasing at a faster rate than the net coal decreases. Summary statistics for the Vermejo coals in the central portion of the study area are presented in Table 5.1.

Table 5.1

Vermejo Coal Occurrences

Location	Vermejo Isopach (feet)	Coal (feet)	% Coal	Ratio coal/sand
Cross Section B-B' West	315	50	16	0.9
Central	388	45	12	0.8
East	225	36	16	0.4
Average	318	35	11	0.7
Cross Section E-E' North	361	17	5	0.5
Central	377	19	5	0.2
South	252	15	6	0.3
Average	342	18	5	0.3

Note: The column heading "ratio coal/sand" is the amount of coal in the section compared to the amount of sand. For example: a value of 1.0 indicates there are equal amounts of coal and sand. A value of 0.9 indicates the coal content equals 90% of the sand content.

Raton Formation

The Raton Formation has been deeply eroded in the central and eastern portions of the study area. Where the stratigraphic top remains (e.g. along cross-section A-A'), the Raton thickens from 1,680 feet at the west end to 1,827 feet four miles east near the basin's paleo-axis. The formation then gradually thins to 1,320 feet at the east end of section A-A'. Locally, the Raton basal conglomerate overlays the Vermejo Formation and is generally 50 feet thick in the proximal western portion of the study area and thins and becomes discontinuous distally to the east. The basal conglomerate thickens into the La Veta syncline as does the entire Raton Formation. Like the Vermejo Formation, the Raton shows a great degree of vertical and horizontal heterogeneity from interbedded sands, silts, shales and coal (Fig. 5.1) and from channels cut into existing coal, shale, and sand beds (Fig. 5.2).

Lee (1917) identified upper and lower coal zones in the Raton Formation, separated by the barren zone, as previously discussed. The Raton coal zones may continue for several miles containing individual discrete coal beds. Unlike the Vermejo Formation, individual coal beds in the Raton coal zones may only continue for a thousand feet or less before pinching out or being truncated by channel sands (Clarke and Turner, 2002).

Figure 5.1 Raton Formation outcrop along Hwy. 12 demonstrating the interbedded layering of sands, coals, and shales.

Figure 5.2 Raton Formation outcrop along Hwy. 12 showing a sandstone channel cutting through interbedded layers.

The Raton coal zones are characterized in detail on the stratigraphic cross-sections (Plate 2, 3, & 8). Coal sequences classified as the upper coal zone (UCZ) occurs at a distinctive stratigraphic interval throughout the upper part of the formation. Coal sequences within the lower coal zone (LCZ) occur at various stratigraphic intervals and in isolated portions of the lower part of the formation. The LCZ is identified on the basis of the occurrence of several coal beds closely spaced in the lower portion of the Raton Formation. The general distribution of dominant coal seams within the LCZ of the Raton Formation are shown on the structural cross-sections (Plates 2 and 3). Depending upon location, the LCZ can be highly variable with many areas containing little to no coal. The greatest occurrence of coal in this zone occurs in the west and central portion of the basin and decreases to the east (Plate 2, cross-sections A, B, and C).

The barren zone, which contains only minor coal seams, lies within the LCZ and may be above and/or below the predominant coal sequences depending upon position within the basin. In some areas of the basin, e.g. the western portion of cross section C-C’, the barren zone dominates the entire LCZ.

The Raton UCZ is the thicker of the two coal zones and is present over most of the study area. The UCZ becomes thinner in the central and eastern portion of the study area where the top of the Raton has been deeply eroded. Summary statistics for the Raton coals, from west to east, along cross-section A-A’ are presented in Table 5.2. Coal statistics for other cross-sections were not calculated because most wells did not have logs covering the full Raton section or the section was removed by erosion.

Table 5.2
Raton Coal Occurrence

Cross Section A-A'	Raton Isopach (feet)	UCZ Isopach (feet)	UCZ Net Coal (feet)	UCZ % Coal	Barren Zone Isopach (feet)	LCZ Isopach (feet)	LCZ Net Coal (feet)	LCZ % Coal
West	1680	794	42	5	470	249	10	4
Central	1575	787	39	5	363	NP	NP	-
East	1320	NPE	NPE	-	299	NP	NP	-

NP – Not Present
NPE – Not - Present Eroded

Poison Canyon Formation

The conglomerates, sandstones, shales, and mudstones of the Poison Canyon Formation are very similar to that of the upper Raton Formation. The basal contact is difficult to identify in both outcrop and on geophysical logs because of this similarity. Over much of the study area, the surface of the Poison Canyon Formation has been eroded and the formation is only present in the northern and southern portions.

6.0 SUMMARY

This report documents the geologic investigations conducted by the Colorado Geological Survey in the Purgatoire River watershed of the Raton Basin of Las Animas County, Colorado. The purpose of this geologic investigation was to provide additional information on the stratigraphic and structural relationships of the coal-bearing formations in the Purgatoire River watershed to assist in the protection and management of both the mineral and water resources contained therein.

The Raton Basin of southern Colorado and northeastern New Mexico is the southernmost of several coal-bearing basins along the eastern margin of the Rocky Mountains. The basin contains a nearly complete Cretaceous and Tertiary stratigraphic sequence of sedimentary rocks that include the coal-bearing Vermejo and Raton Formations (Close and Dutcher, 1990a). Recent subsurface data available from over 3,500 geophysical well logs acquired from coalbed methane exploration and production wells afforded the opportunity for a more complete assessment of subsurface structure and stratigraphic variability than was previously available. This study also identified a series of five, 1:31,680 scale maps produced in the 1950s by USGS geologists G.H. Wood and R.B. Johnson with geologic assistant G.H. Dixon that focused on the geology and coal resources of the area. Their work products were incorporated into this study, through digitization and georeferencing of the original paper products. This digital data then provided an opportunity to integrate existing surface geologic mapping with the subsurface formation and lithologic information derived from well logs utilizing both IHS Petra® and ESRI ArcMap software.

We compiled a composite geologic map of the Raton Basin in Las Animas County, Colorado, by integrating this map series and augmenting areas not covered by the 1950s mapping projects with the more commonly used 1:250,000 scale geologic map of the Trinidad Quadrangle produced by Johnson (1969). The vector data include geologic formation contacts, strikes and dips, intrusive igneous rock contacts, faults, structural axis, and coal beds. Well control points and formation top depths were obtained from the PI/Dwights PLUS® well data base and correlated to the Colorado Oil and Gas Conservation Commission well database. The data presented in this study conform to the general industry formation picks rather than promote new interpretations of the coal-bearing formations. These data were validated for consistency by developing structural maps of each formation using the published tops and well datum elevation data. Specific points or wells that were identified as an "outlier" were verified by correlating the top in question with the geophysical log(s) for the well. Formation tops were adjusted to conform to the industry convention, as necessary.

Six structural cross-sections were constructed using geophysical logs, surface geological mapping, and published measured sections. The section locations were chosen to provide a representation of the structural geometry of the basin as well as portraying the stratigraphic relationships of the fluvial deltaic sediments along both depositional strike and dip. The three east-west cross-sections, A-A', B-B', C-C', were also interpreted as stratigraphic sections with the datum set at the top of the Vermejo Formation. These stratigraphic cross-sections are constructed with a true vertical scale, but with equal spacing between well locations (no horizontal scale) to display visually the discontinuity and heterogeneous distribution of coals and sands in the Vermejo and Raton Formations.

Structure contour maps of the top of the Pierre Shale, Trinidad Sandstone, Vermejo Formation, and Raton Formation were constructed using subsurface-formation, control points obtained from interpretation of well and borehole log databases and surface-contact, control points derived from surface geologic mapping. The structure of each formation demonstrates the asymmetry of the basin with more steeply east-dipping beds on the west side of the basin and a more gentle western dip on the eastern margin. The deepest portion of the study area trend north south along the axis of the La Veta syncline.

