# Oil and Gas Resource Development Potential
# Eastern Valle Vidal Unit

By

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## A 20-year Reasonable Foreseeable Development Scenario (RFDS)
## Carson National Forest

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## Carson National Forest Disclaimer

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# Oil and Gas Resource Development Potential, Eastern Valle Vidal Unit
A 20-year Reasonable Foreseeable Development Scenario (RFDS)
Carson National Forest

## Executive Summary

The Valle Vidal Unit of the Carson National Forest is located in the Raton Basin, a geologic basin in New Mexico and Colorado that is becoming increasingly important in providing the nation with natural gas. The petroleum industry has expressed an interest in leasing within the eastern part of the Unit, an area of approximately 40,000 acres of the 100,000 total acres. The Reasonable Foreseeable Development Scenario (RFDS) is a planning tool. It provides a reasonable estimate of what oil and gas exploration and development activities might be proposed, should a decision be made to lease the area. Under this scenario, the RFDS projects what activities might be conducted by a mineral lessee under current and reasonably foreseeable regulatory conditions and industry interest. The RFDS is a 20-year forward-looking estimation of oil and gas exploration and development that is exclusive of other concerns that might compete for use of land in a multiple-use scenario. As such, it is information about one resource, with a projection of that resource as developed in a reasonable foreseeable manner. This information forms a “knowledge baseline” for the Carson National Forest to consider in any subsequent analyses to examine leasing or development of the resource. The RFDS can be considered by the Carson National Forest if building alternative scenarios of the potential extent and conditions of oil and gas leasing and operations.

The overall potential for occurrence of oil and gas resources in the eastern Valle Vidal Unit is high. This rank is based on geologic conditions predicted to be present at the site relative to adjacent lands that are being actively and economically developed. The primary play of interest is the widespread, shallow (less than 2000 ft deep) coalbed methane and low permeability sandstone natural gas play associated with the Vermejo and Raton Formations. The entire eastern Valle Vidal Unit is underlain by these formations. The coal beds in these formations are assumed to be minimally thermally mature and capable of being economically developed on 160 acre per well spacing. Certainty in this assumption decreases southward over the eastern Valle Vidal Unit due to lack of direct data in the southern part of the Unit. This assumption could be confirmed by core drilling a minimal number of wells, testing the cored coal beds for production potential. Parts of the area (an estimated 6080 acres) could be excluded from being potential for coalbed methane production due to the presence of fractured igneous dikes that could cause excessive water production in nearby wells. Confirming this hypothesis would require drilling, completing, and testing one or more wells in the affected acreage.

Another high potential occurrence play is the fractured “shale” blanket-type Pierre-Dakota play that also has slight possibility of conventional reservoir traps in the Dakota Sandstone. The fractured shale play currently has a poor economic outlook in the short term and is not being pursued adjacent to the eastern Valle Vidal Unit, but it could become significant in the 20-year life of this scenario. A third play, based on postulated presence and source rock potential of the Pennsylvanian Sandia Formation, is assigned a low potential due to uncertainty and lack of positive indicators such as related oil or gas shows nearby.

The potential for development of oil and gas resources in the eastern Valle Vidal Unit is high. If allowed to lease the eastern Valle Vidal Unit, oil and gas operators will be primarily interested in the immediate economic benefit of developing the shallow coalbed methane resources throughout the Unit. Coalbed methane plays benefit from dewatering coal over a large area and it is probable that operators will require large contiguous blocks of acreage in order to operate most efficiently and economically.

Development would likely proceed from an initial phase of exploratory drilling and gas-in-place evaluation at 5 to10 sites spread across the area to evaluate geologic and economic conditions. A second phase would focus on bringing in the proper infrastructure to produce the area as a whole. This would include a pipeline to deliver gas to market and might include electric power. Right-of-way availability and access to pipeline interconnects is a locally sensitive subject that would require negotiation and pose unknown financial considerations to be borne on the part of lessees; thus, pipeline economics were not considered in the RFDS. It is estimated that at least four deep wells would be required for subsurface disposal of produced water in approved saline aquifers. Under this scenario, a third phase would involve drilling every allowed surface location on 160 acre spacing with vertical wells. A fourth phase might involve drilling problematic locations using deviated (not horizontal) wellbores if economics prove to be sufficient. Deep targets would be tested as a side benefit of drilling water disposal wells and do not require additional locations in this scenario.

Development of the coalbed methane resource is not likely to require reflection seismic data. Evaluation of deeper plays would benefit from such data. Operators in the region have expressed interest in 3-D seismic data with lines/cross-lines spaced closer than ¼ mile. No evidence of existence of 3-D seismic data or current acquisition activity was found in the vicinity. It is proposed that once coalbed methane related lease roads were constructed, seismic operations could take place on the road grid.

Over the 20-year life of the RFDS, it is predicted that between 195 and 254 vertical or slightly deviated wellbores could be drilled on 191 to 250 surface locations (well pads) based on current and foreseeable State of New Mexico-regulated well density of 160 acres per well. Four of those wells would be drilled as water disposal wells/deep tests and could be placed on an existing location with a shallow coalbed methane well. If increased-density spacing of 80 acres per well were approved by the State of New Mexico during the term of the RFDS, then the predicted number of wellbores could double to 390 to 508. Associated 80-acre spaced well pads would number 382 to 500. At present, there is no justifiable need to increase density to 80 acres per well, but necessary data could become available over time, derived from 160 acre-spaced wells. The coalbed methane reservoir conditions are not conducive to horizontal drilling due to complicating factors including the difficulty of artificially lifting water, thin discontinuous beds within a thick gross interval, shallow depth, and poor economics. Deviated (not horizontal) drilling methods could help to reduce the surface impacts of development by allowing optional nonstandard locations for construction of well pads, such as locating multiple wellheads on a single pad.

The area of disturbance for each coalbed methane well location need not be large because the shallow depth and minimal required equipment allow for small well pads. Typical surface disturbance associated with current producing well pads in the Raton Basin is about 0.5 acres whereas well pads elsewhere in New Mexico are normally about 2 acres in size. Roadways and right-of-ways add an additional acre of disturbance per 160-acre-spaced well pad. Water disposal and compression facilities add an additional 15 acres. It is estimated that full development as a single lease at 160 acres spacing per well will require between 396 and 777 acres of disturbance over the entire unit depending upon well pad area required. This doubles if 80-acre spacing per well development becomes an option. Innovative and environmentally responsible development practices are encouraged by the authors to reduce impacts on alternative land uses while promoting maximum economic benefit. Flexibility in locating wells within 160 acre spacing units will promote more effective reservoir drainage and may potentially mitigate other impacts.

There is no official government township-grid survey in the eastern Valle Vidal Unit. This information is critical for assigning lease ownership and locating wells. It is recommended that a survey be performed on the ground prior to mineral leasing if the lands are to be offered for lease.

## List of Abbreviations and Acronyms

| | |
|---|---|
| AAPG | American Association of Petroleum Geologists |
| ACCESS | a relational database computer program, product of Microsoft |
| AIME | American Institute of Mining, Metallurgical and Petroleum Engineers |
| ARCGIS | a GIS computer program, product of Earth Science Resources Inc. |
| BBL/bbl | barrels, a volumetric term for water, equals 42 gallons |
| Bw | barrels of water |
| mBw | thousand barrels of water |
| CBM | coalbed methane |
| CIM | Canadian Institute of Mining, Metallurgical, and Petroleum Engineers |
| C. P. G. | Certified Petroleum Geologist |
| DRG | Digital Raster Graphic; a digital image product |
| EIS | Environmental Impact Statement |
| EPA | U. S. Environmental Protection Agency |
| EUR | estimated ultimate recovery |
| ft | feet, foot |
| GIS | geographic information system |
| GOTECH | website by New Mexico Petroleum Recovery Research Center |
| Gp | gas in place |
| GRI | Gas Research Institute |
| ISC | Interstate Stream Commission |
| km | kilometer (s) |
| m | meter (s) |
| NM | New Mexico |
| NMBGMR | New Mexico Bureau of Geology and Mineral Resources |
| NMIMT | New Mexico Institute of Mining and Technology |
| NMOCD | New Mexico Oil Conservation Division |
| ONGARD | Well database by New Mexico Oil Conservation Division |
| P. E. | Professional Engineer |
| RFDS | reasonable foreseeable development scenario |
| RGIS | New Mexico Resource Geographic Information System. |
| Ro | vitrinite reflectance; indicator of source rock thermal maturity |
| scf | standard cubic feet, a volumetric term for natural gas |
| mscf/mcf | thousand cubic feet, standard volumetric unit for market trading |
| mmscf | million cubic feet |
| Bscf/Bcf | billion cubic feet |
| Tscf/Tcf | trillion cubic feet |
| S. P. E. | Society of Petroleum Engineers |
| TDS | total dissolved solids, a water quality measurement |
| U. S. | United State of America |
| VPR | Vermejo Park Ranch, lease name applied to development areas |
| WGR | water to gas ratio; water:gas |
| Wp | water in place |

# Chapter 1 Introduction

## 1.1 Description and location of eastern Valle Vidal Unit

The Valle Vidal Unit is located in the Raton Basin, a geologic basin in New Mexico and Colorado that is becoming increasingly important in providing the nation with natural gas. The Valle Vidal Unit became a part of the National Forest System in 1982 through donation by Pennzoil Corporation. The donation included both the surface and oil and gas mineral estate (including coalbed methane) according to the Carson National Forest. Coal mineral rights are owned by Pittsburg & Midway Coal Mining Company (a division of Chevron). The eastern Valle Vidal Unit, the subject of study for this Reasonable Foreseeable Development Scenario (RFDS), encompasses an area of approximately 40,000 acres of the 100,000 total acres comprising the Valle Vidal Unit. The eastern Valle Vidal Unit includes all the land within the National Forest boundary east of a geologic feature called The Rock Wall as depicted in Figure 1.1. The privately owned Vermejo Park Ranch lies to the north, northeast, and south of the eastern Valle Vidal Unit. The Elliot Barker State Wildlife Area, and privately owned Philmont Scout Ranch and Ponil Ranch lie to the southeast and east.

The Valle Vidal Unit and adjacent properties are subdivided from the Maxwell Land Grant of 1841 (confirmed by the United States in 1887) that includes roughly three-fifths of Colfax County (Pettit, 1966). Landowners within the Maxwell Land Grant have established property boundaries using the metes-and-bounds survey method. There is no official governmental survey available for the land grant that subdivides it into townships based on the New Mexico principal meridian. A few maps in the public domain show township grids based on extrapolation from outside the land grant boundaries, but this is done roughly and inconsistently between maps.

Maps for this report include an unofficial land grid system created from two sources: an unofficial survey extrapolation of townships from the western edge of the land grid used by the National Forest Service, and an unofficial survey extrapolation of townships from the eastern edge of the land grant supplied by the New Mexico Oil Conservation Division that appears to be consistent with well locations on the Vermejo Park Ranch. In general, there is an approximate one mile adjustment at the boundary line between the two surveys, the boundary being the National Forest Boundary as provided by the Carson National Forest.

It is recommended that an official township-section grid survey be performed prior to any mineral leasing of the Valle Vidal Unit. The conclusions of the RFDS will not change significantly by a resurvey because this study is based on general areas of development rather than on specific well locations.

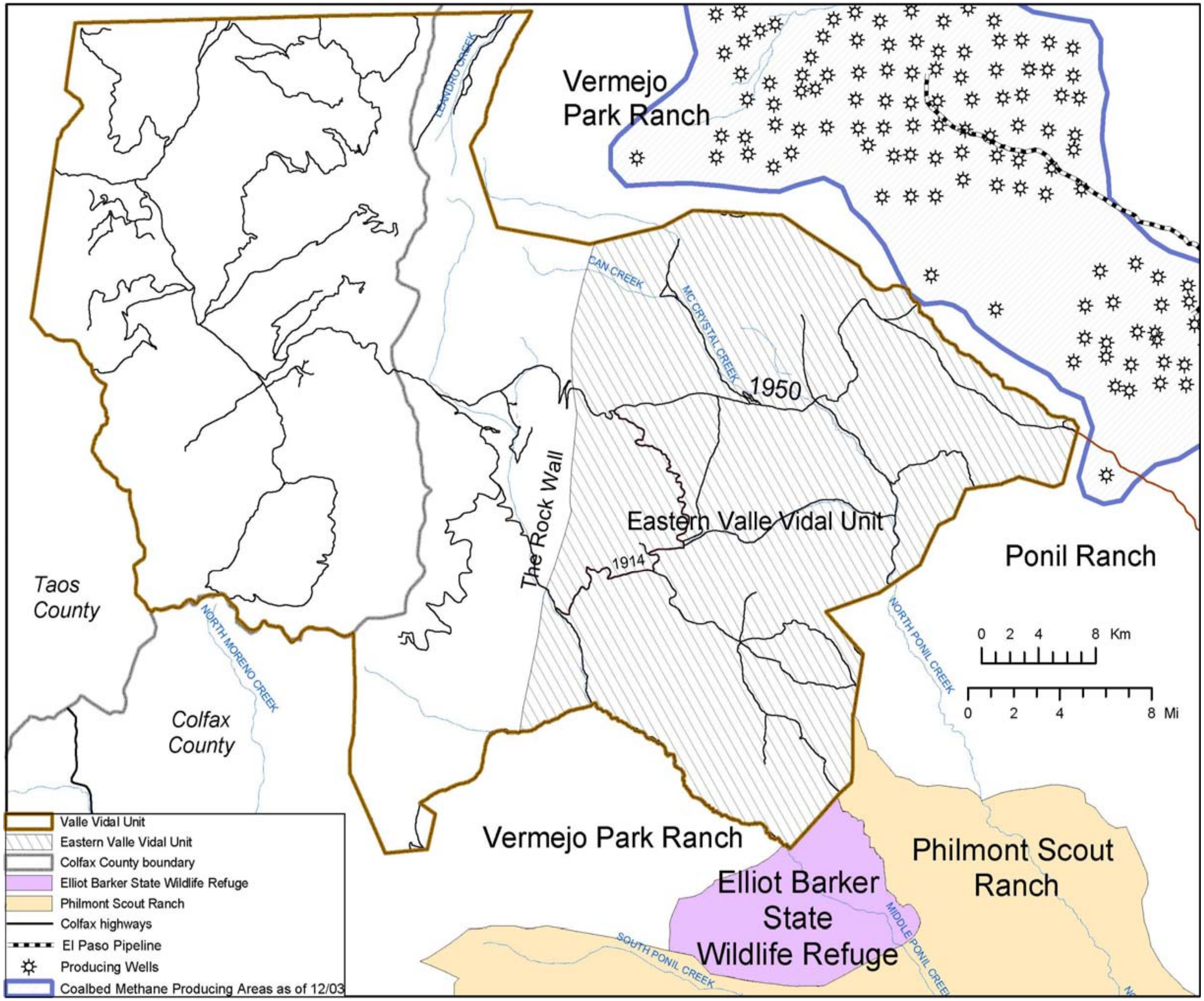


Figure 1.1 Index map showing the eastern Valle Vidal Unit, Carson National Forest and approximate boundaries with adjacent private and state owned lands in Colfax County, New Mexico. Map base reproduced from Carson National Forest (1999).

## 1.2 Purpose and scope of RFDS

The Valle Vidal Unit is currently being managed for multiple uses with special wildlife management emphasis. There are no oil and gas leases or producing wells on the Unit. Carson National Forest Resource Management Plan (1986) is silent in regards to the oil and gas resources. Presently, coalbed methane production operations are being conducted on the Vermejo Park Ranch, which lies adjacent to the eastern Valle Vidal Unit. The Carson National Forest contracted with the New Mexico Bureau of Geology and Mineral Resources to produce the Reasonable Foreseeable Development Scenario (RFDS) after the Forest received petroleum industry requests to make the Valle Vidal Unit available to leasing for similar activities.

The Reasonable Foreseeable Development Scenario (RFDS) provides a reasonable estimate of what oil and gas exploration and development activities *might* be proposed and/or conducted by a mineral lessee under current and reasonably foreseeable regulatory conditions. The RFDS, with an effective beginning date of June 1, 2004, is a 20-year forward-looking estimation of oil and gas exploration and development that is exclusive of other concerns that might compete for use of land in a multiple-use scenario. Subsequent to this report, the Carson National Forest may use the document to inform further analyses, which would consider the impacts of the activities described by the RFDS.

The approach taken by the RFDS team involves three steps:

1) Study and understand the geological factors for hydrocarbon generation, migration and accumulation. Predict potential for oil and gas reservoirs. Identify likely locations of reservoirs where possible.
2) Develop scenarios that describe the conditions and technology necessary to explore for, and access, the predicted oil and gas reservoirs. This step requires an estimation of how technology may evolve in a twenty-year time frame.
3) Estimate the type and amount of surface occupancy and disturbance required to develop the reservoirs.

There are currently no oil and gas related activities being conducted on the eastern Valle Vidal Unit. The RFDS is based in part on study of an adjacent producing property and prediction of geological conditions conducive to oil and gas resources at the Unit. The RFDS includes an analysis of production from nearby and similar coalbed methane fields as an example of what might be expected to occur at the Unit if geological conditions are similar. The RFDS and its authors cannot authorize or endorse oil and gas related activities on any property, nor does it warrant that any production will actually take place, or be economic within, the Unit should leases become available. Instead, it merely predicts what *might* occur if leasing and subsequent activity were allowed. The scope of work for the RFDS does not include evaluation of the various potential environmental impacts of predicted activity, of aquifer characteristics or impacts thereon, or economic or social analysis of predicted activity, production and possible impacts thereon.

# Chapter 2 Methods

## 2.1 Estimation of resource potential and potential for development

The resource potential of the eastern Valle Vidal Unit was estimated based on analyses of oil and gas plays using a petroleum system approach. An extensive body of literature was reviewed in order to evaluate and document the existence of source rock, thermal maturation, reservoir strata possessing permeability and/or porosity, potential migration pathways, and traps for each play. The method and timing of development of each play were determined based upon the current and possible future regulatory and economic climate, and upon current industry best practices in similar plays in the Rocky Mountain region. Each play type is ranked as to its potential for occurrence and development during the 20-year life of the RFDS. Discussions can be found in Chapter 4 of this report.

## 2.2 Production analysis and estimation

The objectives of production analysis are to: (1) analyze current well performance and determine, if possible, the estimated ultimate recovery (EUR) and other production characteristics of the Raton Basin coalbed methane play that is currently being developed adjacent to the Valle Vidal Unit, and (2) to identify any interference, if there is evidence that interference occurs, in the production response between wells and thus qualitatively determine drainage area.

The scope of the study consisted of analyzing and comparing historical gas and water production from different producing regions within the New Mexico portion of the Raton Basin; and then narrowing the focus of the analysis to individual well performance of strategic regions in proximity to the Valle Vidal Unit. All production data through May 2003 was obtained from public domain data in the New Mexico Oil Conservation Division’s ONGARD data set available from the New Mexico Petroleum Recovery Research Center GOTECH web site at *http://octane.nmt.edu/*

Well production data analysis utilized conventional decline and log-log type curve matching techniques to estimate recovery and drainage area. The unique behavior of coals complicates both the analysis and the interpretation. Therefore, identification of various production responses was undertaken to differentiate between coalbed methane response and conventional (low-permeability) behavior. Subsequently, wells that exhibited conventional production decline were analyzed for reservoir/production properties. Detailed discussion of the findings from this work can be found in Chapter 5 of this report.

## 2.3 Prediction of surface occupancy and disturbance

Prediction of surface occupancy (Chapter 6) was based upon an estimate of the number of viable subsurface reservoir cells. Once the number of subsurface reservoir cells was established, two scenarios for surface occupancy and disturbance were derived. The first is based on regulations applied in the Jicarilla District of the Carson National Forest. The second is based on common industry practices in the vicinity of the Valle Vidal Unit. It also considered how much of this activity could reasonably be expected to occur in the twenty-year life of the RFDS.

## 2.4 Operator survey and processing

In order to test base assumptions of the RFDS analyses, a group of oil and gas operators was consulted through a concise and confidential survey. The direct benefit was to tap into the wealth of experience available and obtain currently perceived development strategy for their properties. The industry survey was distributed to all operators of record in the Raton Basin in both New Mexico and Colorado (total of eight). In addition, the survey was made available to the New Mexico Oil and Gas Association and Colorado Oil and Gas Association for distribution to interested members. Operators were given thirty days to respond to the survey. An example of the survey including cover letter is included as Appendix 1.

Chapter 7 contains a summary of the results. These results were compared to our independent analysis, and for any discrepancies identified, further investigation was done to develop an explanation for these differences. The number of returned responses totaled four, which included three from the Raton Basin Operators and one non-Raton Basin response. This response rate seems low unless one considers that the only current operator in the New Mexico part of the Raton Basin has a virtual monopoly through mineral ownership of much of the potential acreage in the basin and controls the only pipeline, perhaps discouraging other operators from having an interest in participating.

## 2.5 GIS project platform and databases

Data sources utilized and assembled for this RFDS were public domain resources. Examples are well-specific data compiled by the New Mexico’s Oil Conservation Division and Bureau of Geology and Mineral Resources, and geographic information made available by the Carson National Forest. Data from oil and gas wells and coal mine information for Colfax County were entered into Microsoft ACCESS databases (see accompanying CD-ROM). The public domain data was formatted to be accessed and displayed using the ARCGIS platform. This software platform was chosen because it is widely utilized by land-use professionals and it accepts and integrates data that was acquired in a variety of formats and projection methods. The purpose of the GIS project was to provide all contractors of the EIS with a common platform early in the process of work.

Data that was collected and integrated into the ARCGIS project include:

- Well and mine location, drilling, testing and completion data compiled from the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) petroleum records and coal data libraries.

- Surface geologic mapping information compiled from the digital and published1:500,000 scale maps by the NMBGMR.

- The State of New Mexico's ONGARD well production database maintained by the New Mexico Petroleum Recovery Research Center and accessible via the GOTECH web site at *http://octane.nmt.edu/*

- Geographic data from U.S. Department of Interior's PLSS system and the Carson National Forest including land grid, detailed roads, surface feature boundaries, U. S. Geological Survey DRG topographic maps, and surface waters. Other data from RGIS, the New Mexico Resource Geographic Information System.

The product of this compilation effort, as delivered to the Carson National Forest, is archived on an accompanying CD-ROM.

# Chapter 3 Background Geology

## 3.1 Geologic setting

There are numerous references that describe the geology of the region encompassing the Valle Vidal Unit, many of which are listed in Appendix 2 of this report. The most recent published paper on the resource potential of the region is by Hoffman and Brister (2003). Some of the discussions that follow are repeated, paraphrased, or expanded from that paper.

The eastern Valle Vidal Unit is located in the southern part of the Raton Basin, a Laramide geologic basin extending through southern Colorado and northern New Mexico (Fig. 3.1). From a physiographic perspective, this area is known as the Raton Mesa region, a highly stream-dissected, east-tilted mesa that marks the transition from the Sangre de Cristo Mountains of the Southern Rocky Mountains Province on the west, to the Great Plains Province on the east. The eastern edge of Raton Mesa in New Mexico is a prominent escarpment west of State Highway 64 between the towns of Raton and Cimarron. The western edge of the Raton Basin/Raton Mesa is essentially marked by two prominent hogbacks, locally known at the “The Wall” (westernmost) and “The Little Wall”/“Ash Mountain” (easternmost) where rock units that crop out in the eastern escarpment are tilted up against the Sangre de Cristo Mountains. From a coal mining perspective, the area is often referred to as the Raton Mesa coal area or region.

The eastern Valle Vidal Unit lies on the western edge of the Raton Basin/Raton Mesa region. The bedrock geologic unit at the surface in the Unit is the Poison Canyon Formation (Paleocene) that consists primarily of arkosic sandstone and conglomerate. The present topography of the Valle Vidal Unit (Fig. 1.1) is due to incision of modern stream valleys tributary to the Ponil and Vermejo Rivers into a planation surface (Pleistocene or older) that caps the hills and higher plateaus. Whitman Vega, the Beatty Lakes and other flat-floored valleys appear to have supported natural lakes during past wetter climates, but have for the most part since been captured and are drained by modern streams. The western margin of the eastern Valle Vidal Unit as addressed in this study is a north-northeast trending topographic ridge known as “The Rock Wall”, caused by differential erosion around a swarm of three erosion-resistant igneous dikes (Fig. 3.2). A similar prominent northeast-trending dike (“Firewall Dike”) forms another ridge informally named the “Firewall” (Fig. 3.3) that bisects the study area.

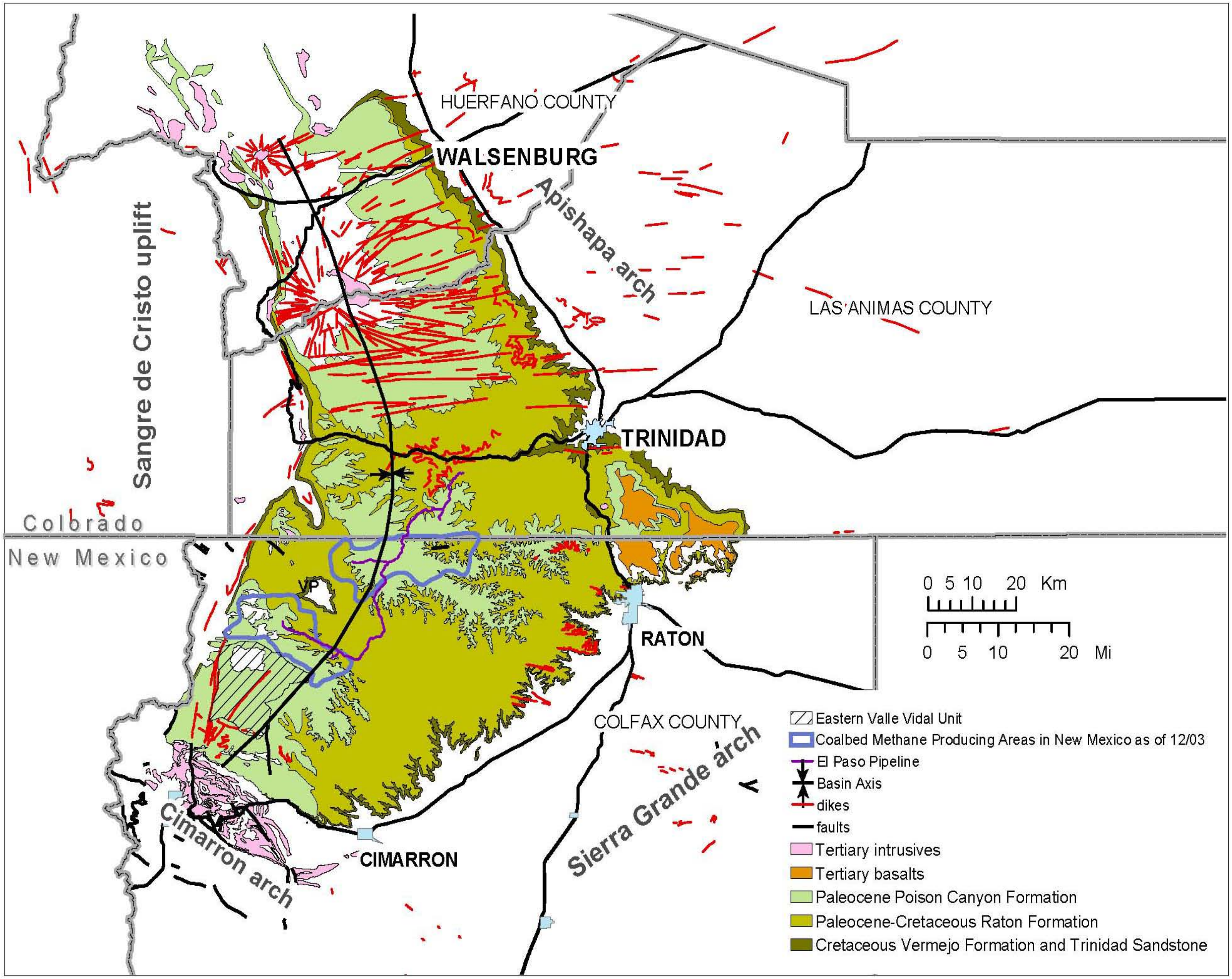


Figure 3.1 Geology and structural features of the Raton Basin, Colorado and New Mexico. Included are the eastern Valle Vidal Unit and coalbed methane-producing areas in New Mexico. VP = Vermejo Park. Geology derived from New Mexico Bureau of Geology and Mineral Resources (2003) and Tweto (1979). Figure modified from Hoffman and Brister (2003).

Figure 3.2 (top) Photograph taken from the vantage point of the Firewall dike near where it crosses North Ponil Creek looking westward. Three mountain ridges are visible in the photo including The Rock Wall, Ash Mountain, and Little Costilla Peak. Photo by Christopher Haley.

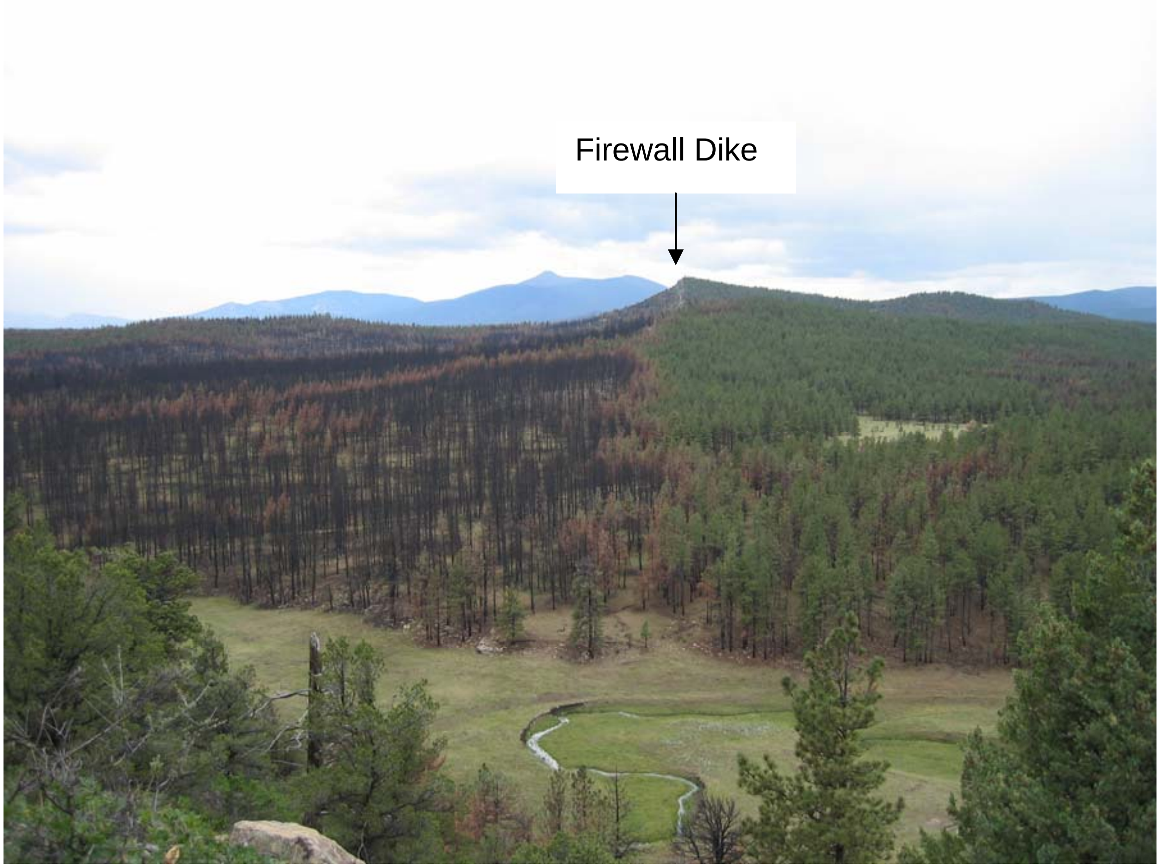


Figure 3.3 (bottom) Photograph taken from same vantage point of Figure 3.2 looking southwest along the Firewall dike. Note burned forest on the left and unburned trees on the right of the dike. Photo by Christopher Haley.

### 3.2 Structural geology

Baltz (1965) provided a thorough description of the Raton structural basin, paraphrased here. The Raton Basin is an elongate, slightly arc-shaped, northerly trending, asymmetric structural downwarp formed during the Laramide orogeny (Late Cretaceous to Eocene; Fig. 3.1). On its steeply dipping to overturned western flank lies the Sangre de Cristo uplift. Structural relief on Precambrian basement at the steep, western limb of the basin may be as much as 12,000-15,000 ft (Cather, 2004). To the north are the Wet Mountains uplift and Apishapa arch. The eastern flank dips gently (less than $3^o$) westward from of the Sierra Grande arch. In New Mexico the post-Laramide Cimarron arch separates the basin into two subbasins, the southern of which was named the Las Vegas Basin by Darton (1928). The Upper Cretaceous to Paleocene coal-bearing Vermejo and Raton Formations of the Raton Basin exist only north of the Cimarron arch. Timing of basin formation is indicated by syndepositional structures in the Vermejo and Raton Formations (Lorenz et al., 2003) and an unconformity that places conglomeratic Paleocene Poison Canyon Formation in angular contact with older rocks at the basin's western and northern flanks (Baltz, 1965).

Cather (2004) describes multiphase Laramide development of the Raton Basin based on the stratigraphic record preserved there. The first phase is represented by the upper Pierre Shale (marine), Trinidad Sandstone (marginal marine-shoreface), and Vermejo Formation (non-marine) that document the regression of the Western Interior Seaway and progradation of sediments derived from the incipient Laramide Brazos-San Luis uplift, the eastern part of which is preserved as the Sangre de Cristo Mountains (Brister and Gries, 1994). The Raton and Poison Canyon Formations are, in part, lateral equivalents derived from the San Luis uplift and mark the medial phase of uplift and associated basin subsidence. The third phase is represented in Colorado by post-Poison Canyon formations. Subsidence of that phase may have been limited to the northern parts of the basin.

Figure 3.4 is a combined geologic and structure contour map of the top of the Trinidad Sandstone interpreted from a variety of data sources including oil and gas wells and published measured sections on the southern edge of the basin. The basin axis wraps around the eastern and southern flanks of the Vermejo Park (VP on maps) dome. It is important to emphasize that there are limited data points on which to base contour lines through the eastern Valle Vidal Unit. We anticipate that the estimated contour lines will move as additional well control points become available. The structure of the basin is an important factor in determining the oil and gas potential of the eastern Valle Vidal Unit. The influence of structure on each play type is discussed in Chapter 4.

It is notable that there is a general lack of faults shown on Raton Basin geologic maps. This may be due in part to the heavy vegetative cover of the region that obscures fault relationships.  Numerous syndepositional faults are known to exist and have been documented in road cuts (e.g. Lorenz et al., 2003).  The existence of fracture systems and their effects on reservoirs are well known (e.g. Stevens et al., 1992).  There appear to be two sets of extensional fractures that have the potential to enhance permeability of reservoirs, with westerly and north-northeasterly azimuths (Scott Cooper, Sandia National Laboratories, 2003, pers. comm.).

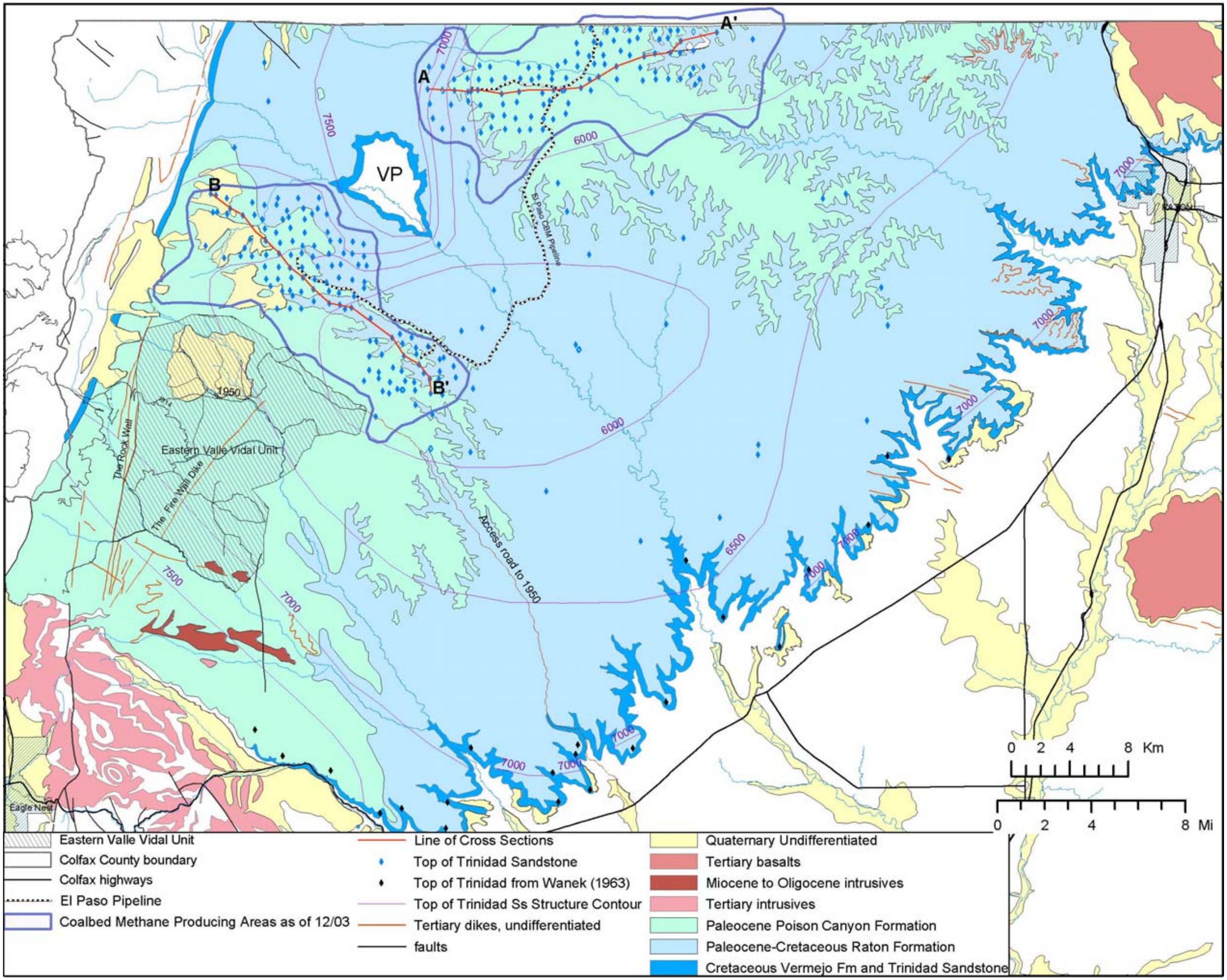


Figure 3.4 Structure-contour map of the top of the Trinidad Sandstone interpreted from well and surface data. VP = Vermejo Park. Contour interval = 500 ft. Modified from Hoffman and Brister (2003).

### 3.3 Stratigraphic summary

Figure 3.5 is a summary stratigraphic column for the eastern Valle Vidal Unit based upon Dolly and Meissner (1977) and Baltz and Myers (1999). It demonstrates the stratigraphic formations present, their general lithologies, oil and gas shows in the region, potential source rocks, and interpreted oil and gas plays. Figure 3.6 is a type lithology log and Figure 3.7 is a cross-section for the Unit.

**Precambrian basement:** Proterozoic supracrustal rocks in northern New Mexico include metavolcanic, metasedimentary and plutonic rocks ranging from 1765 to 1650 Ma, and granitic rocks ranging from 1500-1400 Ma (Williams, 1990). In the vicinity of the Valle Vidal Unit, Grambling and Dallmeyer (1990) describe the Proterozoic rocks outcropping in the Cimarron Mountains to the south, and Smith (1988) and Grambling et al. (1989) describe these rocks in the Taos Range to the west. Such rocks have no potential for generating oil and gas and very low potential for being fractured reservoirs of oil and gas. The Precambrian basement is capped by unconformities and may be overlain by Pennsylvanian or Permian rocks beneath the Valle Vidal Unit.

**Pennsylvanian strata:** Pennsylvanian shale and siltstone sediments may overlie Precambrian basement beneath the eastern Valle Vidal Unit. This assumption is based on early work by Shaw (1956) and later workers that suggest Pre-Pennsylvanian Paleozoic formations were likely eroded from the region prior to deposition of the Sandia Formation (Morrowan-Atokan) as a consequence of Mississippian initiation of uplift (De Voto, 1980) of the Ancestral Rockies.

The Sierra Grande-Apishapa uplift, an element of the Ancestral Rocky Mountains, was an emerging highland during the Pennsylvanian and early Permian (Fig 3.8). Detritus was shed westward into the subsiding intermontane Central Colorado trough, a basin bounded on the west by a southeastern extension of the Uncompaghre uplift (Mallory, 1972a; De Voto, 1980). It is possible, but unknown whether the Central Colorado trough was connected southwestward to the Taos trough and Rowe-Mora basin exposed today in the southern Sangre de Cristo Mountains.