The analysis and interpretations provided herein were made by integrating available surface and subsurface geologic data to develop a geologic model consisting of structural and stratigraphic cross-sections; maps depicting the structural surfaces of the Pierre Shale, Trinidad Sandstone, Vermejo Formation, and Raton Formation; tabulating coal zone characteristics, and assembling a new digital composite surface geologic map from previous geologic investigations in the area. The model components, in digital format, provide for future applications using geospatial analysis and integration into geological and hydrogeological numerical models. The work products presented herein are unique and enhance our understanding of the Raton Basin geology that forms the basis of its water resources and CBM production.

7.0 REFERENCES

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Composite Geologic Map of the Raton Basin In Colorado

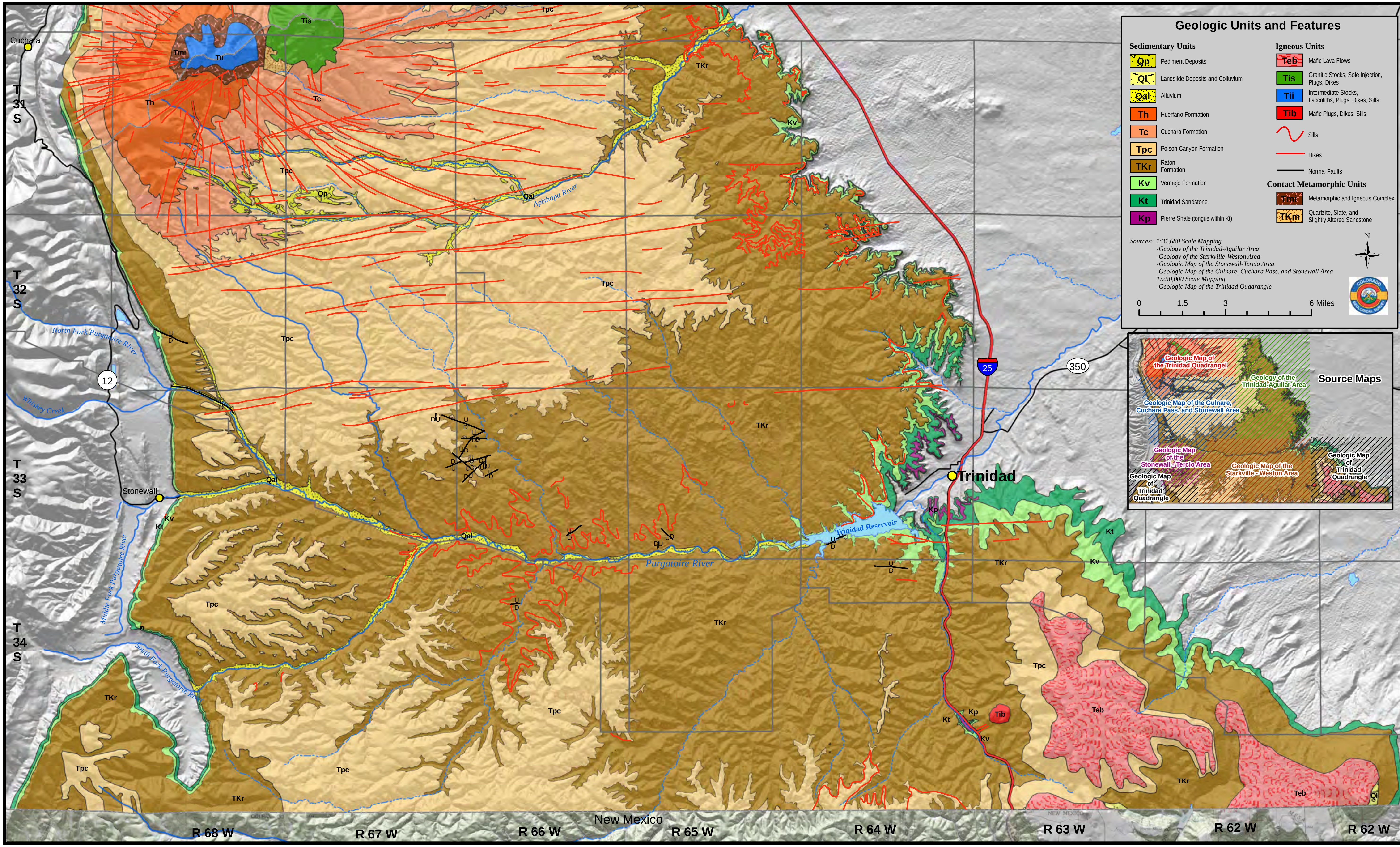
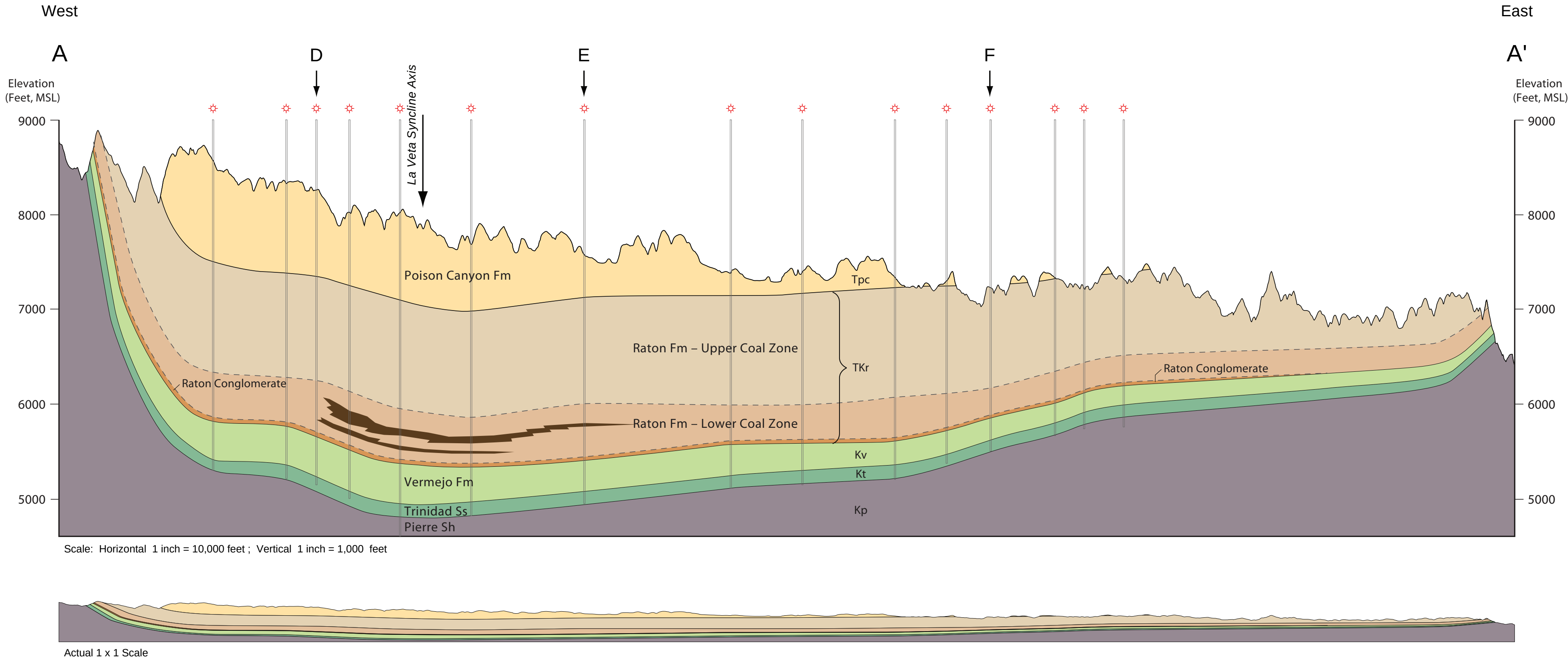