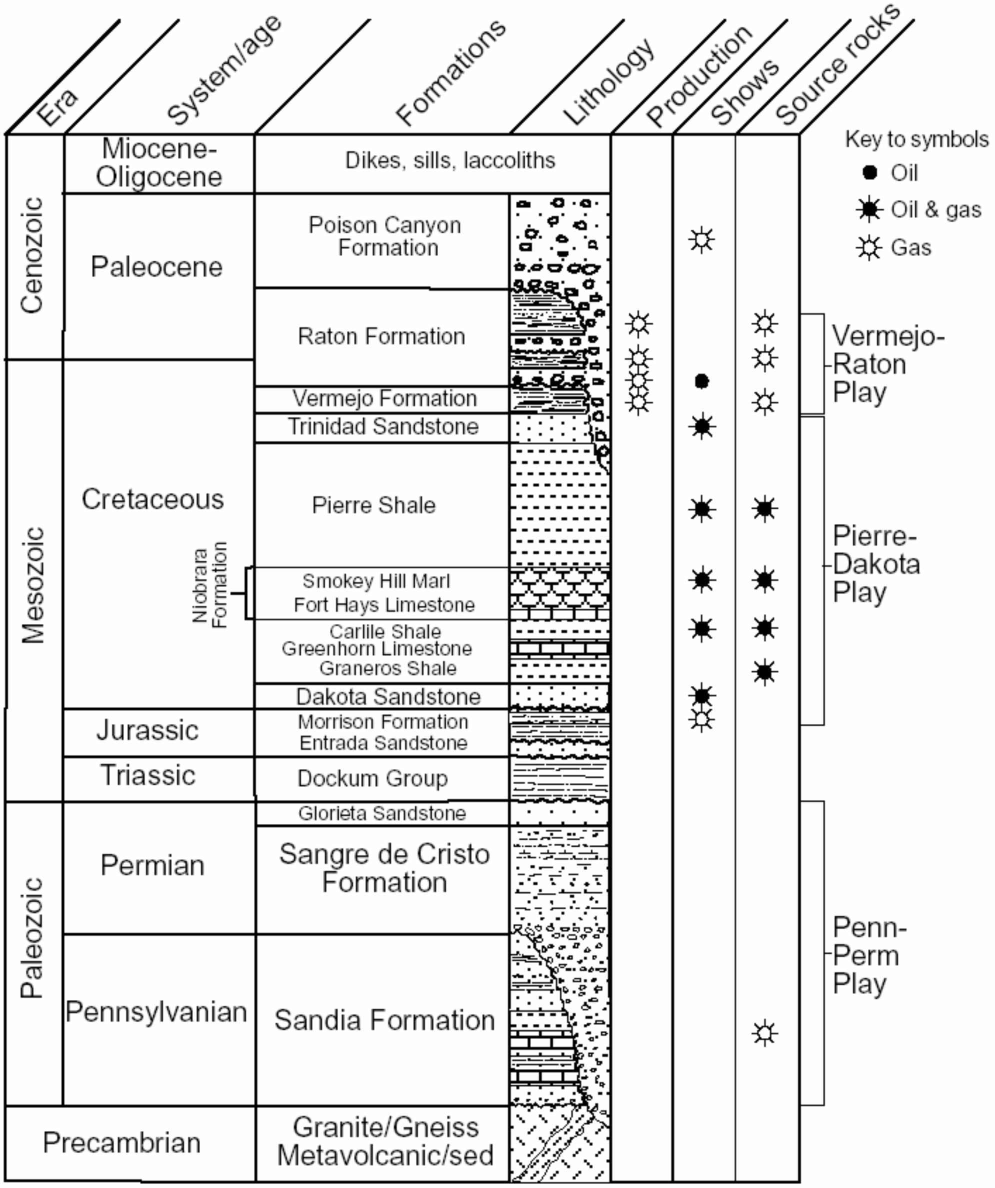
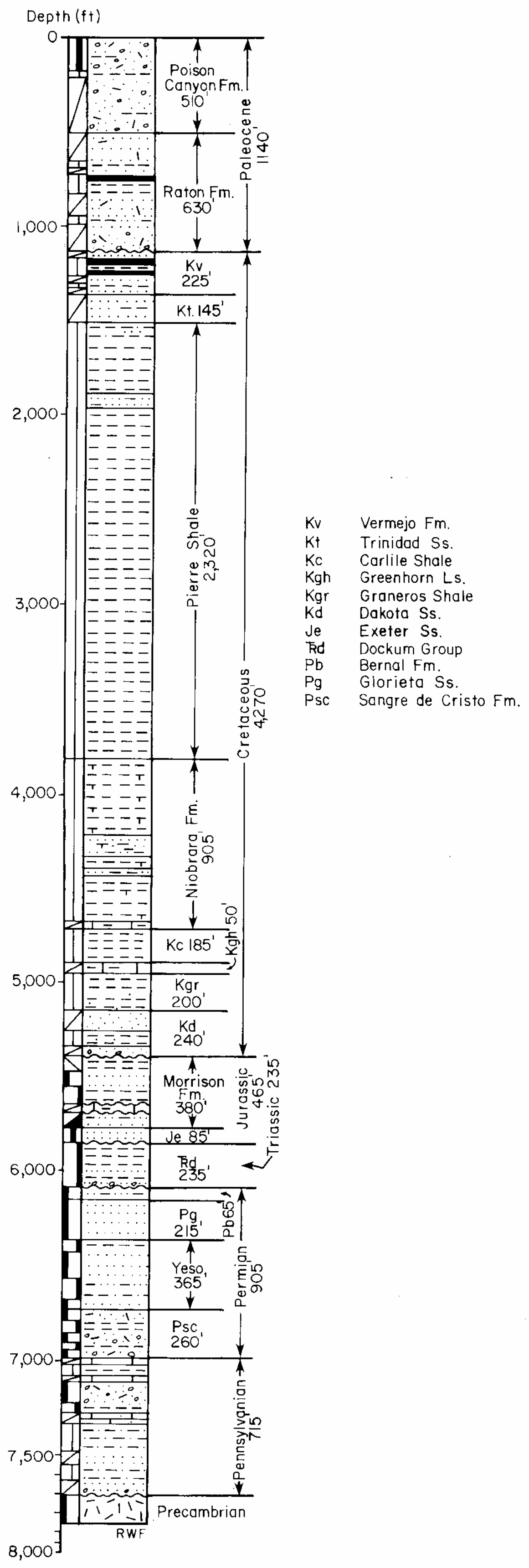


Figure 3.5 Generalized stratigraphic column for the New Mexico portion of the Raton Basin. Modified from Dolly and Meissner (1977).

Figure 3.6 Composite stratigraphic section, vicinity of eastern Valle Vidal Unit, Raton Basin, Colfax County, New Mexico. Surface to Triassic: Gourley No. 1 Vermejo Park, sec. 27, T31N, R17E. Triassic to Precambrian: Continental No. 2 St. Louis, Rocky Mountain, and Pacific, sec. 26, T31N, R21E. From Grant and Foster (1989). See original text for description of units



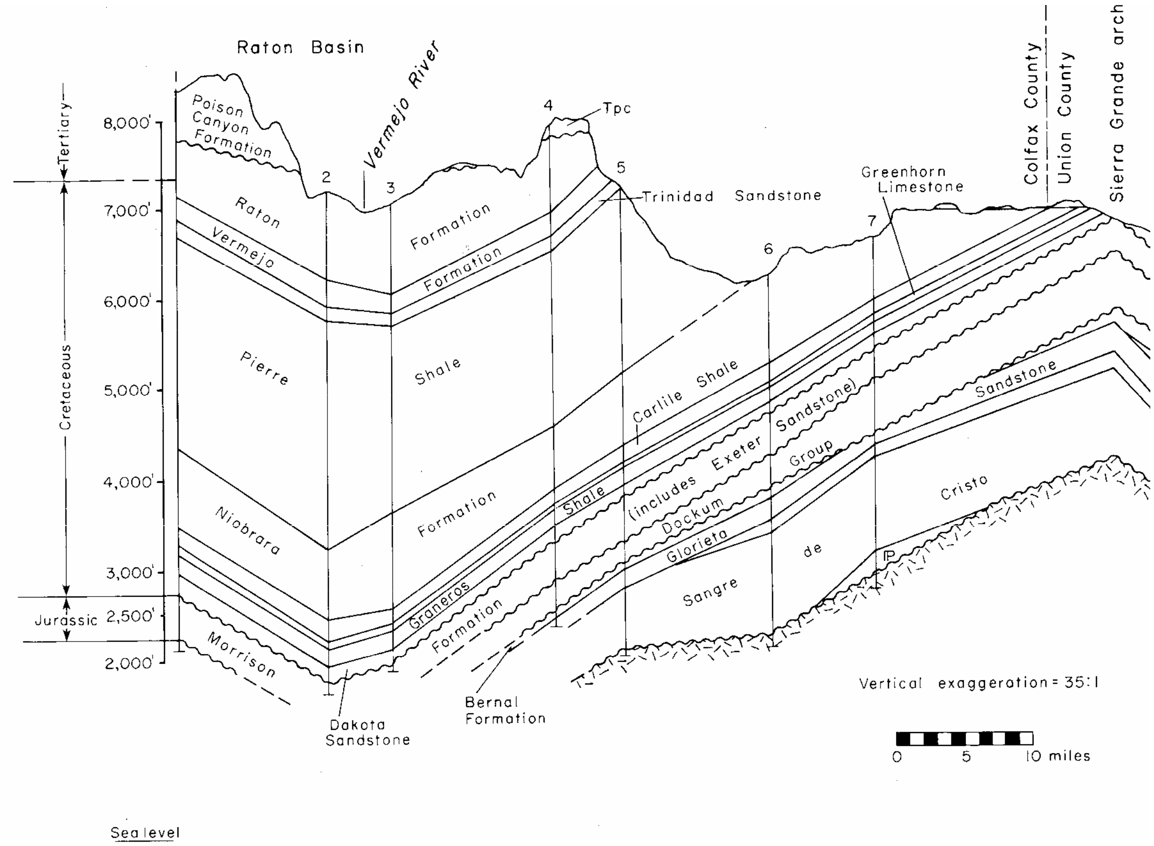


Figure 3.7 West-east cross section, Raton Basin, New Mexico. From Grant and Foster (1989). Wells:

1) Gourley 1 Vermejo Park, Sec. 27, T. 31N., R. 17 E.
2) Gourley 2 Vermejo Park, Sec. 16, T. 30N, R. 19 E.
3) Odessa 2 W. S. Ranch, Sec. 30, T. 30 N., R. 20 E.
4) Conoco 3 St. Louis, Sec. 18, T. 30 N., R. 22 E.
5) Conoco 1 St. Louis, Sec. 24, T. 30 N., R. 22 E.
6) Condron 1 Moore, Sec. 10, T. 29N., R. 24 E.
7) HNG 1 Roach, Sec. 1, T. 29 N., R. 25 E.

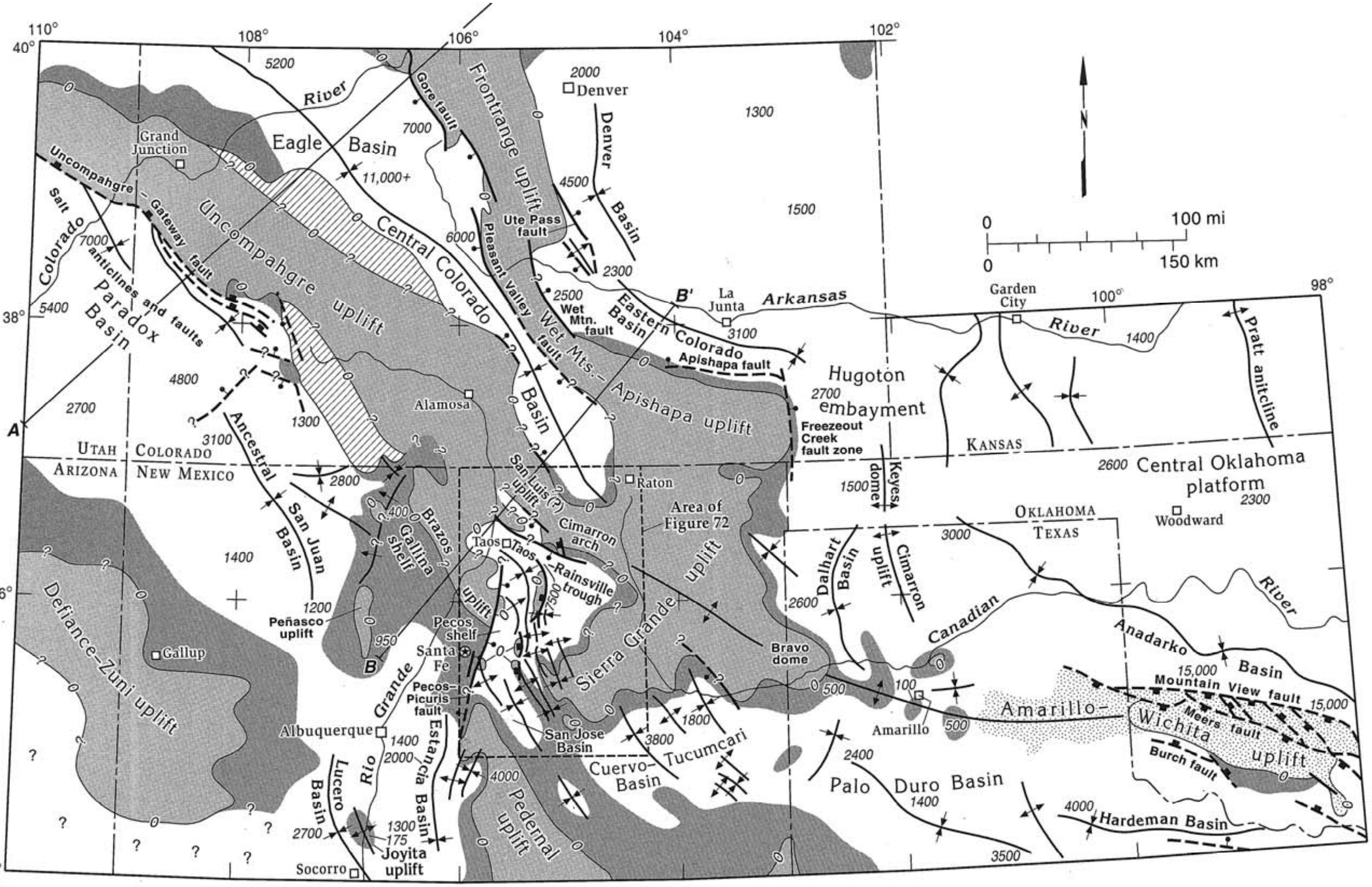


Figure 3.8 Principal late Paleozoic tectonic features of southern Colorado, northern New Mexico, and adjacent parts of Texas and Oklahoma. From Baltz and Myers (1999).

In their memoir on the Paleozoic rocks of the region, Baltz and Myers (1999) described the Sandia Formation as interbedded gray shale, carbonaceous shale, fine- to coarse-grained sandstone and conglomerate, and thin limestone. Minor coal seams were also noted. Gray and carbonaceous shales, and coal, are possible source rock lithologies, whereas sandstones could be reservoir lithologies. Grant and Foster (1989) allow for some potential for stratigraphic and structural traps in the Pennsylvanian in the western Raton Basin. Foster (1966) describes rocks similar to the Sandia Formation in the Conoco #2 Rocky Mountain well (listed in Oil and Gas Well Database on accompanying CD-ROM) drilled northeast of the Valle Vidal Unit by Conoco. No shows were reported for those rocks in that well.

**Permian strata:** Subsidence of the Central Colorado trough continued into the Permian as evidenced by the continued deposition of the conglomeratic upper Sangre de Cristo Formation (Wolfcampian) which eventually lapped eastward onto the Sierra Grande uplift. As the Ancestral Rocky Mountain orogenic event drew to a close, the subdued topography was onlapped by the Yeso Formation in some places, then capped by the marine Glorieta Sandstone (Leonardian). The Glorieta Sandstone is a medium grained, well-sorted sandstone. It is one of the deep saline aquifers used as a disposal zone for produced waters from coalbed methane operations on the Vermejo Park Ranch near the Valle Vidal Unit (Roy Johnson, NMOCD, 2004, pers. comm.). The Glorieta Sandstone is a potential reservoir at the top of the Pennsylvanian-Permian clastic pile. However, no shows of oil and gas have been reported.

**Triassic and Jurassic strata:** According to Grant and Foster (1989), The Triassic Dockum Group redbeds overlies the Permian strata with an unconformable contact. The eolian Entrada Sandstone, otherwise known locally as the Exeter Sandstone, in turn unconformably overlies the Triassic. The Morrison Formation redbeds cap the Entrada Sandstone, also with an unconformable contact. These formations lack source rock potential and have generally not yielded shows of oil or gas. At the Vermejo Park Ranch, the Entrada Sandstone is used as a disposal zone for produced water (Roy Johnson, NMOCD, 2003, pers. comm.). The upper Morrison Formation yielded a gas show of unknown quality while drilling a produced water disposal well on the Vermejo Park Ranch (Roy Johnson, NMOCD, 2004, pers. comm.), but the show apparently has not been confirmed by commercial production.

**Dakota Sandstone through Pierre Shale (Cretaceous):** The Lower to Middle Cretaceous Dakota Group (a.k.a. Dakota Sandstone) was deposited upon an unconformable surface. Its lower half is the deltaic Mesa Rica Formation (Albian; Lucas et al., 1998) or Purgatoire Formation (Baltz, 1965), whereas the upper half is the Romeroville Sandstone (Cenomanian; Lucas et al., 1998), a shallow marine/shoreface unit. The basal unit represents an unconformity-bounded transgressive event whereas the upper part is the base of a better-represented transgressive event in the region that includes the marine Graneros

Shale and is capped by the Greenhorn Limestone. These transgressions mark the advance of the Cretaceous Interior Seaway that eventually covered northern New Mexico. Baltz (1965) described the Dakota Sandstone as nearly all sandstone with lenses of conglomerate in outcrops on the western margin of the Raton Basin. The upper part of the Dakota grades into the marine rocks of the overlying Graneros Shale.

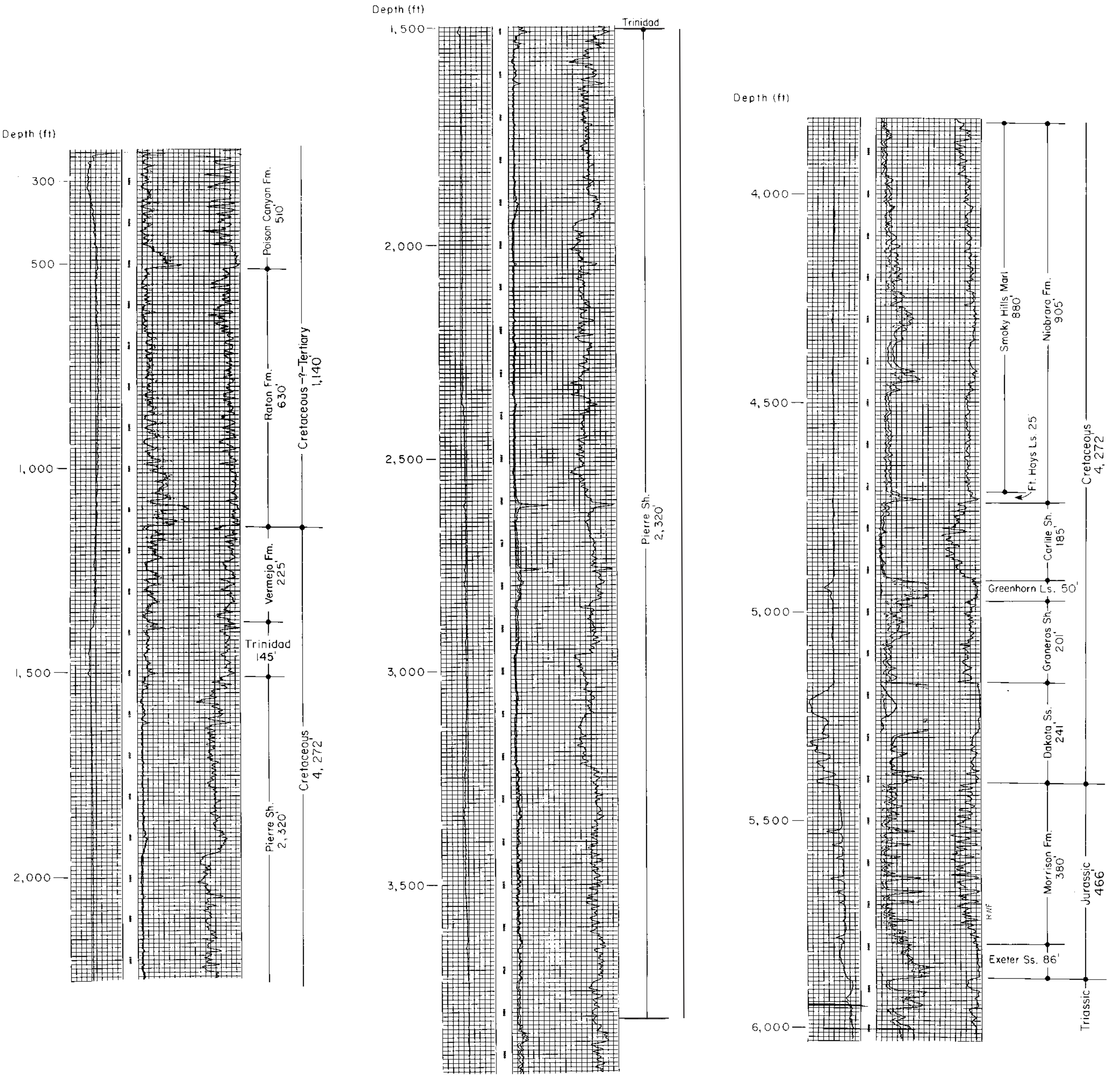
The Dakota Sandstone is about 250 ft thick in the vicinity of the eastern Valle Vidal Unit where it is comprised of porous sandstone interbedded with shale. Where traps exist, the Dakota might make an attractive reservoir target with the overlying Graneros Shale acting as source rock. The Dakota Sandstone has yielded numerous shows of oil and gas in Colfax County (Foster, 1966), but no commercial production. It is a produced water disposal zone at the Vermejo Park Ranch (Roy Johnson, NMOCD, 2004, pers. comm.).

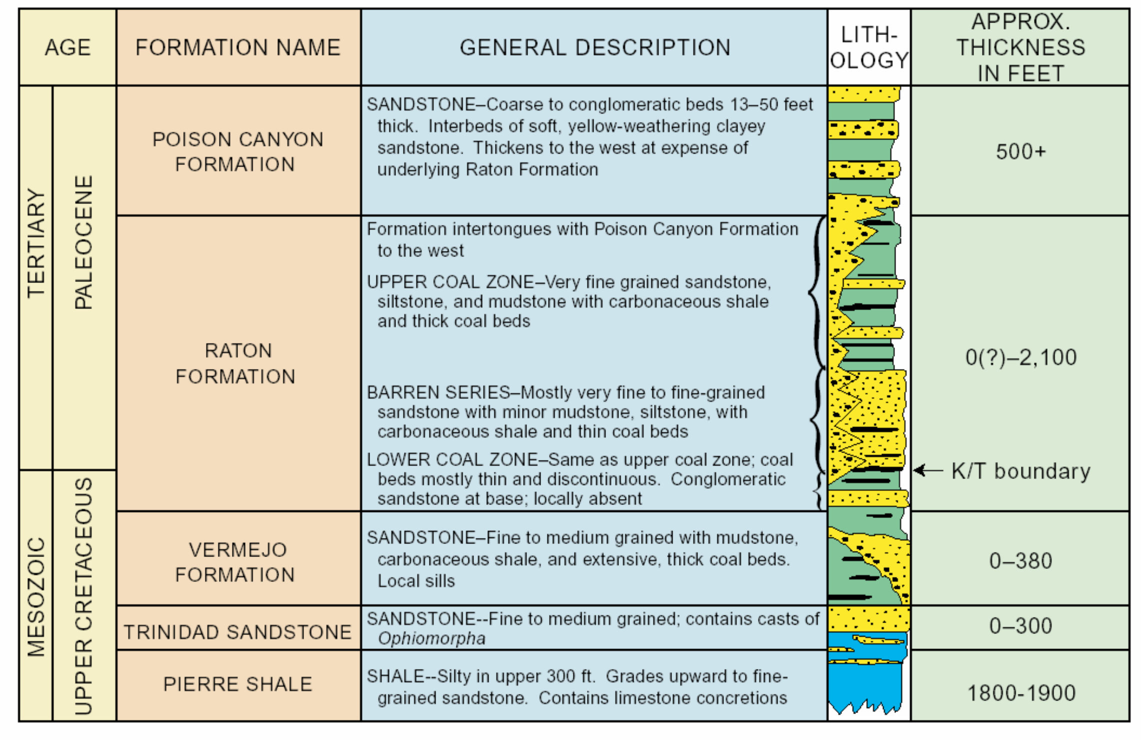
The Graneros Shale is dark gray and contains thin beds of bentonite, limestone, and sandstone, whereas the Greenhorn is thin beds of limestone and interbedded calcareous to chalky shale (Baltz, 1965). Overlying the Greenhorn Limestone is the dark gray Carlile Shale, which is in turn overlain by the Niobrara Formation. The Niobrara Formation is comprised of the Fort Hays Limestone (lower part) and the chalky marls of the Smokey Hill Member. The mixed calcareous and clay-rich composition of the Niobrara Formation makes it a potential fractured reservoir as well as a potential source rock.

Above the Niobrara Formation is the 2000+ ft thick Pierre Shale. Most of the Pierre Shale is dark gray noncalcareous shale. The upper several hundred feet consist of gray, thin-bedded, fine grained sandstone intercalated with thin beds of dark gray silty and sandy shale, essentially distal intertongues with the overlying Trinidad Sandstone (Johnson et al., 1966). The Pierre is an oil- and gas-prone source rock and has yielded numerous shows in the Raton Basin. Figure 3.9 is a type electrical log that demonstrates the great thickness of the Pierre Shale relative to other Mesozoic Formations in the Raton Basin.

**Trinidad Sandstone through Poison Canyon Formation (Cretaceous-Paleocene):** This section is the most important relative to coalbed methane potential of the eastern Valle Vidal Unit. It contains coal beds that serve as source rocks. Reservoir rocks include coal and sandstone beds. The coal-bearing formations in the Raton Basin (Fig. 3.10) are underlain by the Trinidad Sandstone. As thick as 130 ft, it forms a prominent cliff along the eastern edge of the basin. Hills (1899) described the Trinidad Sandstone in the Raton Basin, later to be defined by Lee (1917). The base of the Trinidad can be difficult to pick in electric logs as there is a gradational contact between it and the underlying Pierre Shale. The upward-coarsening sandstones show bioturbation and commonly contain *Ophiomorpha* casts (Flores, 1987) suggesting a shallow marine to shoreface depositional environment. The lower part of the formation

Figure 3.9 Type electric log for the eastern Valle Vidal Unit from the Gourley #1 Vermejo Park well. The location of this well is problematic and is discussed in Section 4.1 of Chapter 4. Figure from Grant and Foster (1989).





| 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 | | 500+ |
| MESOZOIC | UPPER CRETACEOUS | RATON FORMATION | Formation intertongues with Poison Canyon Formation to the west<br>UPPER COAL ZONE–Very fine grained sandstone, siltstone, and mudstone with carbonaceous shale and thick coal beds<br>BARREN SERIES–Mostly very fine to fine-grained sandstone with minor mudstone, siltstone, with carbonaceous shale and thin coal beds<br>LOWER COAL ZONE–Same as upper coal zone; coal beds mostly thin and discontinuous. Conglomeratic sandstone at base; locally absent | | 0(?)–2,100<br>← K/T boundary |
| | | VERMEJO FORMATION | SANDSTONE–Fine to medium grained with mudstone, carbonaceous shale, and extensive, thick coal beds. Local sills | | 0–380 |
| | | TRINIDAD SANDSTONE | SANDSTONE--Fine to medium grained; contains casts of *Ophiomorpha* | | 0–300 |
| | | PIERRE SHALE | SHALE--Silty in upper 300 ft. Grades upward to fine-grained sandstone. Contains limestone concretions | | 1800-1900 |

Figure 3.10 Generalized stratigraphic column for Cretaceous and Paleocene rocks in the Raton Basin. From Flores and Bader (1999), modified from Pillmore (1969), Pillmore and Flores (1987) and Flores (1987).

has ripple lamination that grades upward into planar and trough cross-lamination (Flores, 1987), demonstrating an upward increase in depositional energy and reflecting the overall shallowing and regression of the seaway.

Conformably overlying the Trinidad Sandstone is the coal-bearing Vermejo Formation. However, Lee (1917) and Wanek (1963) recognized transgressive tongues of the Trinidad Sandstone extending into the Vermejo Formation along the southern margin of the basin. Both noted the general thinning of the Vermejo Formation to the east. Lee (1917, p. 51) defined the Vermejo Formation for exposures at Vermejo Park, and described it as the “coal measures lying immediately above the Trinidad Sandstone.” This sequence of sandstone, siltstone, mudstone, shale, carbonaceous shale, and coal averages approximately 350 ft thick. The Vermejo Formation represents delta-plain deposits landward of the shoreface delta-front and barrier-bar sediments of the Trinidad Sandstone (Flores, 1987; Pillmore and Flores, 1987). The thicker coals are commonly concentrated near the base of the Vermejo Formation in proximity to the Trinidad upper shoreface sandstone.

In general, the Raton Formation overlies the Vermejo Formation with an unconformable contact. Lee (1917) divided the Raton Formation into the informal basal conglomerate, lower coal zone, a sandstone-dominated barren series (middle barren sequence herein), and an upper coal zone. The Raton Formation basal conglomerate is a 10- to 30-ft-thick pebble conglomerate to granule quartzose sandstone eroded into the Vermejo Formation. Overlying the basal conglomerate, the 100- to 300-ft-thick lower coal zone consists of sandstone, siltstone, mudstone, carbonaceous shale, and thin, discontinuous coal. This sequence represents meandering stream floodplain deposits that grade upward into braided stream deposits of the overlying middle barren sequence (Flores and Pillmore, 1987; Johnson and Finn, 2001), which varies from 165 to 600 ft thick. The middle barren sequence merges with the Poison Canyon Formation to the west (Pillmore and Flores, 1987). The upper coal zone is a return to finer-grained deposits in an alluvial plain environment (Flores, 1987). Peat swamps developed between the meandering stream channels. Coal beds are lenticular within the upper coal zone but tend to have greater thickness than those in the lower coal zone of the Raton Formation.

The Raton Formation is overlain by and intertongues to the west with the Poison Canyon Formation; the contact can be gradational in parts of the basin. Where the contact intersects the surface, it is mapped as a transitional area (e.g. as mapped by the New Mexico Bureau of Geology and Mineral Resources and others). This is due in part to extensive vegetative cover, but also due to the lack of a detailed study of the Poison Canyon Formation. The Poison Canyon Formation consists of coarse grained to conglomeratic arkosic sandstones. This unit represents prograding conglomeratic lithofacies derived from the Sangre de Cristo uplift. As mentioned previously, this formation is the primary bedrock at the surface in the eastern Valle Vidal Unit.

**Oligocene and younger igneous rocks:** All of the stratigraphic units described above are intruded or domed by Oligocene or younger igneous intrusions somewhere within the region. These intrusions include dikes, sills and laccoliths. Miggins (2002) conducted an extensive study dating many of the igneous features of the region, reporting ages from 33 to 19.7 Ma. At least three oil and gas exploratory wells penetrated igneous rocks (rhyodacite) at shallow depths (less than 4000 ft) over the Vermejo Park dome. Other igneous intrusions in the region include sills in coal beds and dikes that penetrate the entire stratigraphic section. Rock samples from the Firewall dike in the eastern Valle Vidal Unit yielded an Oligocene age of 28.0±0.8 Ma (Million years before present) using the 40Ar/39Ar dating method (Geochronology Laboratory at the New Mexico Bureau of Geology and Mineral Resources, March 18, 2004, unpubl. report).

# Chapter 4 Estimation of Resource Potential and Development

## 4.1 Oil and gas exploration history

Resource potential encourages operators to drill exploratory wells. As exploration proceeds shows of oil and gas and other encouraging information help to build a picture of probable resources available, sometimes leading to commercial production. More than 150 exploratory wells have been drilled in Colfax County, 74 of which reached the Cretaceous Dakota Sandstone. Beginning in 1924 most early exploration focused on finding oil because it could be trucked or shipped by rail to refineries. On the other hand, natural gas required pipelines for transportation. Several larger companies made brief exploration forays into the basin, notably Continental Oil with nine wells in 1954–1955, Pan American with nine wells in 1957–1960 and later as Amoco with eight wells in 1968–1974, and Odessa Natural Gas with eight wells in 1972–1973. These early attempts commonly reported gas shows in the Raton and Vermejo Formations and oil and gas shows in the underlying Trinidad Sandstone through Dakota Sandstone (Baltz, 1965; Foster, 1966; Woodward, 1984). The overall results suggested that the basin might be analogous with the Denver–Julesburg (Woodward, 1984) or San Juan Basins in terms of widespread oil and gas in fractured, low permeability formations. However, the Raton Basin lacked the pipeline infrastructure and moderately porous sandstone reservoirs that made the San Juan Basin so prolific beginning in the late 1950s.

Pennzoil began exploring the potential of its Raton Basin minerals estate in 1981 with several noncommercial deeper Cretaceous tests and shallow coal tests. By 1989 it had assembled a huge 780,000-acre mineral estate, purchased in part from Kaiser Steel in 1989 (Whitehead, 1991). The successful coalbed methane development boom in the San Juan Basin, coupled with Section 29 tax credits for development of unconventional gas reservoirs, encouraged Pennzoil to evaluate the coalbed methane potential around the Vermejo Park area with approximately 30 wells in 1989–1991, 22 of which were produced briefly to evaluate economic viability (Whitehead, 1991). Pennzoil had apparently used the older Kaiser data set as they focused their coal bed exploratory program on areas where the coal was thick and of higher thermal maturity. Unfortunately, the Pennzoil program suffered from the lack of a pipeline, low gas prices at that time, and expiration of the Section 29 tax credits. Information derived from the Pennzoil data set was studied and published in various reports by the Gas Research Institute, notably those of Stevens et al. (1992) and Tyler et al. (1995).

By 1994 the first pipeline was built to transport Raton Basin coalbed methane from the Colorado part of the basin, and a development boom began, accelerating as gas prices improved through the late 1990s. A group of several companies, now consolidated to El Paso Raton LLC, acquired the Pennzoil Vermejo Park mineral estate in New Mexico and began to define the reserves in 1999 with exploratory stratigraphic test wells, many of which were cored.

Commercial coalbed methane production in the New Mexico part of the Raton Basin began in October 1999 upon completion of a pipeline. Subsequent development has expanded concentrically within the areas identified as potential by Pennzoil's 1989–1991 exploratory efforts.

It is important to note that there have been no significant oil and gas exploratory wells drilled within the boundaries of the eastern Valle Vidal Unit to test the three plays listed below. Several shallow coal investigation drill holes were drilled by Kaiser and Pennzoil in the eastern Valle Vidal Unit that support the existence of a coalbed methane play. One oil and gas test was reported, the Gourley #1 Vermejo Park, the location of which would be within the Valle Vidal Unit according to a survey plat filed prior to drilling of the well. This well has been used as a critical data point in the literature (Foster, 1966; Grant and Foster, 1989). Considerable time, effort, and expense were expended in the fall of 2003 to locate the Gourley well on the ground and investigate conflicting information in paperwork on file at the New Mexico Bureau of Geology and Mineral Resources. We believe that the Gourley well was drilled at a location approximately four and one half miles north of the Valle Vidal Unit on the Vermejo Park Ranch as indicated by a location description on the electric log for the well and consistent with the elevation reported for the well (see Oil and Gas Well Database on accompanying CD-ROM for well information). This location is supported by a map provided by the New Mexico Oil Conservation Division (Osterhoudt, 1990, unpublished) that shows the location of the Gourley well in the vicinity of wells drilled or planned by Pennzoil in their 1989-1992 coalbed methane evaluation program.

The lack of oil and gas tests within the Valle Vidal Unit does not compromise the analysis here as the plays described below are not limited in area to the Unit and there is abundant well data in Colfax County upon which to base these plays. The plays and the ranks assigned to them are based on study of data from throughout the southern Raton Basin.

## 4.2 Ranking potential for occurrence

One goal of the RFDS is to estimate the resource potential of the eastern Valle Vidal Unit. Following a review of the literature and past exploration and production activity, we describe the potential of three plays, each play having its own geologically similar traps, potential targets for accumulation of oil and/or gas in porous reservoirs. A modern approach to evaluating oil and gas potential is to examine the factors that contribute to a petroleum system. According to Magoon and Dow (1984), "*Petroleum system* studies describe the genetic relationship between a pod of active source rock and the resulting oil and gas accumulations." The petroleum system analysis qualifies/quantifies the presence of source rocks, capacity and timing of source rocks to produce oil and/or gas, migration of oil and gas to traps, and the location and types of accumulation of oil and gas in reservoir rocks where traps exist. Traps in turn are sealed in some capacity. Often, only parts of the petroleum system are apparent or obvious, other parts must be inferred. See Broadhead (2002) for a layman's description of the origin of oil and gas and the physical requirements for accumulation.

Demonstrated presence of oil or gas by way of "shows", or even better, production from wells, is the best clue of oil and gas potential. Shows indicate that oil/gas have been generated to some extent and are present. However, presence or lack of shows does not determine presence or absence of *economic* accumulations. Economic potential of a resource can be estimated, but in the final analysis is determined by producing oil and gas economically to the marketplace.

A petroleum system-type analysis helps to qualify the oil and gas potential by ranking the presence or absence of key factors. For the purposes of this RFDS, the following ranking system, consistent with petroleum system concepts, was accepted by the Carson National Forest for **ranking potential for occurrence by play**:

**High:** the <u>demonstrated existence</u> of source rock, thermal maturation, reservoir strata possessing permeability and/or porosity, and traps. Demonstrated existence is defined by physical evidence or documentation in the literature.

**Medium:** geophysical or geological data indications that the following <u>may be present</u>: source rock, thermal maturation, reservoir strata possessing permeability and/or porosity, and traps.

**Low:** specific indications that one or more of the following <u>may not be present</u>: source rock, thermal maturation, reservoir strata possessing permeability and/or porosity, and traps.

**None/very low:** demonstrated absence of a petroleum system. This rank would apply to rocks that do not fall into one of the following plays and is therefore not used in this study.

## 4.3 Ranking potential for development

Another goal of this RFDS is to estimate potential for development of the potential oil and gas resources. For the purposes of this discussion, the potential for development is estimated after a ranking assignment for potential of occurrence of the resource. The geologic conditions for oil and gas reservoirs below the eastern Valle Vidal Unit suggest that the resources there will most likely yield unconventional-type, fractured, low-permeability and coalbed methane reservoirs. Such reservoirs vary significantly from conventional porous and permeable reservoirs that have historically better recovery volumes and rates of production, and economics. Unconventional reservoirs tend to be economically marginal and be technically challenging to drill and/or complete. However, the key is that they are often *economically* marginal, not *subeconomic*. The economy of scale plays an important role in development of these reservoirs. Economically marginal and technically challenging conditions do not deter operators from drilling and/or completing wells that will produce. By fine-tuning their economics and techniques to produce such reservoirs, operators can add significant cumulative resources to their long-term reserves inventory. As fuel prices are expected to rise (as domestic production struggles to supply increasing demand) long-lived reservoirs will increase significantly in value.

Conventional reservoirs are often discrete accumulations of oil and gas, whereas unconventional reservoirs are often blanket-type accumulations where oil and gas are trapped by the low capacity of the rocks to conduct fluid under reservoir physical conditions. The unconventional nature of the potential resources is discussed further in the next section. The following simple scheme was used for **ranking potential for development by play**:

**High:** There is high potential for blanket-type unconventional resource occurrence and it is economically and technically feasible to develop most prospective locations using conventional technology within the time constraints of the RFDS based on current or anticipated well spacing rules that apply to the area being developed. For conventional resources, this ranking assumes a high potential for resource occurrence, and favorable technical and economic conditions for development of conventional oil and gas fields. Geophysical data may be desirable to guide development of conventional and unconventional plays.

**Medium:** The potential for occurrence is ranked high or medium, but viable production from the play has not been demonstrated on or near the area being evaluated. This ranking assumes that there will be sufficient interest to drill one or more wildcat wells to test resource occurrence, and evaluate economic and technical feasibility. Speculative geophysical data acquisition may be attempted to further evaluate the play.

**Low:** The potential for occurrence is ranked low or very low. It is unlikely that wildcat wells will be drilled in the 20-year time frame to specifically test the play because of either low prospectivity or poor economic potential. Speculative geophysical data acquisition may be attempted to further evaluate and possibly upgrade the resource potential rank.

### 4.4 Vermejo-Raton coalbed methane play (Potential for occurrence = High, Potential for development = High)

Coalbed methane has been recognized as an important and widespread resource in the U.S. only since the 1980s. There are a few key papers that describe the conditions favorable for coalbed methane reserves in the Raton Basin. A pioneering study of coalbed methane potential in the Raton Basin by Jurich and Adams (1984) estimated a total resource of 8–18 trillion cubic feet of gas (Tcf) for the entire basin. Close (1988) updated the earlier work and included a detailed study of the depositional environments, cleat orientation and fracture patterns, thermal maturity parameters, and regional thermal history of the basin. Close and Dutcher (1991) estimated the coalbed methane resource to be 40 billion cubic feet (Bcf) per square mile with an estimated ultimate reserve base of one Tcf. The Gas Research Institute (GRI) published a coalbed methane assessment of the Raton Basin (Stevens et al., 1992) that summarized reservoir characteristics and estimated the mean coalbed methane resource of the Raton and Vermejo coals at 10.2 Tcf. New data from wells drilled in the basin were incorporated into the GRI report along with gas desorption measurements and new vitrinite reflectance data, collected in part from coal cores available at the NMBGMR (Stevens et al., 1992, p. 41). Flores and Bader (1999) summarized previous studies and future potential of mining and coalbed methane without including a specific resource assessment of the basin. Johnson and Finn (2001) evaluated the potential for basin-centered gas in the Raton Basin in the sandstones in the Trinidad, Vermejo, and Raton Formations.

An exploration and pilot development drilling project conducted by Pennzoil in 1989–1991 demonstrated that a coalbed methane resource existed in the New Mexico portion of the Raton Basin, but economics and lack of a pipeline prevented the onset of production until 1999. In 1999 a new pipeline allowed production of coalbed methane to begin on the Vermejo Park Ranch which lies adjacent to, and north of, the Valle Vidal Unit. All current coalbed methane production operations in the New Mexico portion of the Raton Basin are being conducted by El Paso Raton LLC in cooperation with the Vermejo Park Ranch. Hoffman and Brister (2003) reviewed the status of the play as of May 2003 when 256 wells had accumulated more than 22 billion cubic feet of coalbed methane from coals in the Upper Cretaceous to Paleocene Vermejo and Raton Formations. An additional 44 wells were producing as of the end of December 2003. The production is from two areas; one is northeast of Vermejo Park and the other generally southwest of Vermejo Park and adjacent to the Valle Vidal Unit. In addition, potential for production from Raton Formation sandstone reservoirs is indicated for a large area where coal beds are currently being developed. The Vermejo Park Ranch is anticipating significant additional development by El Paso Raton LLC in the region between the two existing areas of production and between the southwestern producing area (VPR D and B) and the eastern Valle Vidal Unit (Rich Larson, Vermejo Park Ranch, 2003, pers. comm.).

Coalbed methane is similar to natural gas produced from conventional gas fields, varying only slightly in molecular composition. Coalbed methane is considered an unconventional resource. The coal assumes the function of source rocks, having high total organic carbon, and of reservoir rocks, having the potential for storing methane. The matrix of coal generally has low values of porosity, but it stores methane nonetheless due to physical adsorption of methane molecules on organic matter particles. Coals have cleats (fractures) that create a drainage network for moving water and methane through the coal bed; the two products are extracted together with water being an unavoidable byproduct. Chapter 8.4 includes discussions of the challenges faced when dealing with produced water.

Coal thickness, bed continuity, and coal quality are important factors to consider in evaluating coalbed methane resource potential. Most of the coalbed methane wells in the New Mexico part of the Raton Basin produce methane from the Vermejo Formation with contributions in some wells from the Raton Formation. Well logs were examined from throughout the Vermejo Park producing area at a density of one well per square mile where available, recording thickness of coal beds greater than or equal to 1 ft thick. Lack of lateral continuity for most of the coals in the Vermejo and Raton Formations dictates grouping the coals together by formation to do any valuation of the overall thickness characteristics. Table 1 is a compilation of the publicly available data. These wells are concentrated in the areas northeast and southwest of Vermejo Park. The data are derived almost entirely from interpretation of geophysical logs from *producing* wells. The entire Raton Formation was not recognized in the open-hole geophysical logs because wells are cased to 300-ft depth to protect shallow ground water. Any coals above this depth are not represented in the data in Table 1. The average and maximum total coal thickness and number of seams is greater in the Raton Formation. The maximum average seam thickness is the only statistic that is significantly greater for the Vermejo Formation. A tally of individual seams from 1 ft to > 10 ft from these same data indicates 84% of Raton coals are 1–3 ft thick, whereas 93% of Vermejo coals are in this same thickness range. Vermejo coals 5 ft thick or greater make up about 8% of the data set, and Raton coals 5 ft thick or greater account for 3% of the data set.

Table 4.1. Coal thickness and seam properties of Vermejo and Raton formations. Data from coalbed methane and oil and gas geophysical logs. Raton coal picks from logs with 1400 ft of section from base of Raton. Vermejo coal picks from logs with base of Raton and top of Trinidad. (updated 5/19/04)

| | **Total Coal (ft)** | | **No of Seams** | | **Average seam thickness per well** | |
|---|---|---|---|---|---|---|
| *Formation* | Raton | Vermejo | Raton | Vermejo | Raton | Vermejo |
| *Average* | 26 | 15.97 | 14 | 7 | 2 | 3.1 |
| *Max* | 64 | 33 | 30 | 13 | 3.3 | 10.7 |
| *Min* | 8 | 4 | 4 | 2 | 1.2 | 1.3 |
| *Count* | 59 | 133 | | | | |
| *Std Deviation* | 12 | 6.5 | 6 | 2 | 0.5 | 1.6 |

**Vermejo Formation:** The Vermejo Formation contains some of the thickest coals in the Raton Basin. Figure 4.1 is a map of net Vermejo Formation coal derived from well log interpretation (sum of Vermejo coal beds greater than or equal to 1 ft thick, wells with complete section of Vermejo). In the wells examined, net Vermejo coal ranges from 4 to 33 ft supporting observations from surface work and mining that describe lenticularity of coal beds and associated variability in individual and net total coal bed thickness. Figure 4.1 further illustrates the lenticularity or lack of continuity of the coal seams within the Vermejo Formation. Given the current density of wells we believe that there is insufficient control to draw meaningful contour maps. Wells examined that are encompassed by the two producing areas average approximately 18 ft net thickness for the southwestern area (63 wells) and 16 ft net thickness for the northeastern area (57 wells). Several wells on the map fall outside the producing areas (thus 133 wells total).