Plate 1

Cross Section A – A'



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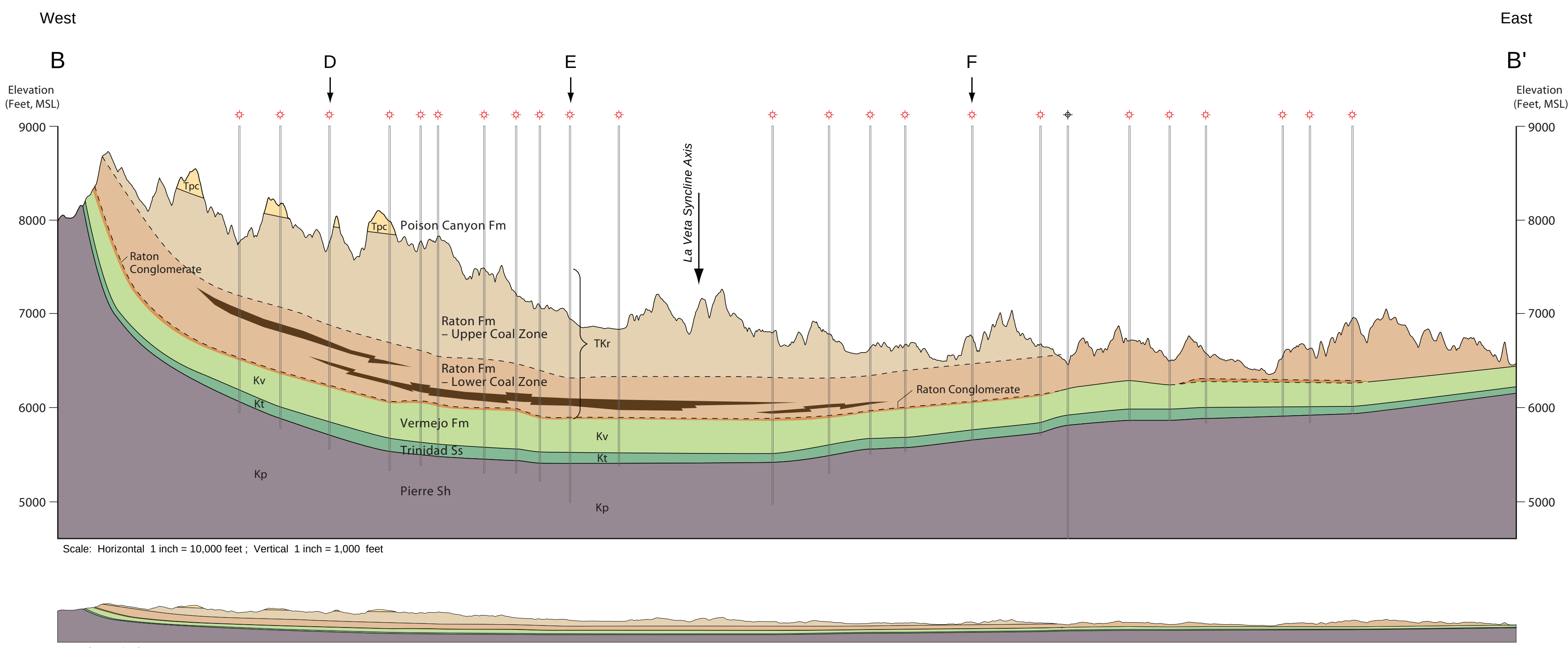


Cross Section C – C'

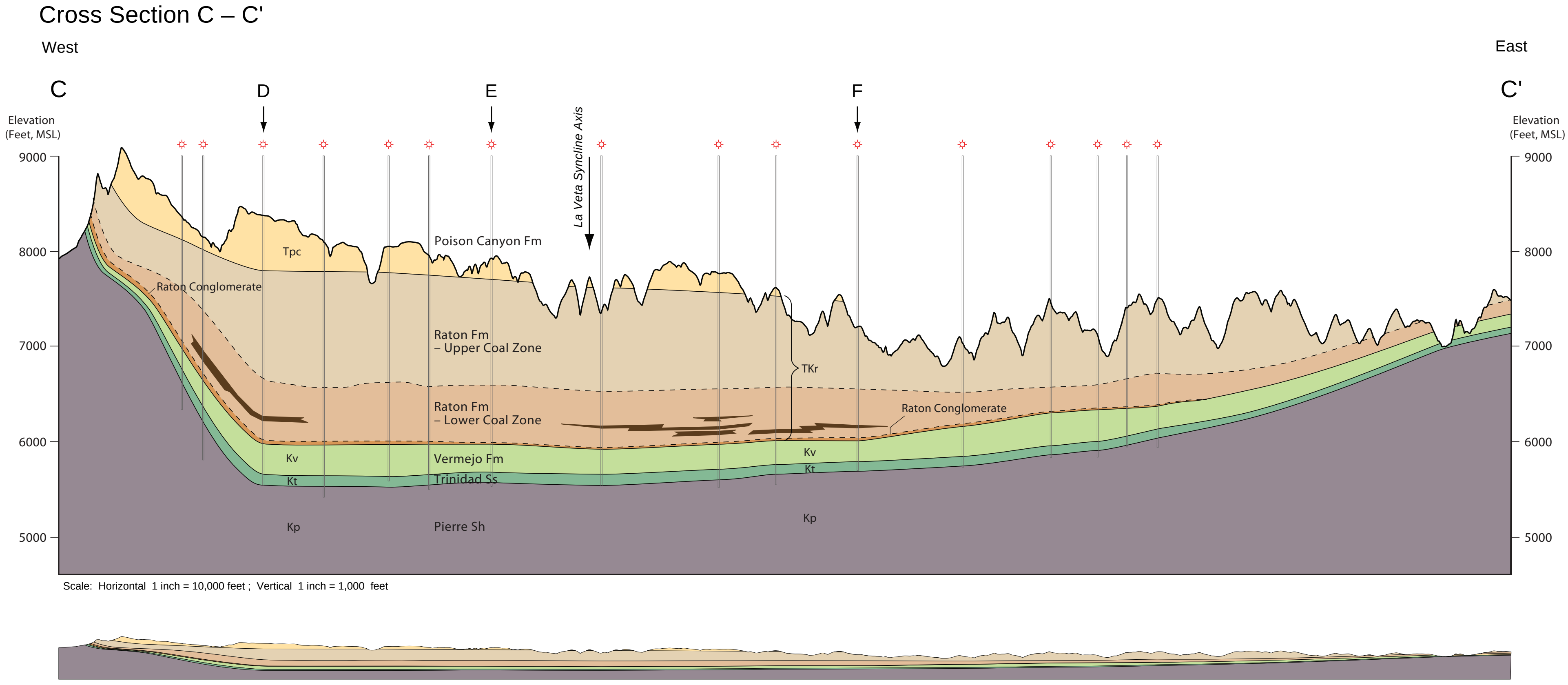
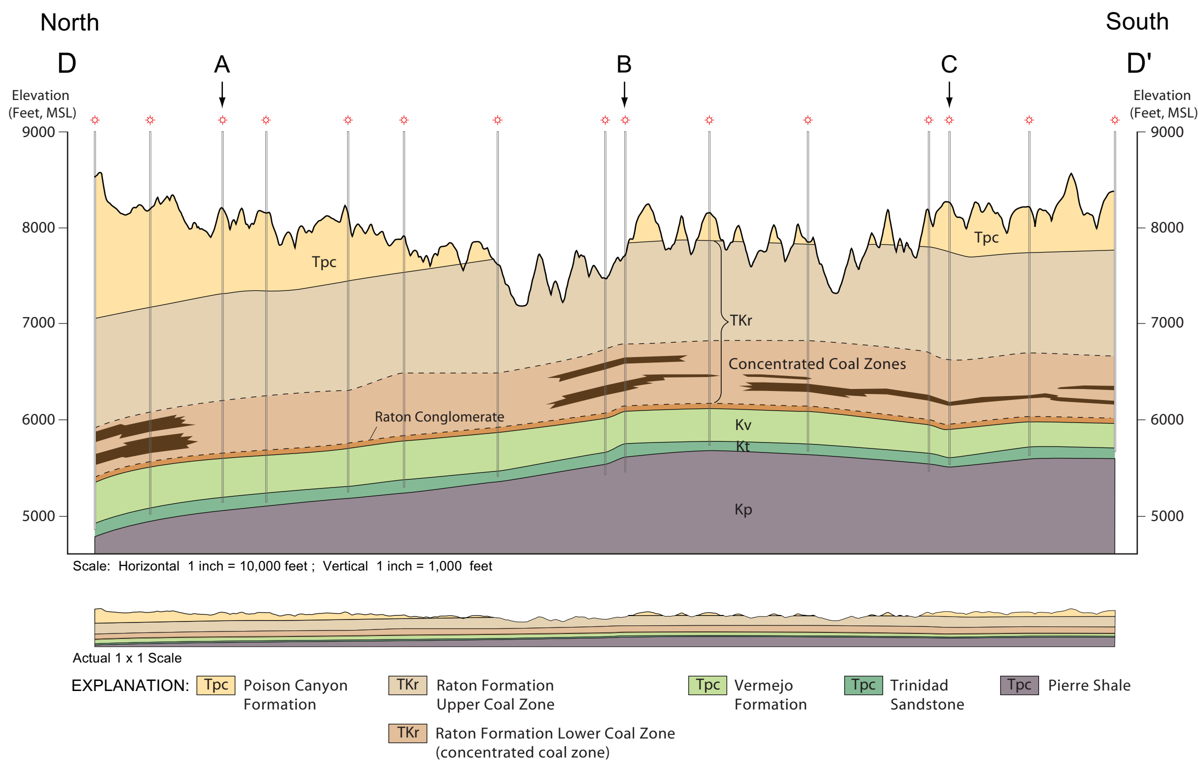