Figures 4.2 and 4.3 are stratigraphic cross sections based on wells spaced approximately 3/4 to 1 mi apart, and they depict coal beds interpreted from geophysical logs and those coals that were completed for coalbed methane production. Coal beds cannot be readily correlated between wells at this well spacing. This degree of stratigraphic complexity adversely affects the ability to *efficiently* drain reservoirs with widely spaced wells at the current density of 1/2 mi spaced wells (area of 160 acres/well). This does not suggest a lack of potential, rather it reinforces the concept of necessity to drill more wells to more efficiently drain the reservoir. Overall, the Vermejo Formation thins eastward, but the number and thickness of coal beds does not appear to change significantly. The Vermejo Formation may be important for coalbed methane production over a large area.

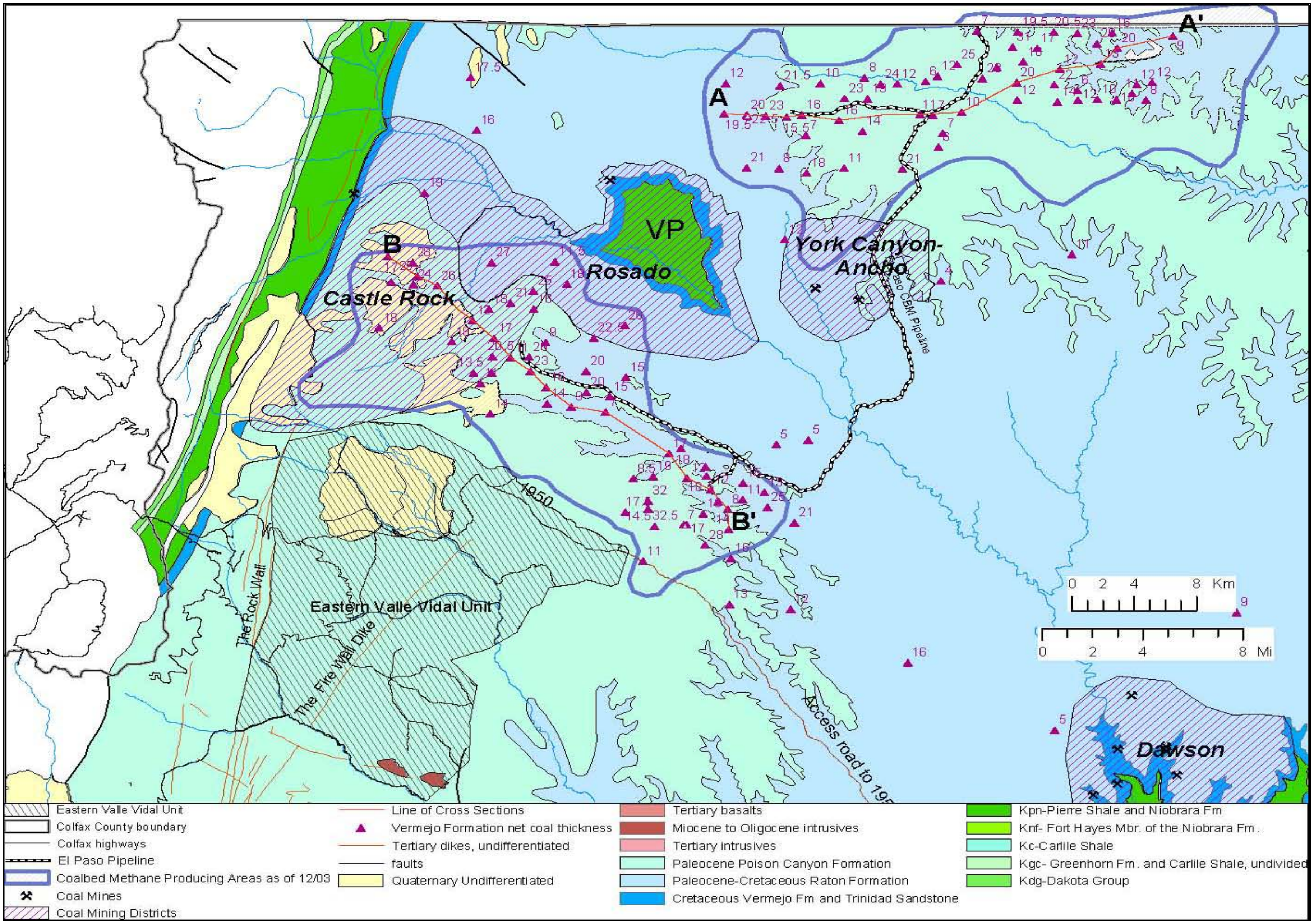


Figure 4.1 Vermejo Formation net coal thickness interpreted from geophysical logs of wells with complete Vermejo section. VP = Vermejo Park.

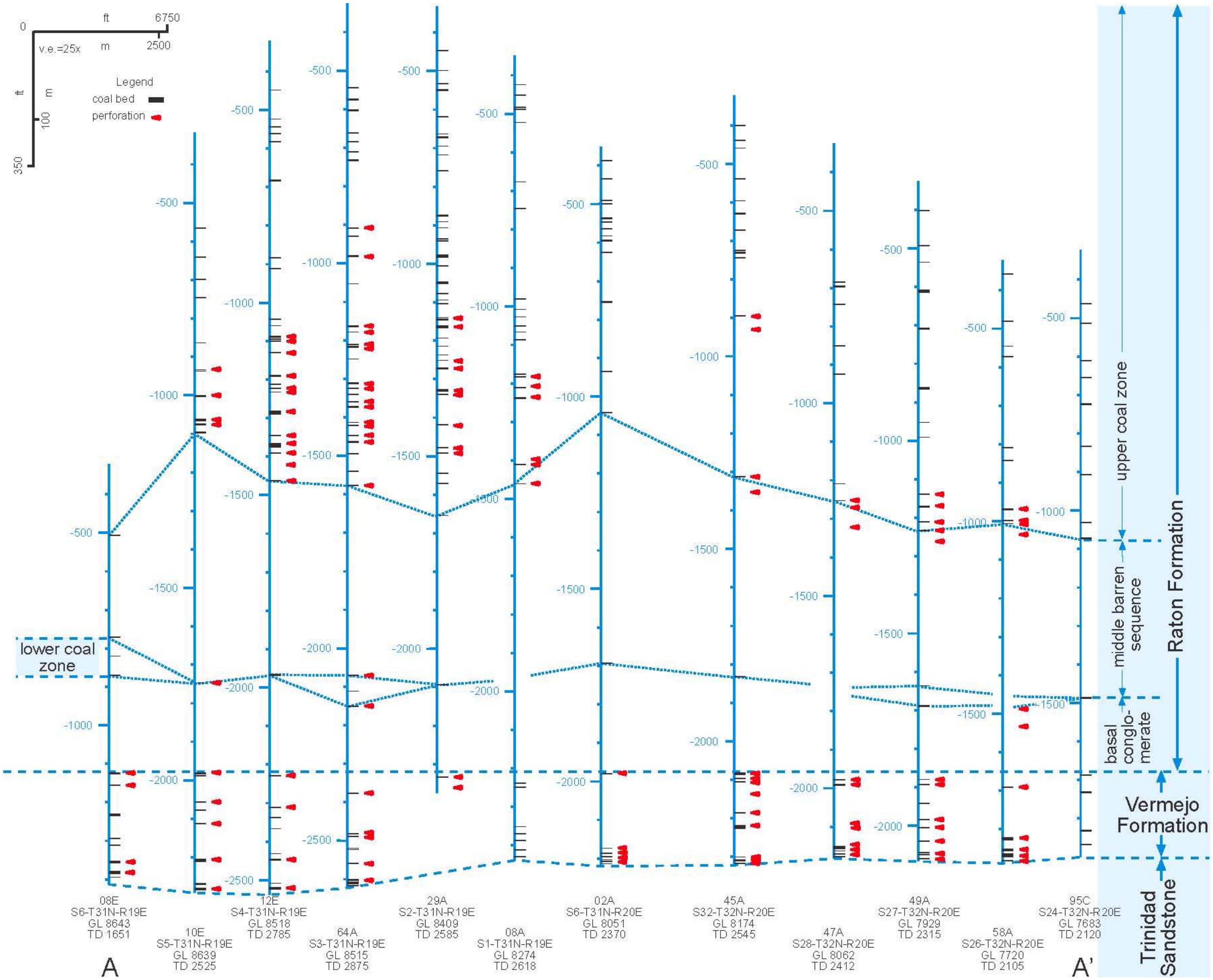


Figure 4.2 Cross-section A-A' (west to east). Approximate spacing between wells is 1 mi. Line of cross section shown on maps in Figs. 4.1 and 4.4. Wells arranged such that the top of the Vermejo Formation is the stratigraphic datum. The top of the Trinidad Sandstone is the base of the well columns. The top of each well column is the top of the open-hole logged part of the well from which data are derived. Depth markers (e.g. –500 ft) are indicated for each well. "Perforation" refers to points where the well that have been targeted for production.

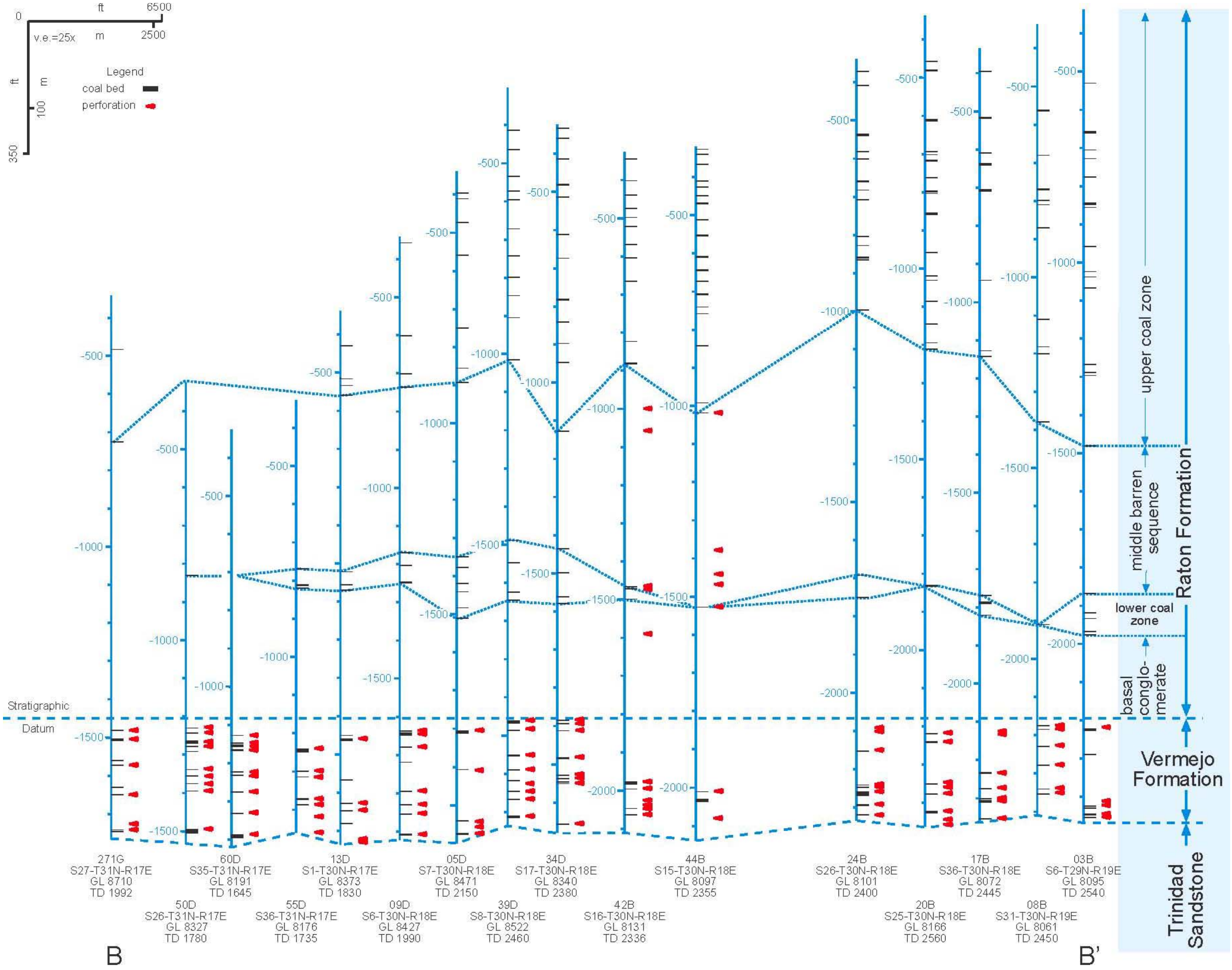


Figure 4.3 Cross-section B-B' (west to east). Approximate spacing between wells is 3/4 mi. Line of cross section shown on maps in Figs. 4.1 and 4.4. See Fig. 4.2 for comments on cross section construction.

**Raton Formation:** The lower coal zone of the Raton Formation has several thin lenticular coals that have been completed in many coalbed methane wells. The upper coal zone may have more economic potential for coalbed methane as it tends to have some lateral continuity. The York Canyon coal bed in the upper coal zone averages 5–6 ft thick and was the principal bed mined at the York Canyon complex that lies between the two Vermejo Park coalbed methane producing areas. In the Upper York or Left Fork district where the Cimarron underground mine operated, there are two coals that range in thickness from 3.5 to 11 ft.

Figure 4.4 is a map of net Raton Formation coal from well log interpretation (sum of Raton coal beds greater than or equal to 1 ft thick, wells with a minimum of 1,400 ft of Raton section logged). Like the Vermejo coal beds, Raton coals tend to be discontinuous or lenticular. We believe that the existing well control does not reveal their complexity, making contour mapping problematic. In the wells examined, net Raton coal ranges from 8 to 64 ft thick. Wells examined that are encompassed by the two producing areas average approximately 24 ft net thickness for the southwestern area (29 wells) and 29 ft net thickness for the northeastern area (30 wells). It is significant to point out that many wells do not produce from the upper coal zone, particularly in the southwestern area. Most wells are not completed above the 1,000-ft (305-m) depth presumably to avoid excessive water production. Figures 4.2 and 4.3 show that, like the Vermejo Formation, individual coal beds in the Raton Formation have limited extent and thickness and tend to be concentrated into zones.

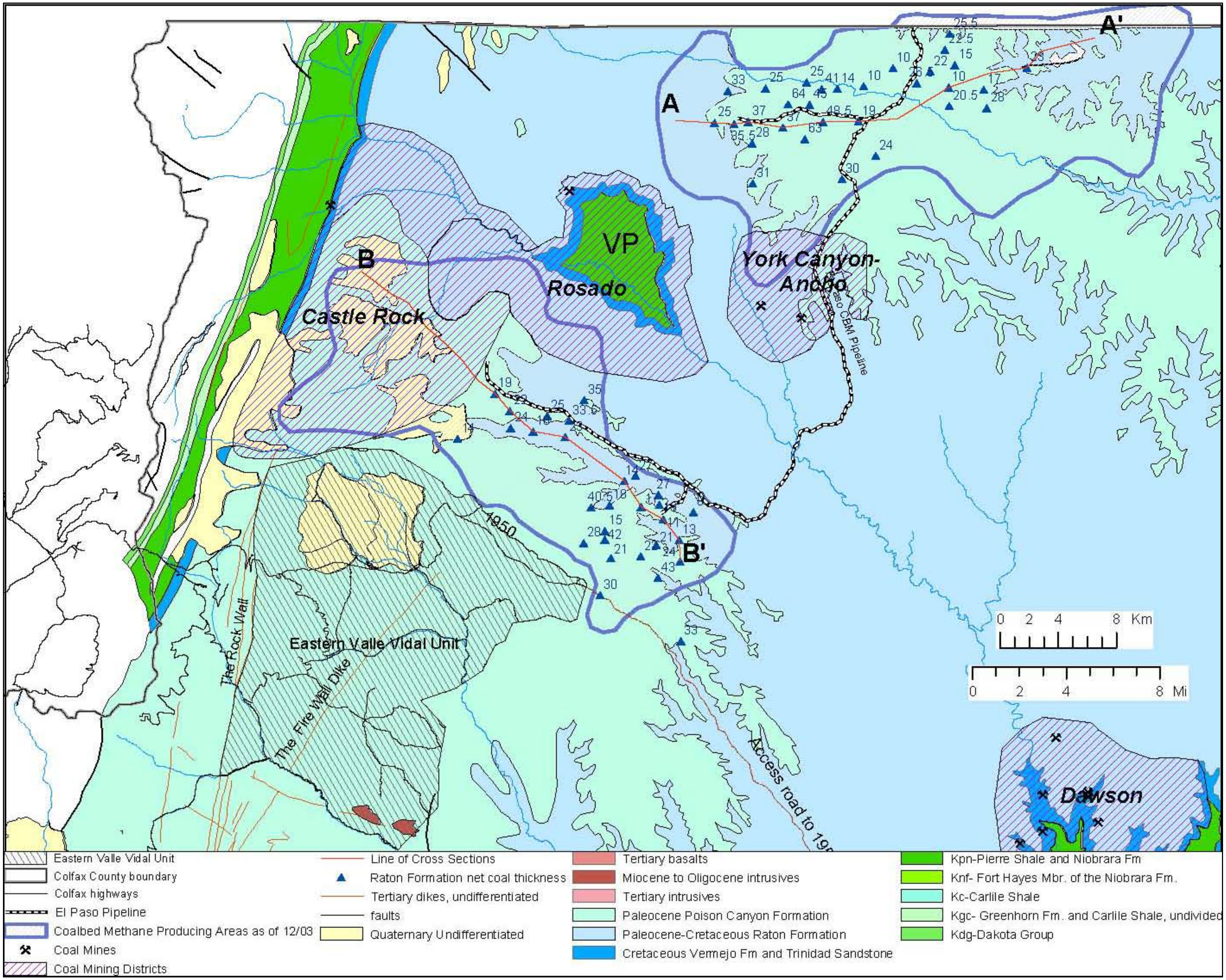


Figure 4.4 Raton Formation net coal thickness interpreted from geophysical logs. Wells included only where 1,400 ft or more of Raton Formation was logged. VP = Vermejo Park.

**Coal quality:** The Vermejo and Raton Formations contain low-sulfur, moderate-ash coals of high-volatile A to B bituminous rank. The quality of the coals within the two formations does not vary significantly (Hoffman, 1996). However, there are areas within the coal field where Oligocene and younger sills have intruded coal seams, destroying the economic potential of the seam. The high-volatile bituminous rank indicates that these coals have reached the bituminization stage (Levine, 1993) when generation and entrapment of hydrocarbons takes place, vitrinite reflectance (%Ro—a method to estimate thermal maturity) increases to 0.6–1.0, and the moisture content of the coal decreases. Less than half of the prospective area as delimited by the presence of thermally mature coal has been developed.

Coal rank and maturity indicators in the Raton Basin coal beds strongly suggest that the coalbed methane gas being produced today was thermally rather than biologically generated. Thermal generation depends in part on depth of burial and regional heat flow. There is evidence from fission track studies (Hemmerich, 2001) that approximately 3600 ft of denudation has occurred in the Vermejo Park region since the Miocene. Miggins (2002) conducted an extensive study dating the igneous intrusions of the region, and he reported ages from 33 to 19.7 Ma, most being clustered around 25 Ma. Like the Spanish Peaks in Colorado, the structural dome of Vermejo Park is probably a result of laccolithic intrusion; wells on the Vermejo Park structure bottom in igneous rocks at atypically shallow depths relative to wells outside of the dome. Although dikes and sills in the area tend to have a limited direct effect (contact metamorphism) on adjacent rocks, regionally elevated heat flow and convection of associated hot ground water can influence a much greater volume of the coal-bearing sequences. Thus the combination of both maximum paleoburial depth and elevated heat flow during the Miocene is the likely cause for relatively high thermal maturity of coals shallowly buried today.

Some unpublished vitrinite reflectance (%Ro) thermal maturity data are available for the Raton Basin in addition to the published data (See Oil and Gas Well Database on accompanying CD-ROM). Most of these data are from surface channel samples, either from outcrops or at mine faces; the remainder are from cores. There are 19 samples from the Raton Formation and 14 samples from the Vermejo Formation. Figure 4.5 shows the deep and surface vitrinite reflectance data and the producing areas within the Raton Basin in New Mexico. The data shown have not been adjusted to any set depth or datum. The data close to the edge of the basin range from 0.45 to 0.75 %Ro. Given that coal is primarily a gas-prone source rock and that thermogenic gas becomes significant at approximately 0.8 %Ro, these areas have possible potential for coalbed methane but they are relatively thermally immature compared to the northwest corner of the New Mexico portion of the Raton Basin which has the greatest coalbed methane potential with %Ro greater than 0.8. We believe that coals above the water table have no production potential but public domain water table data for the coal-bearing units was not available for analysis in this study.

In Figure 4.5 an attempt was made to draw a smooth 0.8 % Ro contour through the basin, guided in part by structural elevation of the Trinidad Sandstone, but honoring control data, to delineate those areas that are *most* prospective. Note that this line is dashed due to uncertainty. Unfortunately there is only one control point in the Valle Vidal Unit, very near the northern boundary with the Vermejo Park Ranch. Although the contour was drawn to honor this data point, the line probably depicts a minimum scenario. It is truly unknown how the line should be drawn *through* the eastern Valle Vidal Unit (including only part of the unit in the prospective area), or *around* the eastern Valle Vidal Unit (including the entire Unit in the prospective area). The igneous intrusions in the southern part of the study area may have elevated thermal maturity of coals in the southern part of the eastern Valle Vidal Unit and this could easily justify including the entire area. Due to the uncertainties, the authors have chosen not to discount any part of the eastern Valle Vidal Unit on the basis of thermal maturity because of a simple lack of data in that area that could be proved by the drilling of one or more core tests. Stevens et al. (1992) were willing to assign a 4-8 Bcf/mi gas in place estimate to this area. It is our interpretation that in the entire eastern Valle Vidal Unit, the coal is below the water table and minimally mature such that coalbed methane is present and will be an inviting target for development by potential future mineral lessees.