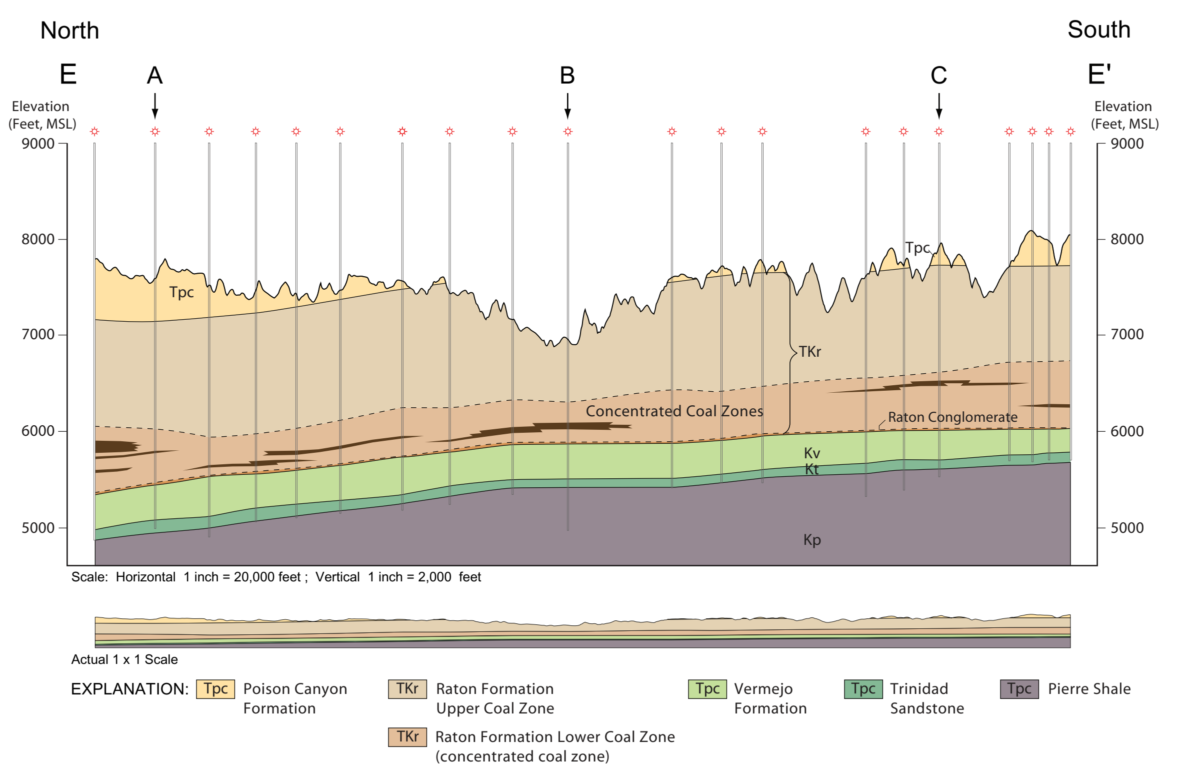
Plate 2

East-West
Structural Cross Sections
A, B, and C

Cross Section D – D'



Cross Section E – E'



Cross Section F – F'

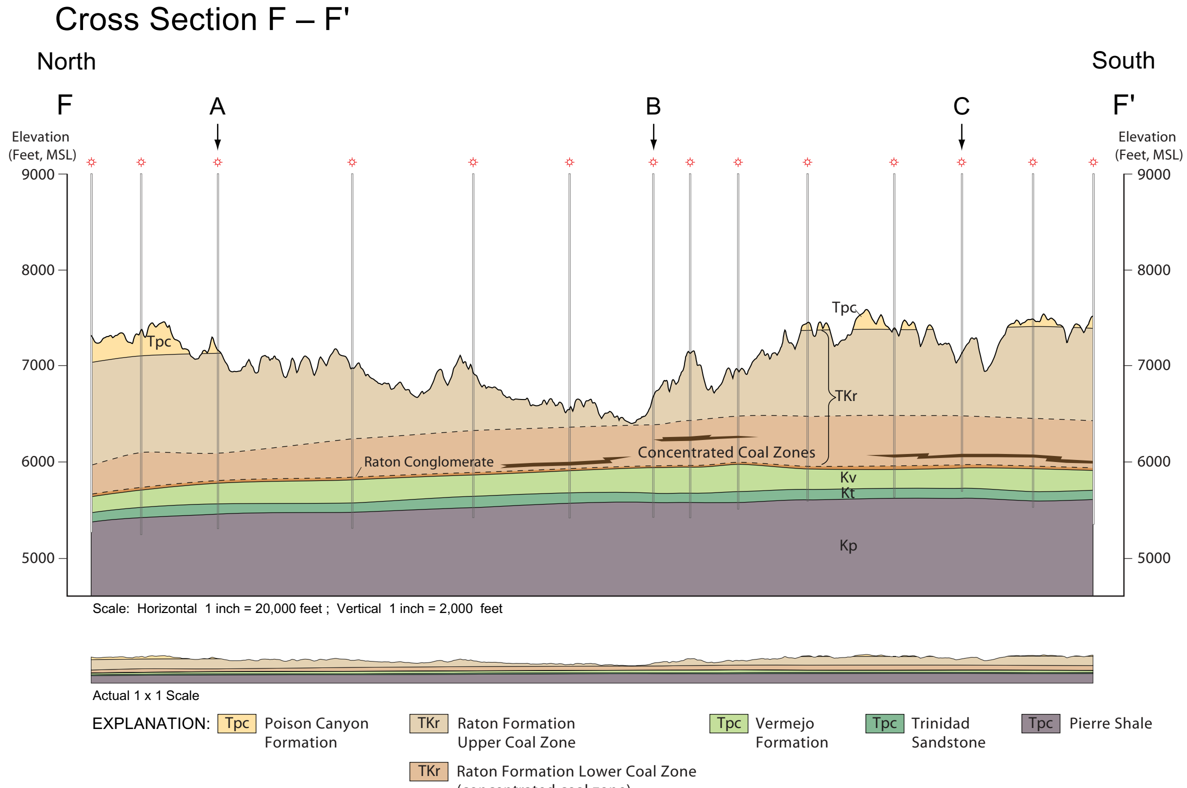


Plate 3

North-South
Structural Cross Sections
D, E, and F

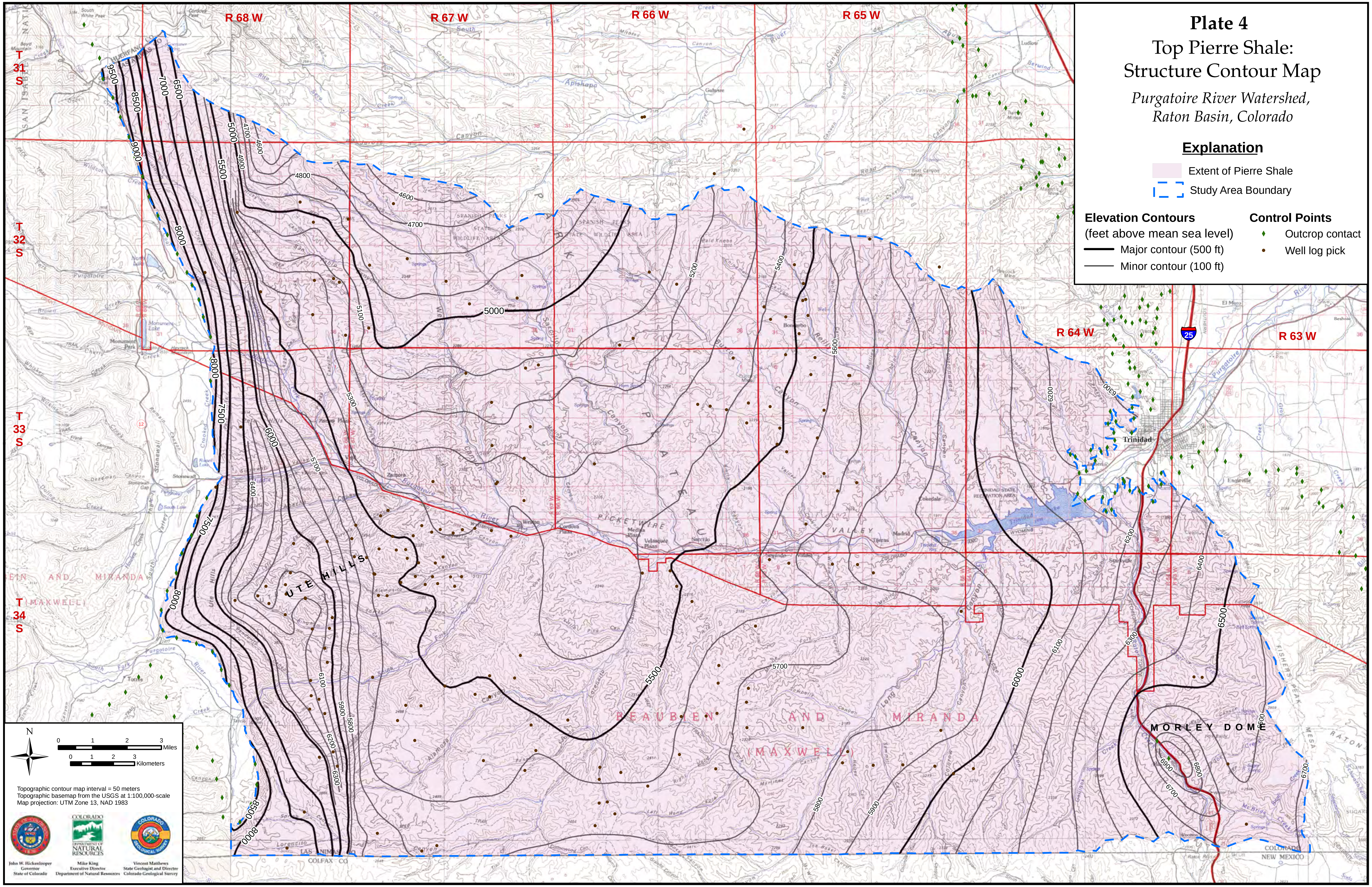


Plate 4
Top Pierre Shale: Structure Contour Map
Purgatoire River Watershed, Raton Basin, Colorado
Explanation
Extent of Pierre Shale
Study Area Boundary
Elevation Contours (feet above mean sea level)
Major contour (500 ft)
Minor contour (100 ft)
Control Points
Outcrop contact
Well log pick
R 68 W
R 67 W
R 66 W
R 65 W
R 64 W
R 63 W
T 31 S
T 32 S
T 33 S
T 34 S
UTE HILLS
PICKETWIRE VALLEY
BEAUBIEN AND MIRANDA
MAXWELL
MORLEY DOME
Trinidad
N
0 1 2 3 Miles
0 1 2 3 Kilometers
Topographic contour map interval = 50 meters
Topographic basemap from the USGS at 1:100,000-scale
Map projection: UTM Zone 13, NAD 1983
John W. Hickenlooper
Governor
State of Colorado
Mike King
Executive Director
Department of Natural Resources
Vincent Matthews
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Colorado Geological Survey