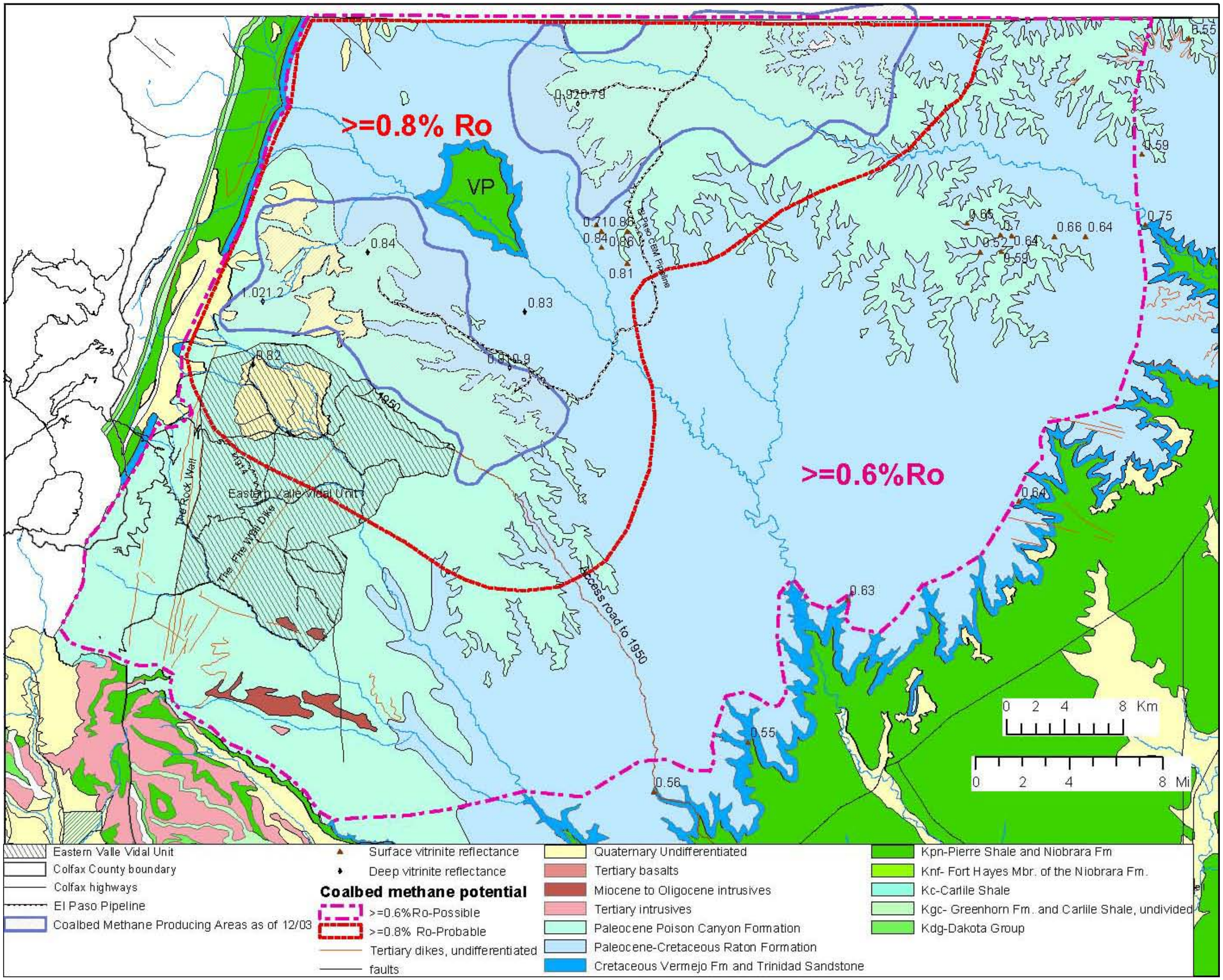


Figure 4.5 Map of vitrinite reflectance (%Ro), a source rock thermal maturity indicator. Area of probable coalbed methane productivity is suggested by thermal maturity contour value ≥0.8 % Ro; area of possible potential for coalbed methane production is suggested by thermal maturity contour value ≥0.6%Ro. Vitrinite reflectance data is from the Oil and Gas Well Database on the accompanying CD-ROM. Points depicted include only raw data that have not been adjusted for depth and come from a variety of sources of unknown reliability. Coal mines depicted are further described in the Raton coal mines database on the CD-ROM that accompanies this report. VP = Vermejo Park.

**Related gas sands:** In their 2001 study, Johnson and Finn consider the Raton Formation through Trinidad Sandstone in the Raton Basin to have basin-centered gas potential. The basal Raton Formation conglomeratic unit shows evidence of gas saturation in many wells in both producing areas. The presence of gas in sandstones is suggested from well logs where neutron log porosity is reduced and density porosity is elevated such that there is a crossover of the two log curves. Figure 4.6 is a well log cross section through the western part of the northeastern coalbed methane production area. The cross section shows all sand beds greater than 6 ft in thickness and coal beds greater than or equal to 1 ft thick, and indicates which sands have the well log gas effect. These wells are spaced only 1/2 mi apart, but similar observations can be made about the continuity of sandstone beds as for coal beds. Although the sandstone beds fall within zones, it is often difficult to correlate individual lenticular fluvial sandstone beds between wells. A number of wells in the southwestern producing area show similar log cross-over and two wells have been completed as sandstone-only wells. Chapter 5 includes a production analysis of the VPR D area, adjacent to the Valle Vidal Unit that suggests gas sands do contribute to production from coalbed methane wells.

**Potential for occurrence:** Coal beds exist in the Raton and Vermejo Formation in the eastern Valle Vidal Unit at similar depths as in the adjacent Vermejo Park Ranch where economic coalbed methane production operations are ongoing. Coalbed methane production in the adjacent property is expanding over time suggesting that economics have continued to be favorable. There is no reason to believe that this will change as development approaches the boundary of the Valle Vidal Unit. Although bed thickness of these coals is minimal, multi-bed completions allow for enough coal per well to justify development based on proven production from multiple such wells. The coals are lenticular and difficult to correlate between wells at 160 acre per well spacing suggesting that this may not be the optimum spacing (requires closer well spacing) for development in the long term. The coals are high quality and assumed to be minimally thermally mature although there is uncertainty in this assumption and new well data is needed to prove and quantify this. As will be discussed in Chapter 5 the thermally generated gas resides in the coals as adsorbed and free gas. Distance of migration and migration pathways are not a significant factor because the gas is essentially trapped where generated, suggesting low formation permeability. Some interbedded sandstone units have gas saturations that probably contribute to production, but these don’t appear to be discreetly trapped. This is a regional play with a large area of prospectivity; there is no need to rely upon presence of discreet traps for production. The combination of these factors leads to the conclusion that the potential for occurrence cannot be ranked less than high.

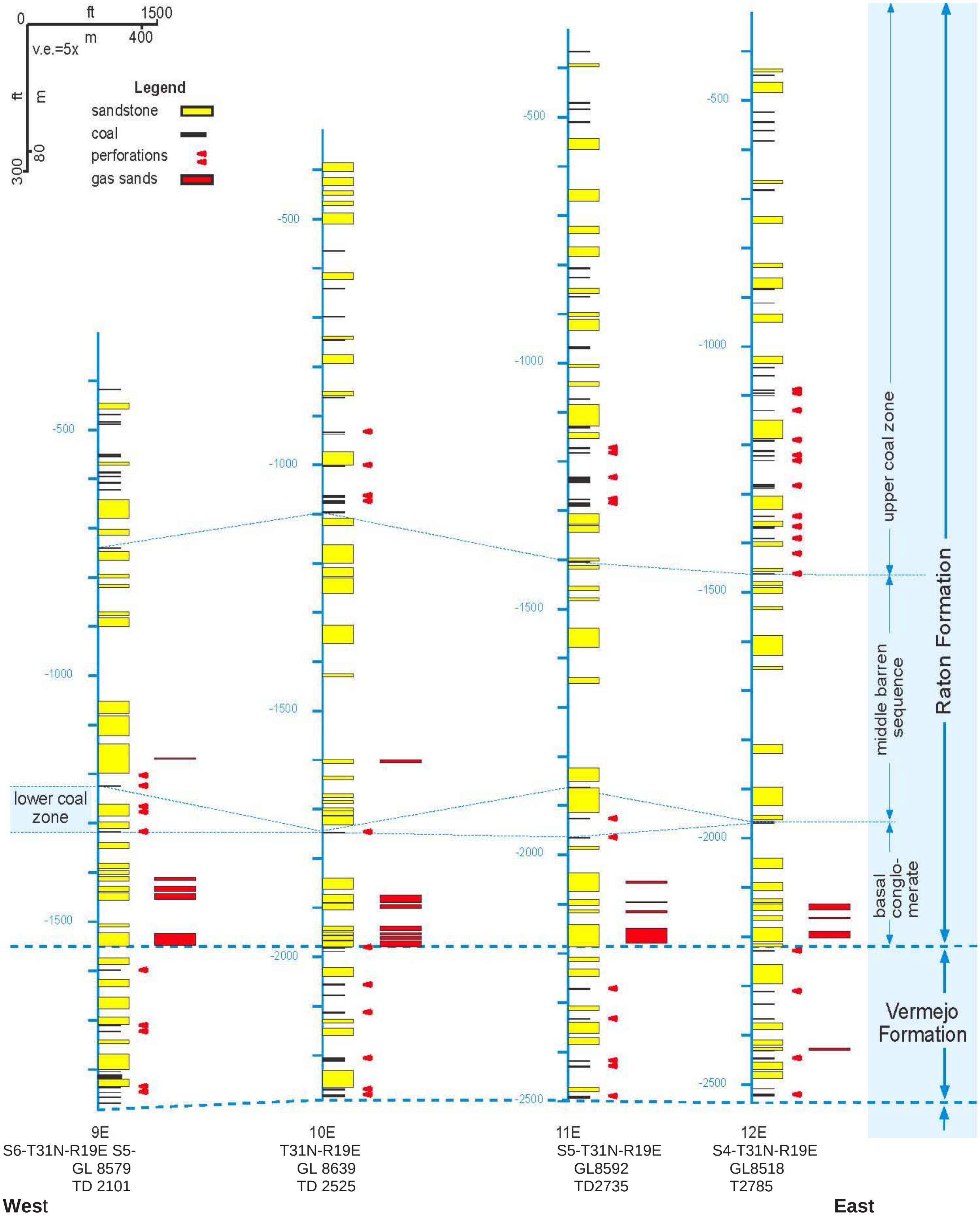


Figure 4.6 Cross section that provides a closer spaced view of the western part of cross section A-A' (Fig. 4.2). Sandstone beds interpreted to be gas charged are indicated by red rectangles. Approximate spacing between wells is ½ mi. See caption for Figure 4.2 for other comments on cross section construction.

**Potential for development:** Coalbed methane plays in general tend to be widespread reservoirs that cover large areas. The physical characteristics of the coal-bearing intervals determine how consistent production will be well-to-well. In plays like the Raton Basin play, stratigraphic complexity could be responsible for significant inconsistency in production as compared between wells. As such, development operations tend to mimic modern manufacturing businesses where every well is constructed similarly and the economy of scale becomes an important factor in minimizing cost. Often there is significant per well deviation from average well production, but better wells are not easy to predict, nor poor wells avoidable, prior to the expenditures of well drilling and completion. Thus, most locations will be drilled with the average production from all wells determining the economics of the total operation. The potential for development of coalbed methane over the entire eastern Valle Vidal Unit is predicted to be high because the resource potential is high and infrastructure requirements and development investments will encourage operators to maximize the number of locations developed to improve the financial bottom line. In order for operators to take advantage of the economy of scale, large contiguous areas of development would need to be allowed for in the Forest Plan.

### 4.5 Pierre-Dakota oil and gas play (Potential for occurrence = High, Potential for development = Medium)

Thousands of feet of shale formations with source rock potential combined with peak gas-generating thermal maturity conditions make the Pierre Shale through Dakota Sandstone interval an attractive play on a first-pass examination. More than 74 Dakota wells have been drilled in Colfax County and many have reported oil and gas shows. However, no commercial production has been established to date. Lack of a pipeline before 1999 was a good explanation for this and there have been no attempts to establish production in this stratigraphic interval since the pipeline was constructed. There are two possibilities for occurrence examined here, one being conventional traps and the other being a blanket-type, fractured, low-permeability, unconventional play.

**Shows and thermal maturity:** Oil and gas shows in Cretaceous rocks have been described by a number of authors, notably Baltz (1965), Foster (1966), Woodward (1984; 1987), Grant and Foster (1989), and Johnson and Finn (2001). In addition, oil and gas shows are commonly noted on scout cards (well records) from Cretaceous-penetrating wells. Wells that found Cretaceous rocks at shallow depths on the eastern basin margin or outside of the basin are typified by oil shows, whereas those wells that have drilled Cretaceous rocks below the thermally mature coals have had predominantly gas shows. Marine shales, particularly those described as dark gray to black, tend to contain oil-prone source rocks. When thermal maturity rises through time due to burial and elevated formation temperature, organic matter reaches the “gas window” where oil molecules begin to crack into lighter gaseous molecules. Thus oil-prone rocks could yield primarily natural gas above about 1.0 % Ro vitrinite reflectance, the thermal condition assumed for these rocks in the axial area of the basin.

**Conventional traps and accumulations in reservoirs:** There are two issues to examine here. One is that in the Cretaceous strata there is a shortage of conventional-type reservoir rocks with reasonable porosity and permeability, an exception being the Dakota Sandstone. The other issue deals with traps. A convenient horizon for mapping Cretaceous structure in the basin is the Fort Hays Limestone. A structure contour map of the top of the Fort Hays Limestone (Figure 4.7) based on a very small number of data points reveals no inter-basin positive structures of large scale. However there is not enough well control to demonstrate the Vermejo Park dome (VP on figures), a large dome caused by intrusion of a laccolith, thus structures of considerable size could be present. Small structures are more likely. A deliberate search, perhaps seismically driven, for small structural and stratigraphic traps will be required to find areally limited reservoirs of gas in the Dakota Sandstone in the eastern Valle Vidal Unit.

**Unconventional reservoirs:** Woodward (1984) summarized the potential for fractured low permeability reservoirs in the Raton Basin. Carbonate-rich beds of the Greenhorn Limestone and the overall Niobrara interval, and siliceous silty and sandy interbeds of the Graneros, Carlile, and Pierre Shales may provide naturally fractured reservoirs. Similar reservoirs include the Lewis Shale of the San Juan Basin, an economically marginal (not subeconomic), gas producing formation where fractured siliceous zones contribute on average less than ½ Bcf of gas to Mesaverde Group wells. The Barnett Shale play of the Fort Worth Basin in Texas is probably the most outstanding example of an economically marginal play fractured shale play that became a wildly lucrative play due to technical advances in artificial hydraulic fracture stimulations (Brister and Lammons, 2000). However, Cretaceous shale formations tend to be sensitive to damage by the fresh water used to perform these stimulations (Brister, 2001) and more expensive to stimulate satisfactorily. Fractured “shale” plays are an emerging contributor to U. S. gas resources, but there is much left to understand about the physical conditions of the reservoirs and the technical requirements for accessing the reserves economically.

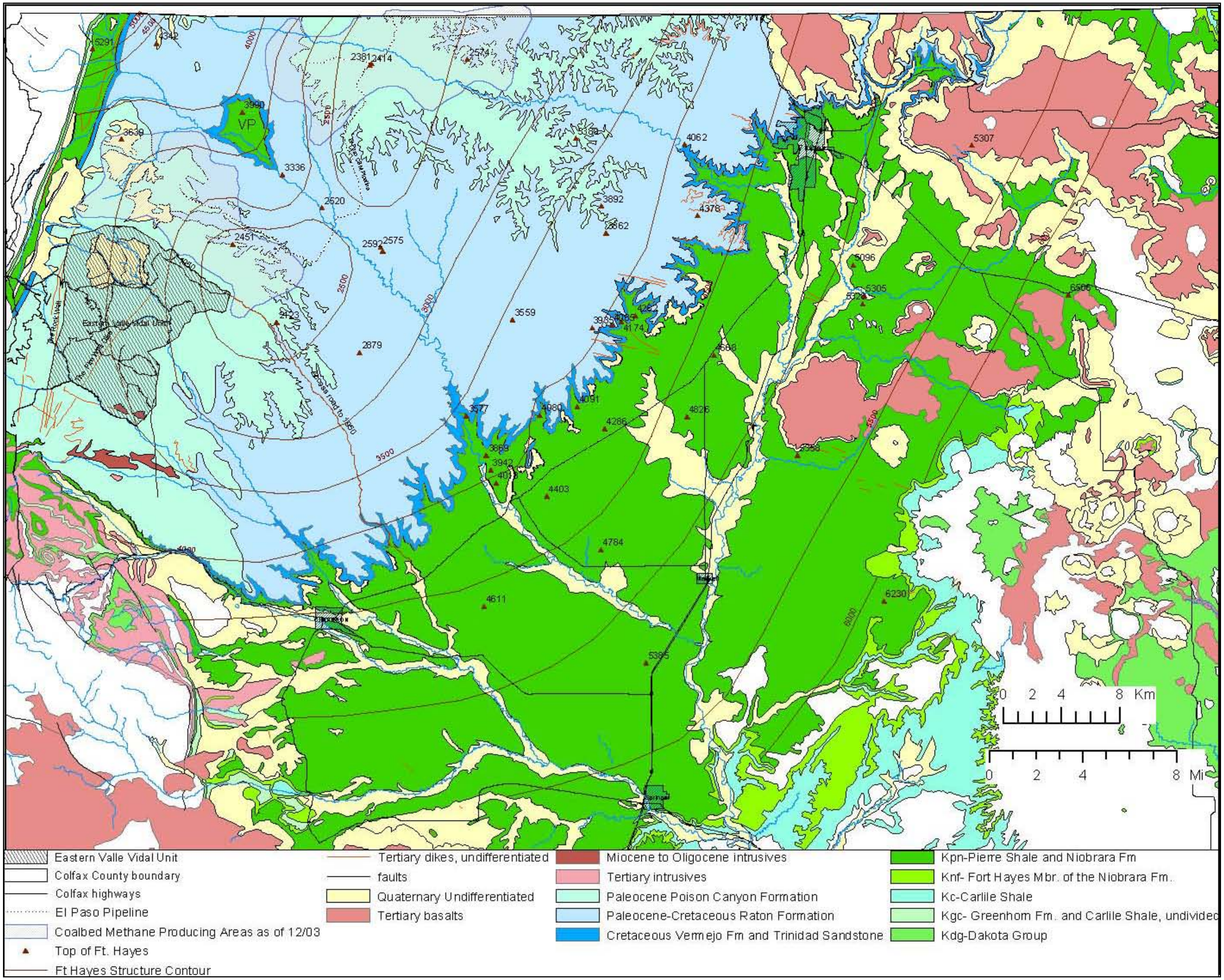


Figure 4.7 Structure-contour map of the top of the Fort Hays Limestone interpreted from well data. VP = Vermejo Park.

**Potential for occurrence:** The potential for occurrence of a predominantly gas fractured Cretaceous play in the eastern Valle Vidal Unit is high based upon the demonstrated shows of oil and gas in the Raton Basin. If significant reservoirs exist, gas would be trapped in discreet stratigraphic and structural traps in the Dakota Sandstone or in blanket-type fractured “shale” reservoirs, the latter being more likely to exist.

**Potential for development:** The potential for development is medium at best within the 20-year time frame of the RFDS. There is no current activity focusing on exploring in this play at this time. It is possible that geophysical prospecting might be applied to search for fracture zones or conventional traps, with seismic data being the most expensive but effective geophysical tool. Importantly, this play would be tested several times as deep water disposal wells would be drilled to accommodate produced water from a coalbed methane development program. Encouraging shows might encourage drilling of additional wells to confirm the shows, but these wells could be “twinned” with coalbed methane production wells by drilling both wells from the same pad. Another possibility is that exploratory wells could be planned such that if they fail to establish production in the play, they can be plugged back and recompleted as coalbed methane wells. This is an economically favorable practice if conducted in early stages of development of the eastern Valle Vidal Unit.

### 4.6 Pennsylvanian-Permian gas play
### (Potential for occurrence = Low, Potential for development = Low)

The premise of this play is that there is a westward-thickening wedge of Sandia Formation (Pennsylvanian) rocks containing potential petroleum source rock lithologies beneath the eastern Valle Vidal Unit. Given the level of maturity of source rocks in the Cretaceous-Paleocene coal-bearing formations at relatively shallow depths, source rocks in the Sandia Formation, if they exist, would be mature. They could potentially be overmature where hydrocarbons have been cooked to form carbon dioxide ($CO_2$). Foster (1966) reported $CO_2$ in Permian rocks in the Conoco #3 Rocky Mountain well (listed in Oil and Gas Well Database on accompanying CD-ROM). Other shows have been noted in the Dakota and Permian rocks east of the Raton Basin. It should be noted that $CO_2$ is also commonly found associated with volcanism thus the Pennsylvanian is not the only potential source in the region. In the Las Vegas Basin and southern Sangre de Cristo Mountains, Northrup (1946) and Baltz and Meyers (1989) described a number of oil shows (lower maturity) there in the Pennsylvanian and Permian strata. Natural gas potential is more likely given the maturity of younger, shallower source rocks.

Pennsylvanian and Permian strata from the synorogenic Minturn (Atokan-Desmoinesian) and Sangre de Cristo Formation (Missourian-Wolfcampian; Mallory, 1972b; De Voto, 1980) are predominantly arkosic redbeds with lithologies ranging from coarse conglomerate to shale. Red coloration is typical of oxidized sediments that tend to have little surviving organic content. It is doubtful that these formations have thick sealing shales or large traps for oil and gas generated by the Sandia Formation, but instead allow vertical migration into traps in the overlying Permian strata, particularly the Glorieta Sandstone that could be poorly sealed by the Dockum Group.