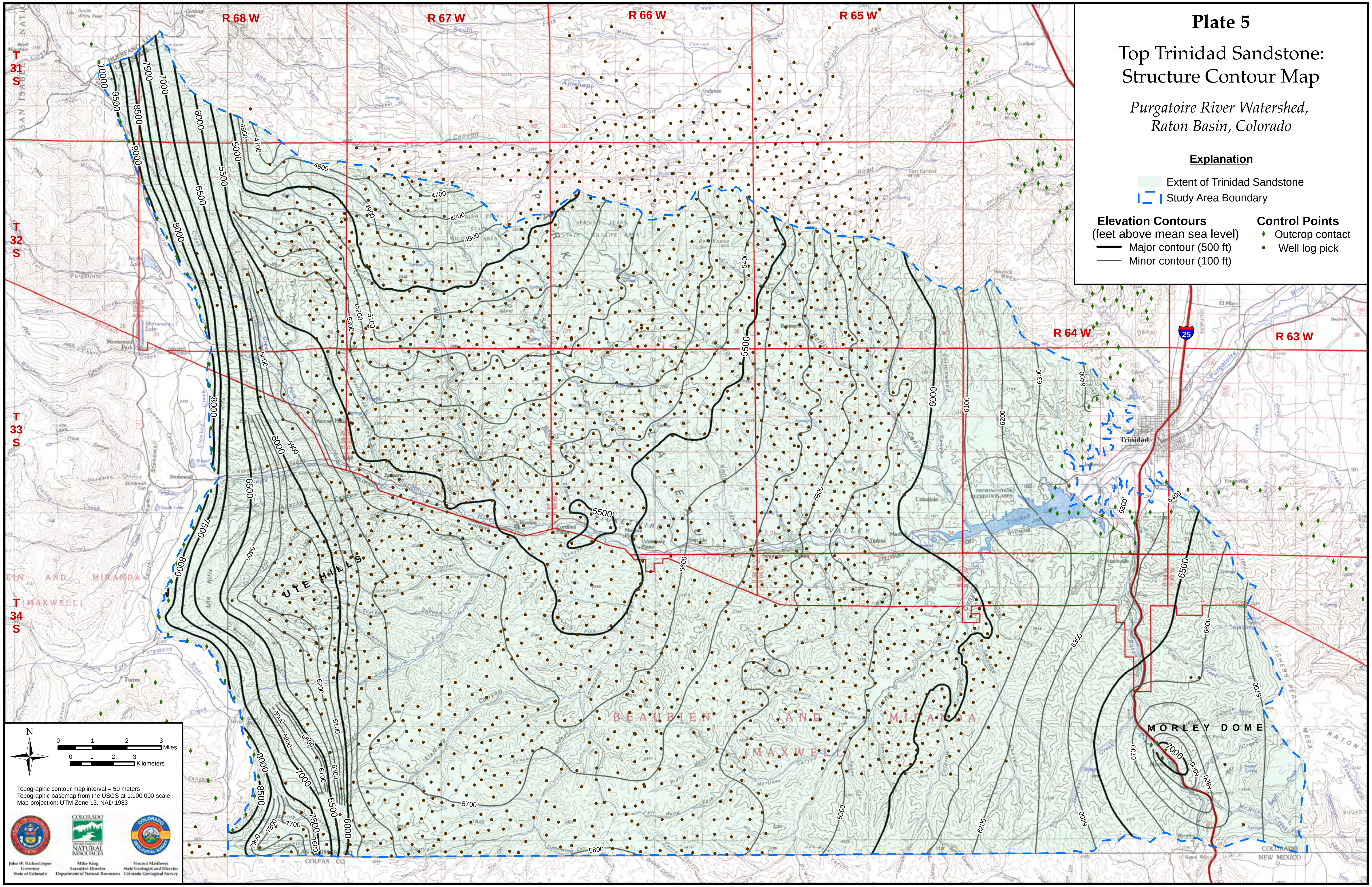

Plate 5
Top Trinidad Sandstone: Structure Contour Map
Purgatoire River Watershed, Raton Basin, Colorado
Explanation
Extent of Trinidad Sandstone
Study Area Boundary
Elevation Contours (feet above mean sea level)
Major contour (500 ft)
Minor contour (100 ft)
Control Points
Outcrop contact
Well log pick
R 68 W
R 67 W
R 66 W
R 65 W
R 64 W
R 63 W
T 31 S
T 32 S
T 33 S
T 34 S
UTE HILLS
MORLEY DOME
Trinidad
N
0 1 2 3 Miles
0 1 2 3 Kilometers
Topographic contour map interval = 50 meters
Topographic basemap from the USGS at 1:100,000-scale
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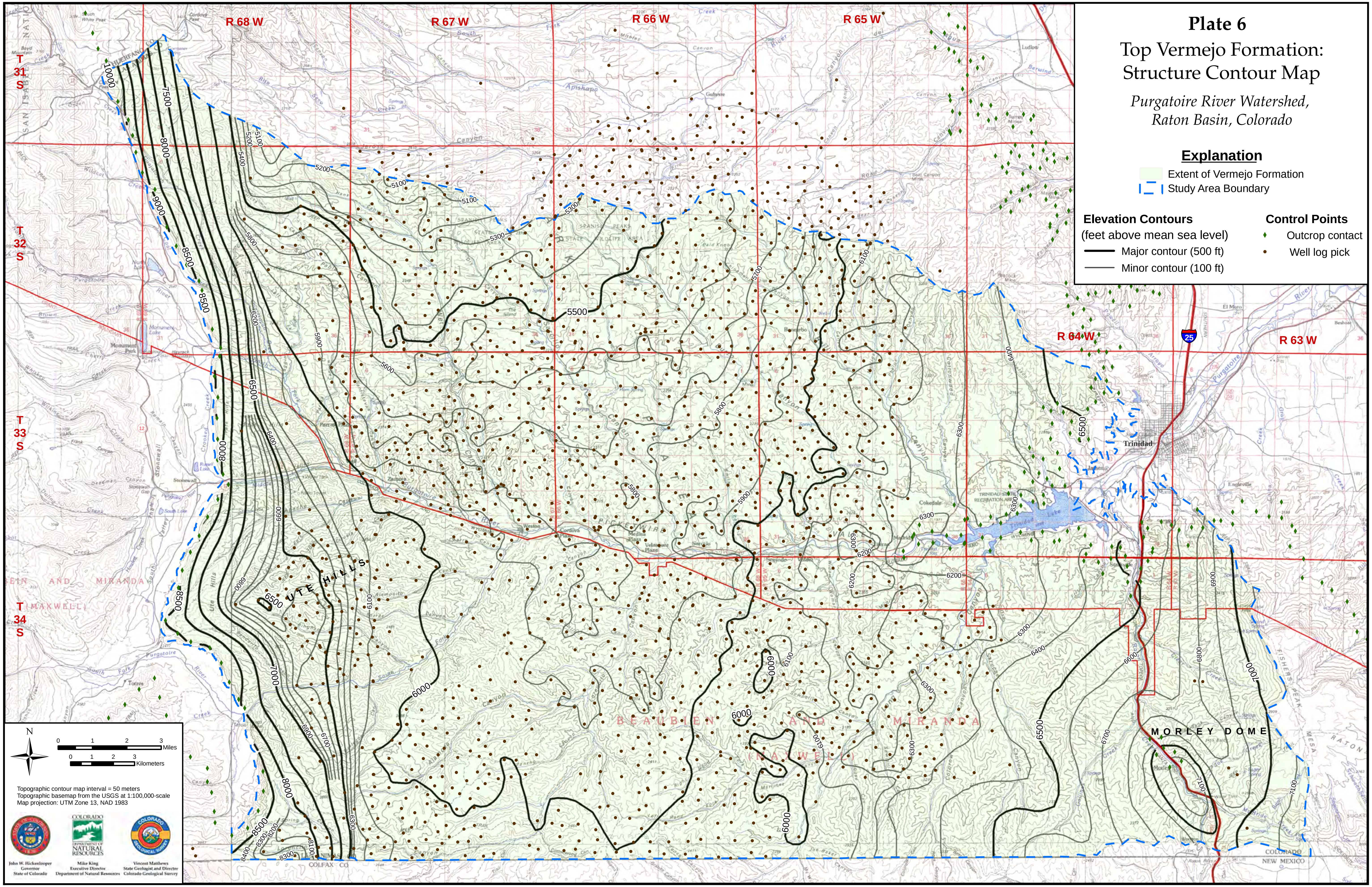
Plate 6
Top Vermejo Formation: Structure Contour Map
Purgatoire River Watershed, Raton Basin, Colorado
Explanation
Extent of Vermejo Formation
Study Area Boundary
Elevation Contours (feet above mean sea level)
Major contour (500 ft)
Minor contour (100 ft)
Control Points
Outcrop contact
Well log pick
R 68 W
R 67 W
R 66 W
R 65 W
R 64 W
R 63 W
T 31 S
T 32 S
T 33 S
T 34 S
UTE HILLS
MORLEY DOME
BEAUBIEN AND MIRANDA
Trinidad
COLORADO
NEW MEXICO
COLFAX CO
Miles
Kilometers
Topographic contour map interval = 50 meters
Topographic basemap from the USGS at 1:100,000-scale
Map projection: UTM Zone 13, NAD 1983
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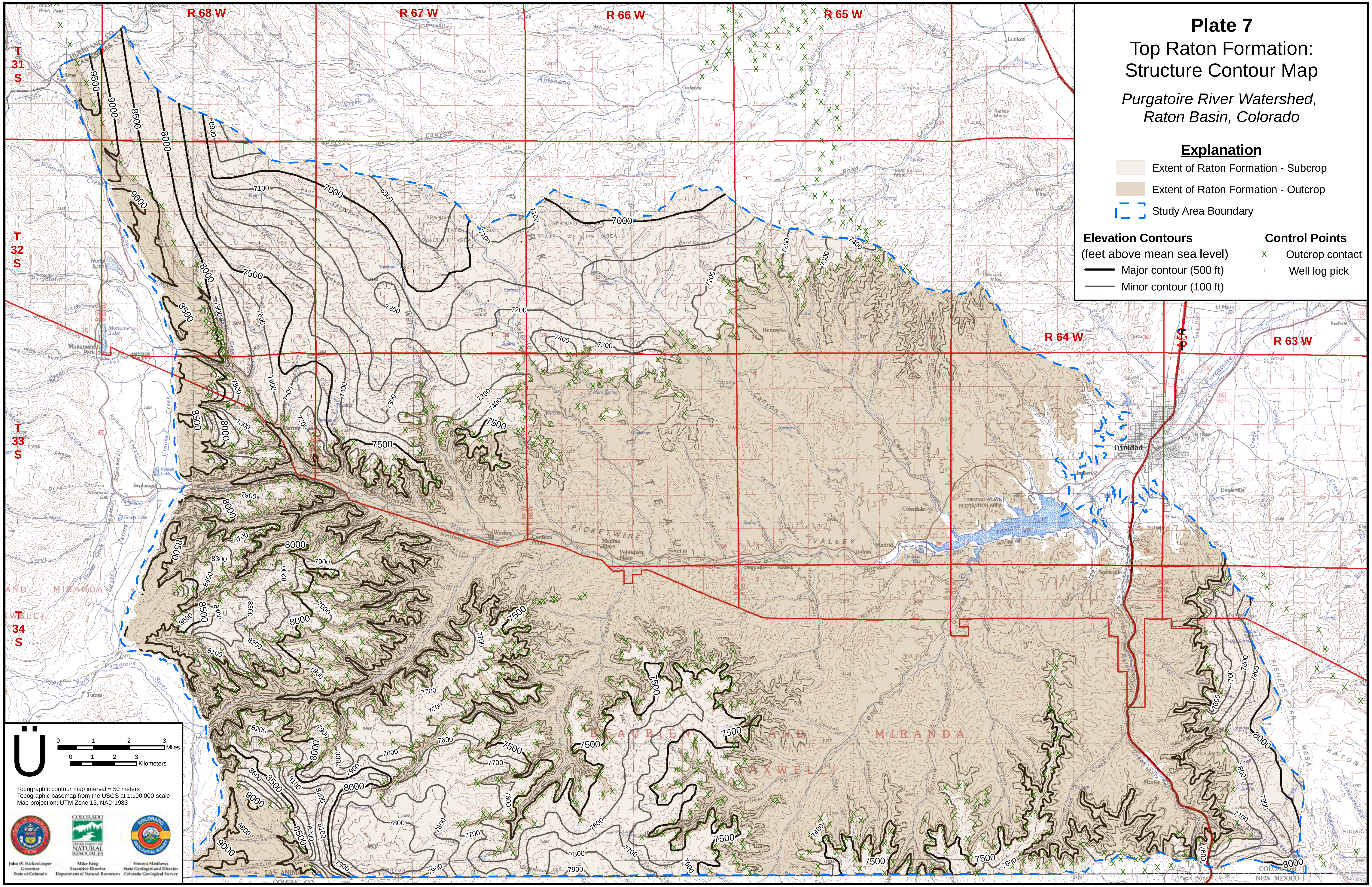
Plate 7
Top Raton Formation: Structure Contour Map
Purgatoire River Watershed, Raton Basin, Colorado
Explanation
Extent of Raton Formation - Subcrop
Extent of Raton Formation - Outcrop
Study Area Boundary
Elevation Contours
(feet above mean sea level)
Major contour (500 ft)
Minor contour (100 ft)
Control Points
Outcrop contact
Well log pick
R 68 W
R 67 W
R 66 W
R 65 W
R 64 W
R 63 W
T 31 S
T 32 S
T 33 S
T 34 S
Trinidad
Miles
Kilometers
Topographic contour map interval = 50 meters
Topographic basemap from the USGS at 1:100,000-scale
Map projection: UTM Zone 13, NAD 1983
John W. Hickenlooper Governor State of Colorado
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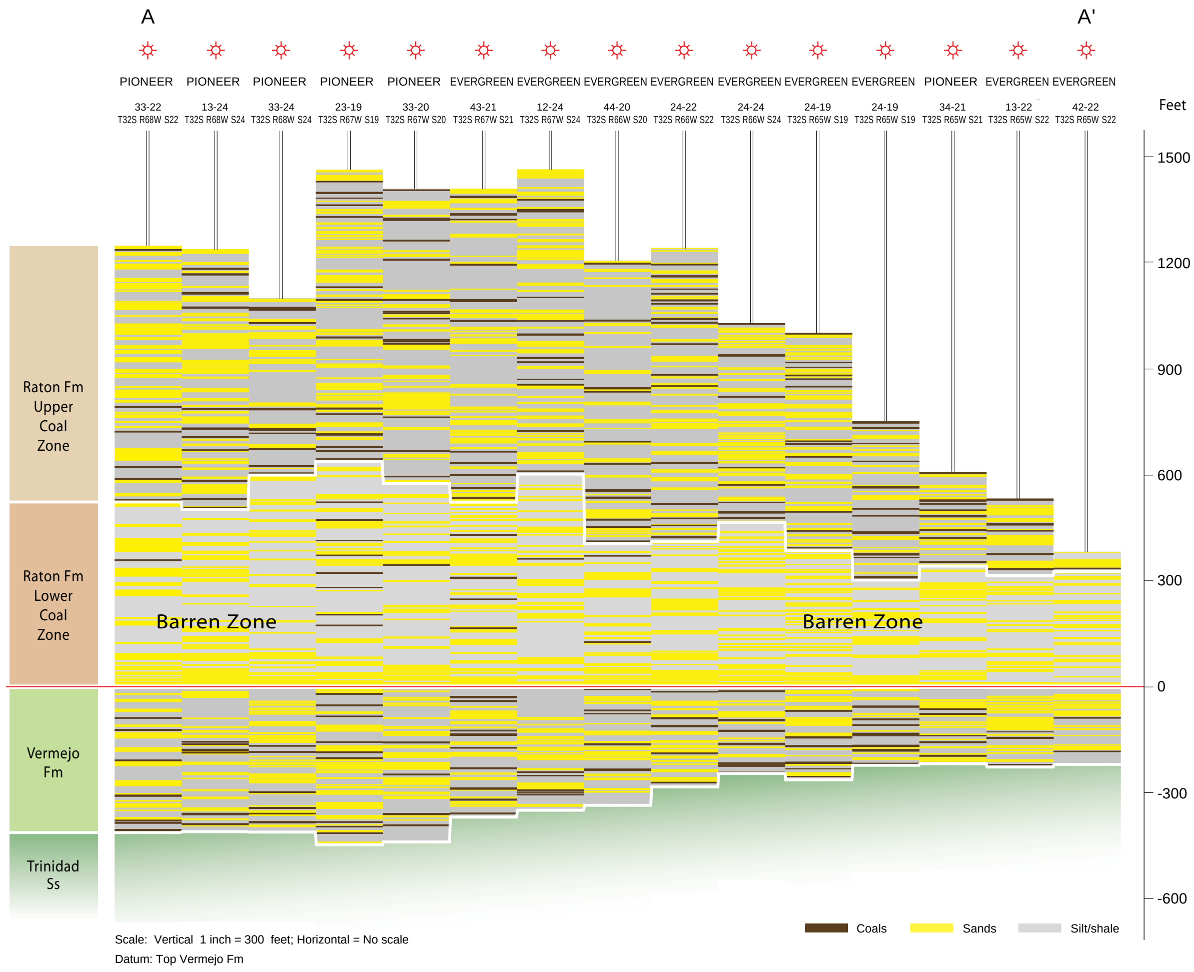