**Potential for occurrence:** There have been no reported shows of oil or flammable natural gas from Pennsylvanian and Permian strata in the vicinity of the Valle Vidal Unit, but there have been very few wells drilled to test the potential of these strata. The presence of source rocks is only inferred from poorly constrained regional paleogeographic information. There is a significant possibility that if source rocks do exist they are overmature. In a vertical migration scenario, there are no obvious rocks with excellent sealing lithologies. These characteristics combined with the obvious lack of interest in drilling wildcats to test this play in the past forty years suggests that this play would not see much activity in the coming 20 years. The potential for occurrence cannot be elevated above "low" at this time.

**Potential for development:** It is possible that seismic data might be acquired to attempt to image the strata associated with this play and this should be considered in the Forest Plan. Otherwise, there is no obvious reason to drill wells specifically for targeting this play and the development potential is "low". It should be noted that El Paso Raton LLC drills water disposal wells to the Permian. Such a practice would essentially allow a test of this play if one or more disposal wells were drilled deeper, essentially to the Precambrian basement.

Table 4.2. Summary of potential for occurrence of oil and gas and development of eastern Valle Vidal Unit.

| *Units/ type of play* | **Potential for occurrence** | **Potential for development** |
|---|---|---|
| *Raton-Vermejo Coalbed methane* | High | High |
| *Pierre-Dakota Oil and Gas* | High | Medium |
| *Pennsylvanian-Permian Gas ($CO_2$)* | Low | Low |

# Chapter 5 Production Analysis and Estimation

## 5.1 General characteristics

The objectives of this chapter are to address the following key points: (1) to analyze current well performance and determine the estimated ultimate recovery (EUR) and other production characteristics of the Raton Basin play, and (2) to identify any interference in the production response between wells and thus qualitatively determine drainage area.

Cumulative gas and water production to May 2003 from the New Mexico portion of the Raton Basin was 22.1 Bscf (billion standard cubic feet) of gas and 18 million barrels of water, respectively. Figure 5.1 illustrates the trend in development since the date of first production in October 1999.

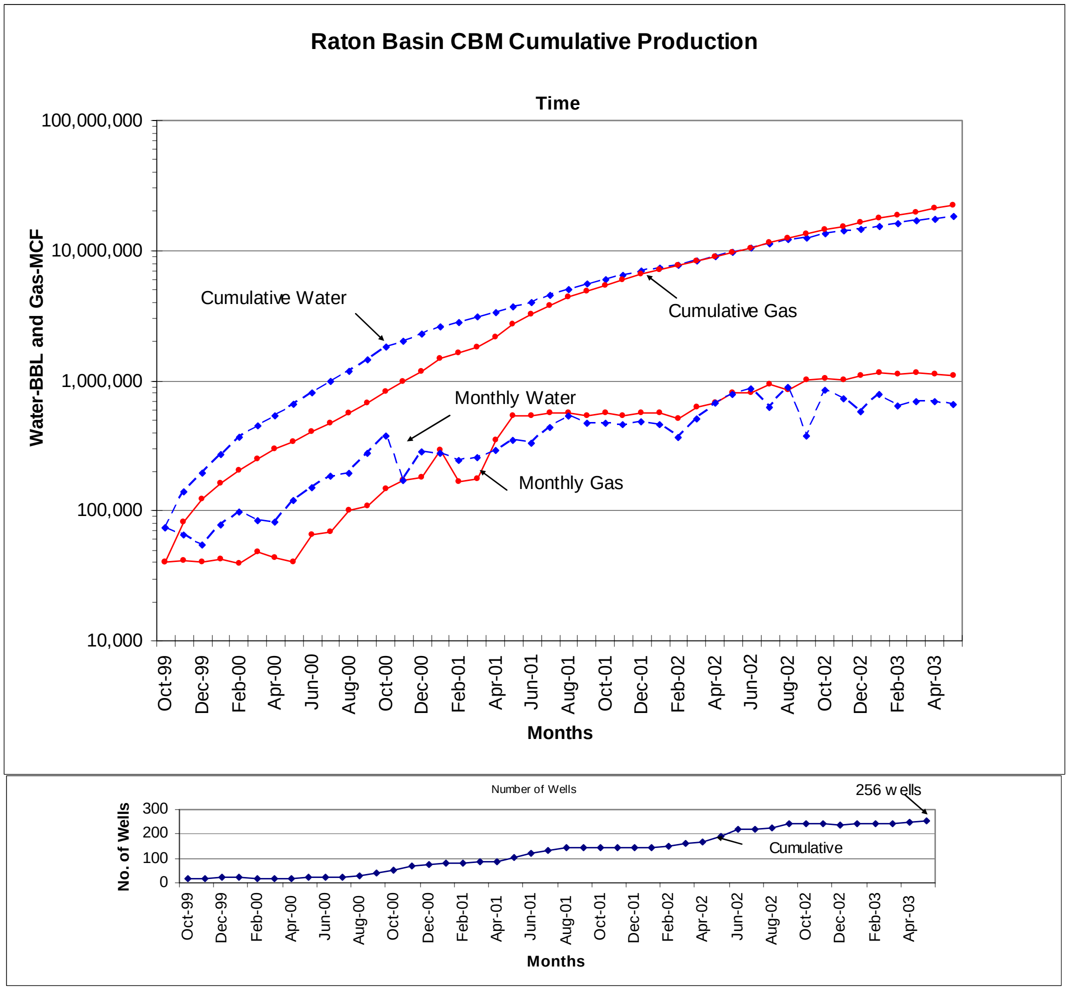


Figure 5.1 Cumulative and monthly gas and water production from all wells in the New Mexico portion of the Raton Basin, with active wells shown at the bottom. Individual well data production is available in the Oil and Gas Well Database on the accompanying CD-ROM.

It is evident from the increasing number of wells that this pool is currently undergoing active development. In response to the additional wells, monthly production has increased until mid-2002 at which time production has remained constant. Latest monthly production rates (May 2003) are 1.1 Bscf/month and 660,000 barrels of water/month from approximately 260 producing wells.

The production from the Raton Basin in New Mexico can be divided two areas as shown in Figure 5.2. These individual areas of development are defined by geological and/or surface restrictions. Individual production plots for each lease (A, E, C, in northeast area and B, D in southwest area) are shown in Figures 5.3 through 5.7, respectively. Each figure includes cumulative and monthly production for gas and water and the active number of wells on a monthly basis.

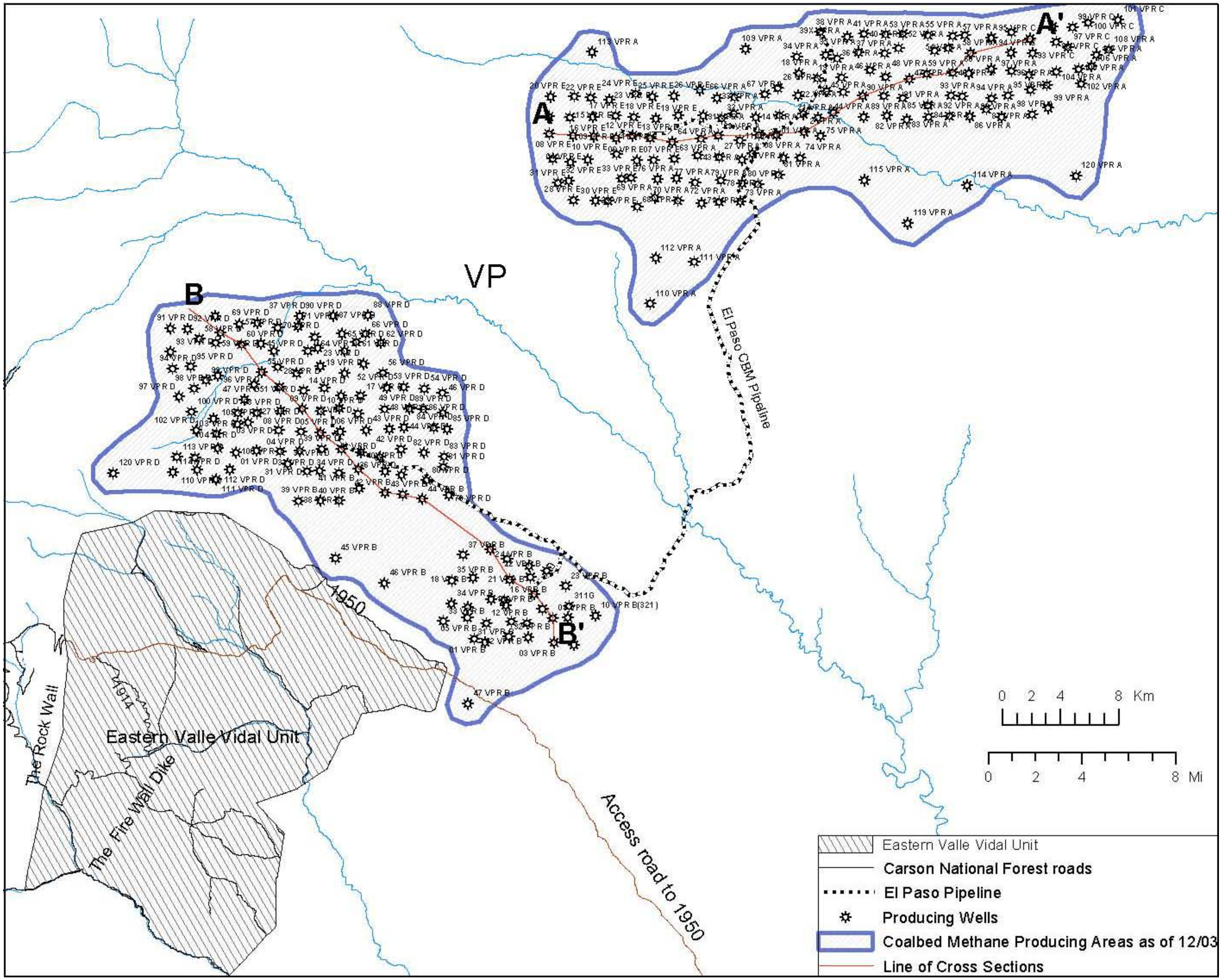


Figure 5.2 Location map identifying the areas of coalbed methane development northeast and southwest of Vermejo Park (producing wells on this map are current through 2003).

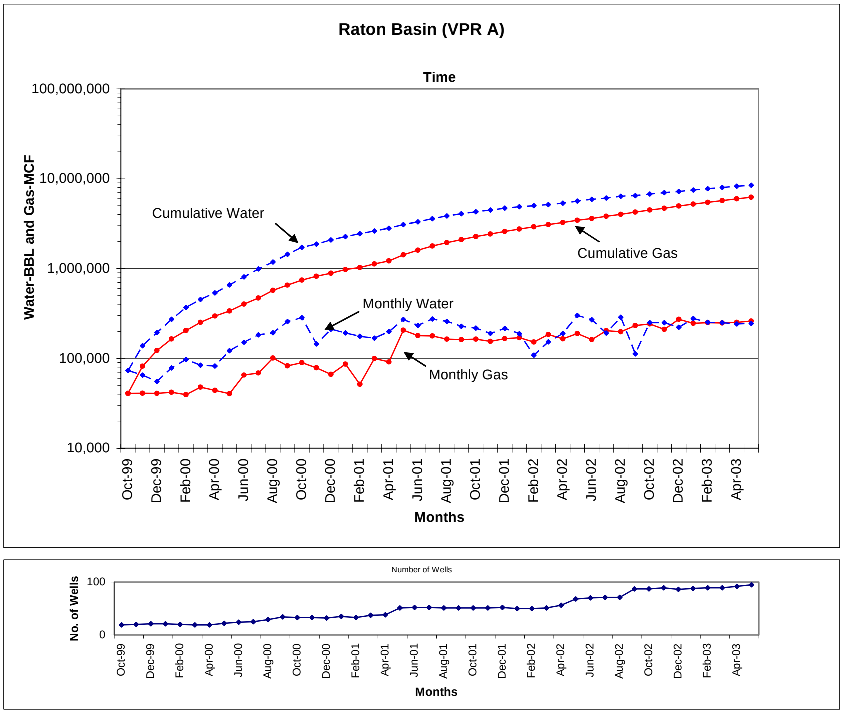


Figure 5.3 Cumulative and monthly gas and water production for **VPR** (Vermejo Park Ranch) **A wells** (central part of northeast producing area, refer to Fig. 5.2 for location) in the New Mexico portion of the Raton Basin, with active wells shown at the bottom.

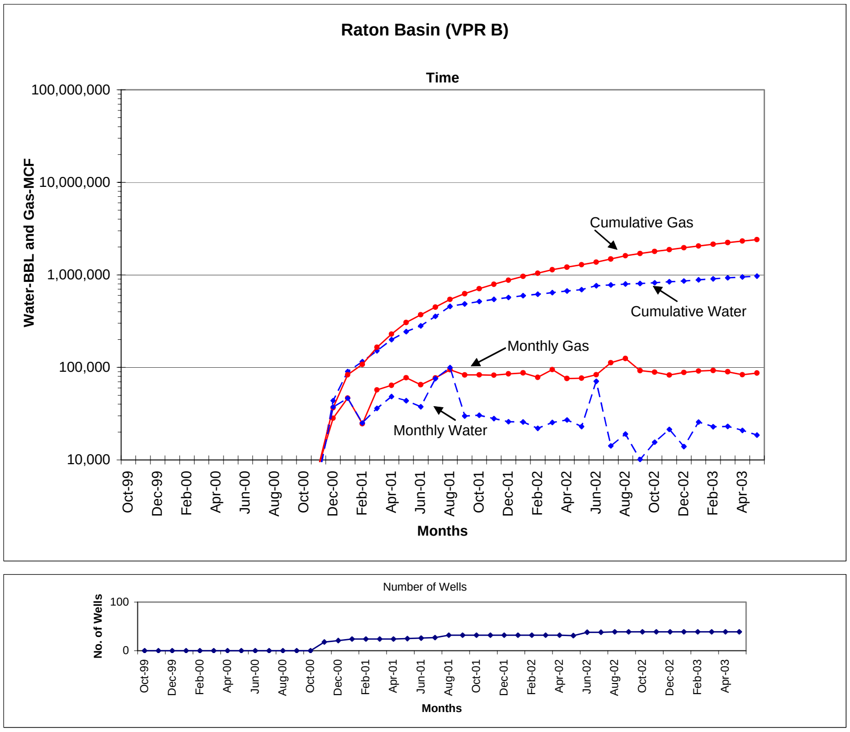


Figure 5.4 Cumulative and monthly gas and water production for **VPR B wells** (eastern part of southeast producing area, refer to Fig. 5.2 for location) in the New Mexico portion of the Raton Basin, with active wells shown at the bottom.

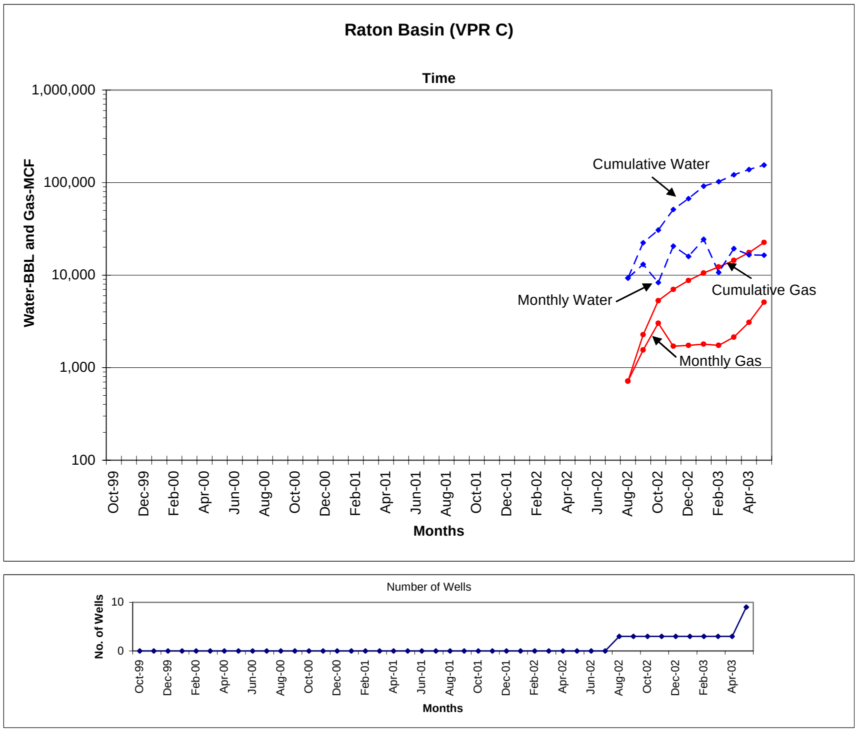


Figure 5.5 Cumulative and monthly gas and water production for **VPR C wells** (eastern end of northeast producing area, refer to Fig. 5.2 for location) in the New Mexico portion of the Raton Basin, with active wells shown at the bottom.

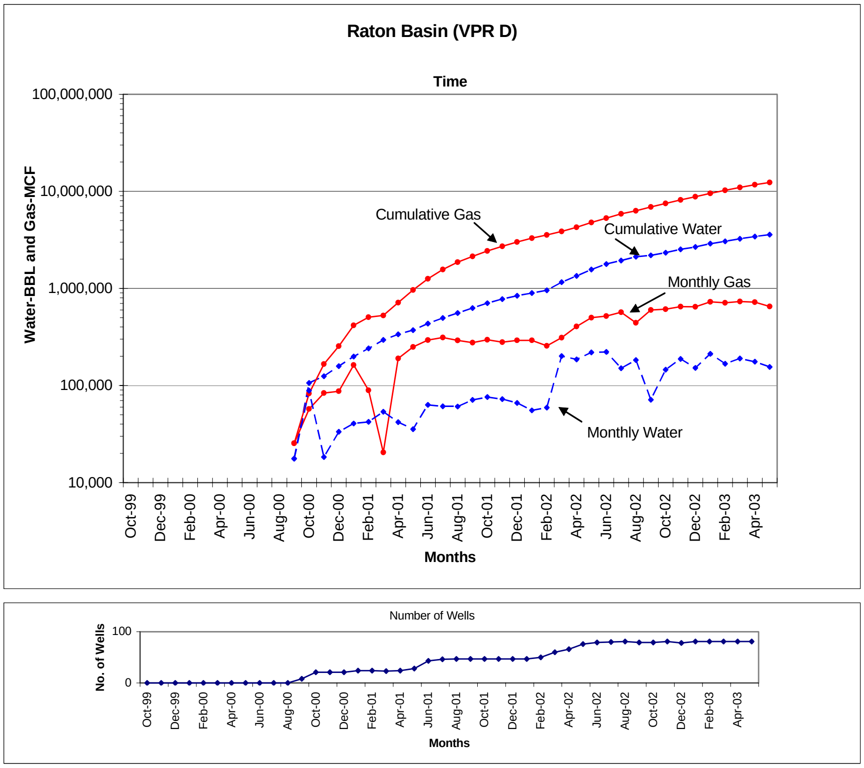


Figure 5.6 Cumulative and monthly gas and water production for **VPR D wells** (western part of the southeast producing area, see Fig. 5.2 for location) in the New Mexico portion of the Raton Basin, with active wells shown at the bottom.

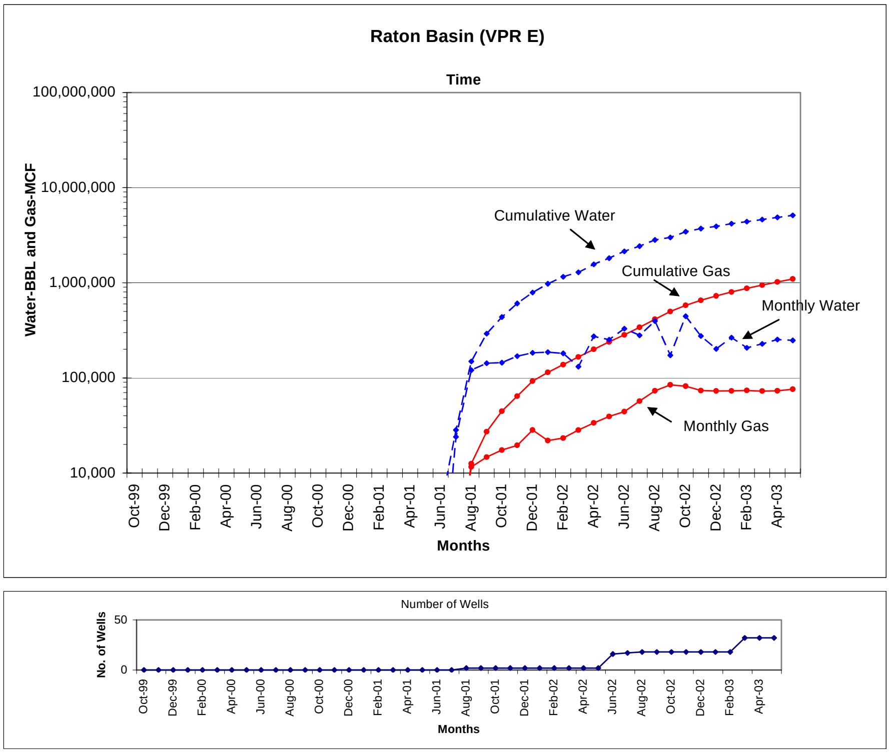


Figure 5.7 Cumulative and monthly gas and water production for **VPR E wells** (western part of the northeastern producing area, refer to Fig. 5.2 for location) in the New Mexico portion of the Raton Basin, with active wells shown at the bottom.