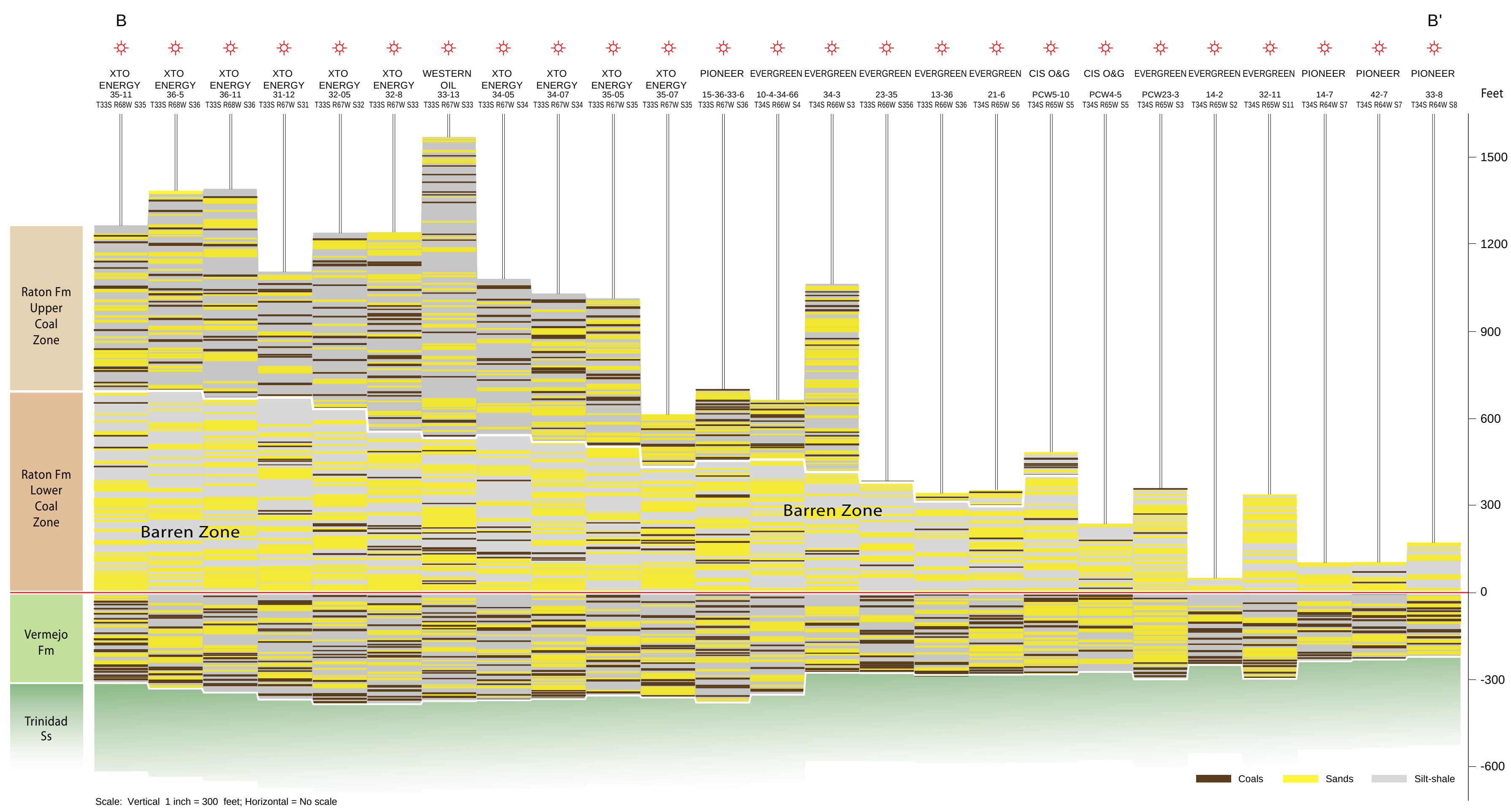

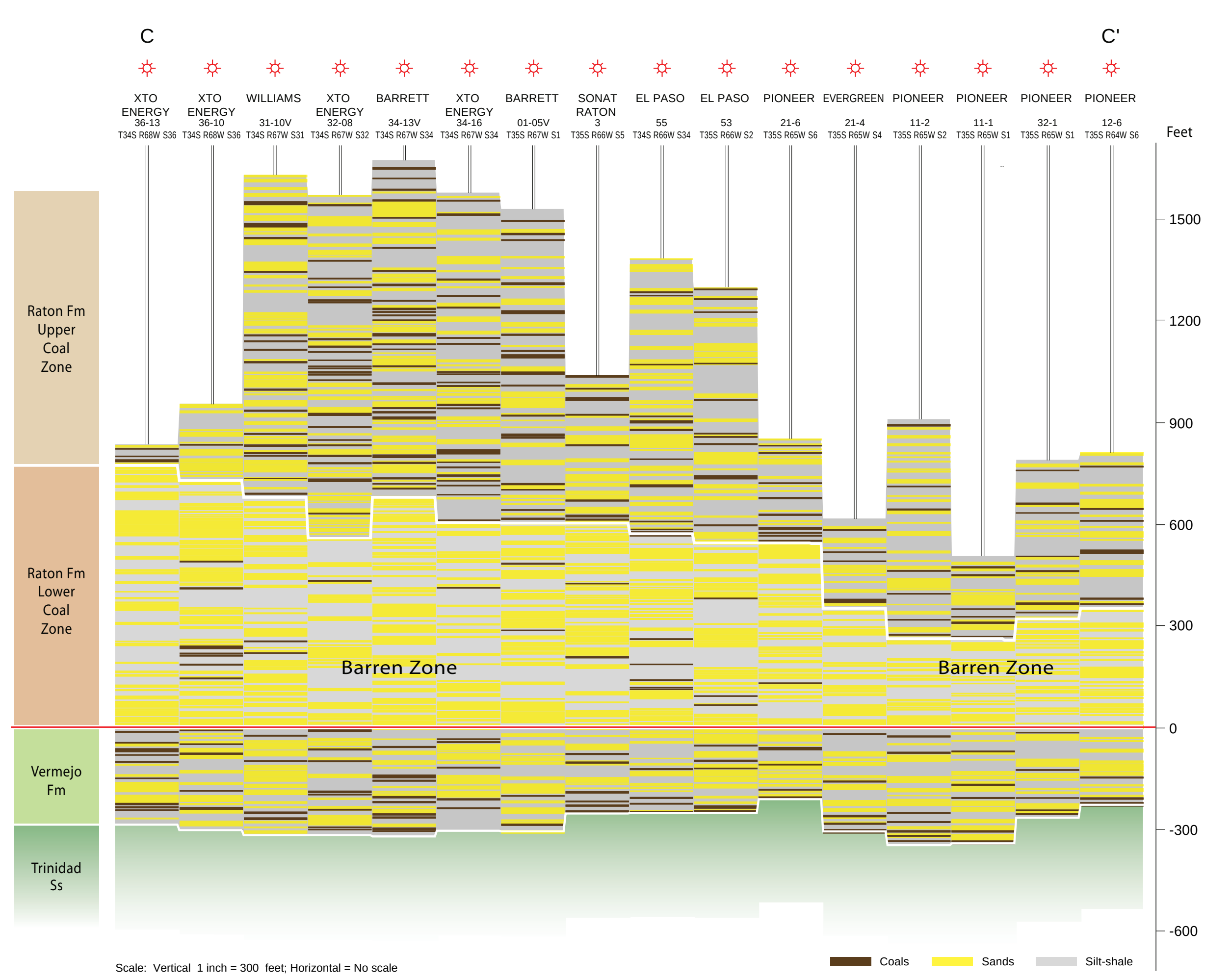

Plate 8

Stratigraphic Sections A, B, and C

COLORADO GEOLOGICAL SURVEY