A comparison of production statistics by region is shown in Table 5.1. The most prolific group of wells is in VPR D, where 56% of the cumulative gas production has occurred as of May 2003. VPR A, which has the highest percentage of wellbores (37%), has the distinction of producing the highest cumulative water at 46%. In fact, regions A, C, and E have significantly greater cumulative water-gas-ratios (WGR) than regions B and D.

| Lease | Date of 1$^{st}$ production | No. of wells | Gp mmscf | Wp mBw | Gp/well mmscf | Wp/well mBw | WGR |
|---|---|---|---|---|---|---|---|
| A | Oct 1999 | **95** | 6,227 | **8,490** | 66 | 89 | 1.36 |
| B | Nov 2000 | 39 | 2,405 | 969 | 62 | 25 | 0.40 |
| C | Aug 2002 | 9 | 23 | 154 | 3 | 17 | 6.81 |
| D | Sep 2000 | 81 | **12,351** | 3,576 | **152** | 44 | 0.29 |
| E | Jul 2001 | 32 | 1,096 | 5,116 | 34 | **160** | 4.67 |
|  | *total* | 256 | 22,102 | 18,305 |  |  |  |

Table 5.1 Production characteristics for Raton Basin

## 5.2 Analysis of single well performance

The Vermejo Formation producing interval consists of a series of thin coal seams interbedded with sandstone beds. Subsequently, without individual zone tests, it is only possible to determine production for a well with any accuracy, and not for a formation or a zone. Furthermore production from many wells is commingled with the shallower Raton Formation. Table 5.2 provides production statistics for the Vermejo-only completions and compares the results to the total Raton Basin play.

| Lease | No. of Vermejo-only wells | % of total in region | Average net perforated thickness Ft | Gp mmscf (Vermejo only) | % of total in region | Wp mBw (Vermejo only) | % of total Vermejo-only in region |
|---|---|---|---|---|---|---|---|
| A | 22 | 23 | 19 | 1,605 | 26 | 3,569 | 42 |
| B | 30 | 77 | 33 | 2,123 | **88** | 875 | 90 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D | 68 | 84 | 26 | 11,546 | **93** | 3,123 | 87 |
| E | 1 | 3 | 14 | 48 | 4 | 311 | 6 |
| total | 121 | 47 | 26 | 15,322 | 69 | 7,878 | 43 |

Table 5.2 Production statistics for Vermejo Formation-only completions (excludes wells where Raton Formation production is commingled with Vermejo Formation production). There are no Vermejo-only wells in the C Lease. Gp = gas production, Wp = water production, mmscf = million standard cubic feet of gas, mBw = thousand barrels of water.

A total of 121 wells are completed only in the Vermejo Formation, or 47% of the total completions to May 2003. These wells contribute 69% of the cumulative gas production and 43% of the cumulative water production, respectively. Investigating production from individual leases reveals that a majority of the gas production from VPR B and D is from the Vermejo Formation, 88 and 93%, respectively. Furthermore, a majority of water production is from the Raton Formation in VPR A and E, respectively.

A major challenge in evaluating production is to distinguish the unconventional coalbed methane response from the conventional gas sand response. Examining the production curves for the existing wells resulted in identifying four scenarios as shown in Figure 5.8. Type I exhibits the classic coalbed methane response; i.e., brief, initial high water production followed by a normal decline and initial low gas production which steadily increases to a peak after some period of time, followed by normal decline behavior. In Type II, the volume of water production is low with a small to non-existent decline, while the gas inclines and remains at a stable value (no decline observed). Type III is similar to Type I except the rate of incline of gas is slower and thus extended. The final type, IV, exhibits a conventional decline response. In this case, both gas and water are declining, typically at the same rate.

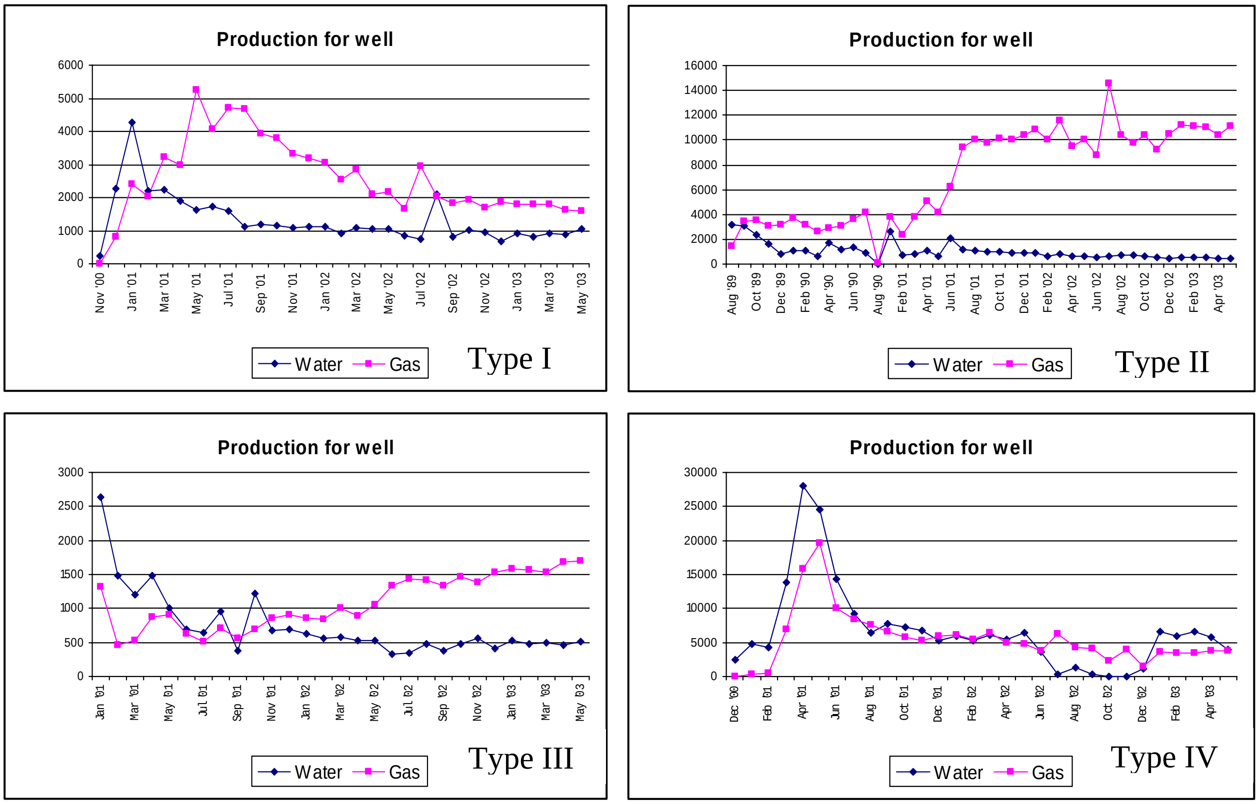


Figure 5.8 Various production behaviors for Raton Basin Wells

Since VPR B and D are adjacent to the Valle Vidal Unit, emphasis was on analyzing the production response from these wells.

**VPR B:** As mentioned previously, the majority of wells in VPR B produce from only the Vermejo Formation. Also, the average water-gas ratio for this region is low, 0.40, and therefore it is not a major water producer. However, on examining each well's performance, a maximum WGR of 2.9 was determined for a given well. Furthermore, the majority of wells in this region exhibit the type IV behavior described above, and these wells result in the highest WGRs. Figure 5.9 is a bar graph illustrating the frequency of each type for a given range of WGR.

Estimated ultimate recovery (EUR) for a well was determined using decline analysis of production rate vs. time. Notice, only Types I and IV display gas decline and therefore can be analyzed. On average, the EUR for Type I and IV wells is approximately 150 mmscf (million standard cubic feet) of gas. Types II and III are anticipated to have greater recovery.

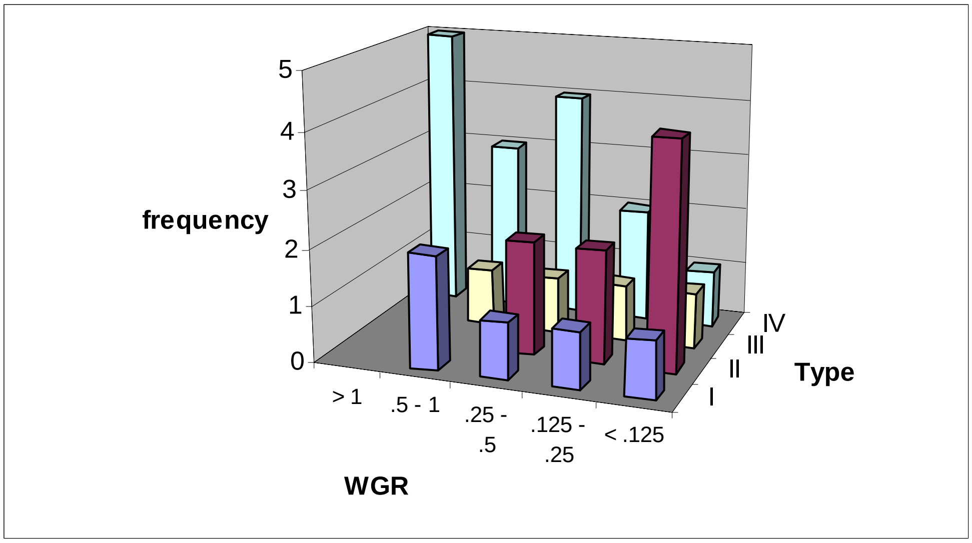


Figure 5.9 Frequency of the various production types for different WGR in VPR B.

**VPR D:** VPR D exhibits the lowest WGR of all the regions, and the highest percentage of wells completed only in the Vermejo Formation. Analysis of the various production curves resulted in the majority exhibiting either Type II or IV behavior. Furthermore, a subset of Type IV was identified and is labeled IV*. This subset follows the general conventional response as described for Type IV above; however the gas production is significantly greater than the water production. Figure 5.10 is an example illustrating this behavior.

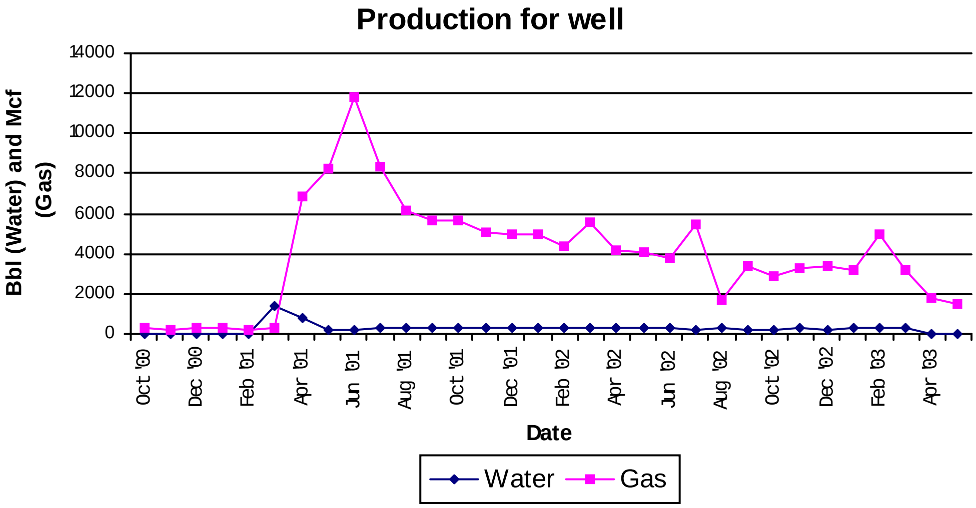


Figure 5.10 Example of Type IV* production behavior.

An investigation into the WGR for the various production types is shown in Figure 5.11. For the wells included in the figure, the overall WGR is low, especially for types II and IV*. However, the wells with the greatest WGR did not follow any of the identified production trends, but instead have inclining water behavior and therefore are not included in the figure. The ten wells exhibiting this behavior account for 25% of the total water production from VPR D. Eight of those occur immediately adjacent to the outcrop of the Vermejo Formation at the Vermejo Park Dome and may reflect the influence of direct aquifer recharge, but we have not data to confirm this possibility. Two are probably due to an erroneously high data anomaly in the public dataset available (we suspect data entry error or allocation error). EUR for VPR D wells is much better than VPR B, averaging 300 mmscf per well.

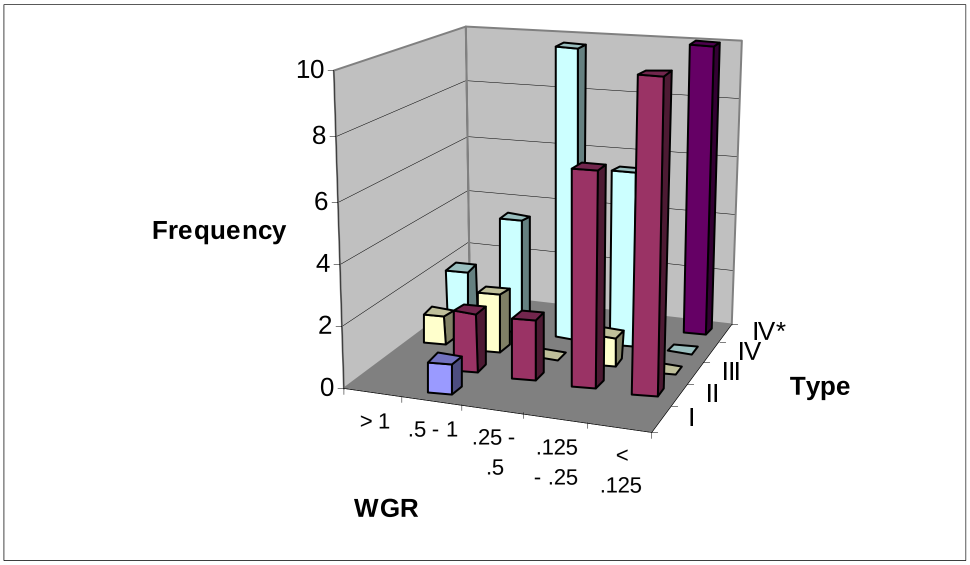


Figure 5.11 Frequency of the various production types for different WGR in VPR D.

## 5.3 Multi-well production response

A log-log plot of rate vs. time developed by Fetkovich (1980) provides the classic technique to identify if a well is in depletion mode; i.e., has achieved boundary dominated flow. Figure 5.12 illustrates the type curve generated for matching production data and determining reservoir and well parameters.

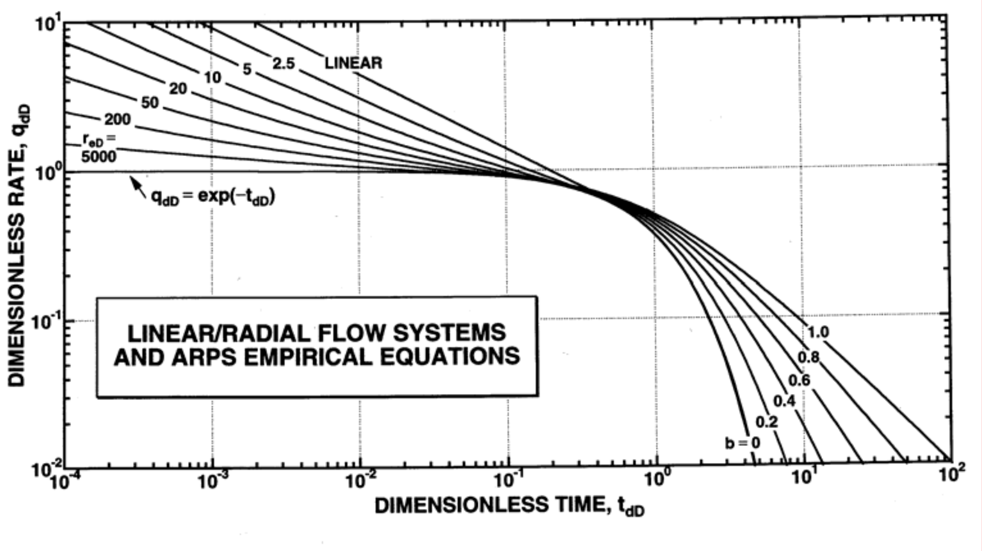


Figure 5.12 Log- log plot of rate vs. time (after Sunde et al., 2000)

The objective is to match production data to the depletion stem of the type curve and therefore be able to estimate drainage area. Due to the limited time these wells have been producing, (at best 30 to 33 months for leases B and D, respectively) no discernable match was achieved. Figure 5.13 is an example illustrating the transient response.

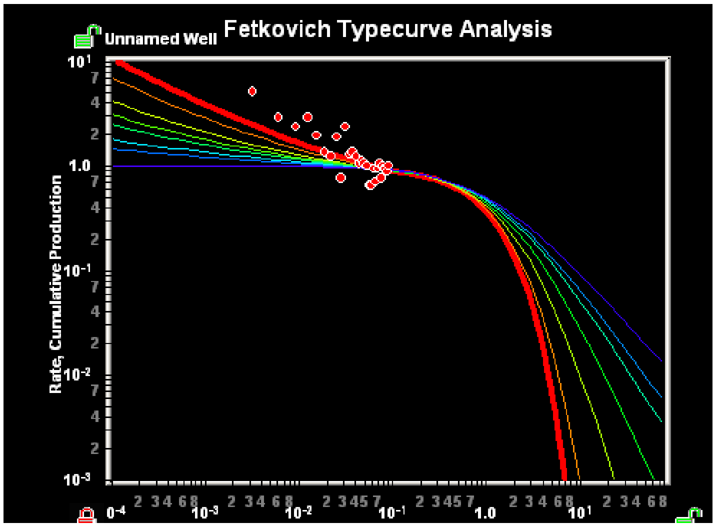


Figure 5.13 Example of a Raton Basin well illustrating limited data for matching.

## 5.4 Coalbed methane modeling

To interpret the production response a CBM model (Fekete, 2003) was applied to the data with observed CBM response. Input variables necessary for this analysis was taken from various sources (Close & Dutcher, 1990; Mavor et al., 1990; Stevens et al., 1992) and are listed in Table 5.3. No matrix shrinkage was included in this work.

| Parameter | Parameter | Parameter |
|---|---|---|
| $V_L$ = 450 scf/ton | $P_L$ = 500 psi | $P_{abnd}$ = 50 psi |
| $P_i$ = 600 psi | GC = 250 scf/ton | k = 1-5 md |
| A = 160 acres | h = variable, ft | $C_p = 50x10^{-6}$ $psi^{-1}$ |
| $\rho_b$ = 1.75 gm/cc | T = 90-115 deg F | |
| $\phi$ = <2% | $S_{wi}$ = 100 % (cleat) | |

Table 5.3 Parameters for CBM model

The objective was to determine original gas-in-place for a generic coalbed methane well. Based on the above parameters, gas-in-place in VPR B and D is estimated to be 3 Bscf and 2.4 Bscf, respectively for a quarter section. This translates to 5 % to 12% recovery using the before-mentioned EURs for VPR B and D, respectively. To put this in perspective, the Potential Gas Committee in 2000 reports recoveries of 12% for the Fruitland Coal of San Juan Basin and 37% for the Raton and Vermejo Coals of the Raton Basin (including the Colorado portion). The VPR wells are relatively young in their production cycle and it will take several more years of production (at minimum) to be able to predict accurate EURs for these wells based on decline-curve analysis or modeling.

## 5.5 Summary

Development in the New Mexico portion of the Raton Basin is subdivided into five leases defined as VPR A, B, C, D, and E. Since VPR B and D are adjacent to the Valle Vidal Unit, emphasis was on analyzing the production response from these wells. Results indicate a reduced water-gas ratio (WGR) in VPR B and D with respect to the rest of the basin.

Production is commingled from numerous coal seams and sand lenses from both the Vermejo and Raton Formations. Production responses for individual wells were divided into four categories, several of which exhibit a coalbed methane type response. However, the most prevalent category exhibited conventional depletion behavior for water and gas in a low-permeability formation. This implies a contribution from the sandstones along with the coals.

Estimated ultimate recovery (EUR) was determined for only those wells that exhibited production decline. On average, these type of wells in VPR D are anticipated to recover 300 mmscf and in VPR B, approximately 150 mmscf, respectively. These recoveries are minimum values, and do not account for wells with no decline (Type II and III) or the possibility of a delayed coalbed methane response beyond the current production time. As can be seen, better recovery is anticipated in VPR D (by almost double) than in VPR B. Consequently, development in and adjacent to VPR D is more favorable. This does not mean that VPR B wells are subeconomic. Analysis could not determine a typical drainage area for wells in VPR B and D; therefore, results are inconclusive in support of or against the potential for 80-acre development. Key factors relevant to not obtaining drainage areas are: (1) the time dependency of the method to achieve a match for estimating drainage area. Production type curve matching requires sufficient data to achieve the depletion match and thus determine drainage volume. In this work, production has occurred for only 30 to 33 months, exhibiting only transient flow conditions and not sufficient time to determine depletion parameters. (2) aquifer support may mask depletion effects, and (3) desorption may mask or delay effects.

# Chapter 6 Surface Occupancy and Disturbance

## 6.1 Approach

Chapter 4 established that the shallowest formations of interest, the Vermejo and Raton Formations, have the highest potential for resource occurrence and development. The RFDS anticipates that development would begin with an initial test drilling phase where some (perhaps 5 to 10) wells would be drilled and tested to confirm resource potential and then subsequently completed as producers once infrastructure is available. It is believed that all available 160-acre equivalent coalbed methane *subsurface reservoir cells* would be developed within the 20–year duration of the RFDS. A subsurface reservoir cell is the term used here to describe the 3-dimensional reservoir volume that statutory regulations allow an operator to drain with one vertical or near-vertical deviated well. A cell will usually have a square 160-acre surface projection with a drilling "window" for a vertical-well pad to be placed near the center of this area. With regulatory approval, irregularly-dimensioned cells may have an irregular projection at the surface. Depending upon if, and when, downspacing might occur during the 20-year life of the RFDS (an event we cannot predict or assign a probability to) some or all of 80-acre equivalent infill (reduced density) cells could be added. Deeper, non-CBM targets are possible, but these could be tested as a consequence of drilling deeper for the purpose of disposing of water produced by the shallow CBM play. The approach taken in Chapter 6 is to estimate the number of feasible subsurface completions (one in each cell for vertical wells) that would be desirable under a full development scenario and then estimate the surface disturbance area associated with these completions.

Not all subsurface completions cause additional *surface locations* (well pads) to be constructed. For example, there are savings in terms of number of surface locations if water disposal wells and deep tests can be placed on pads that also accommodate producing CBM wells. There are also potential savings in the number of surface locations if directional drilling should prove economically feasible in the 20-year term. At present we believe that it is currently not *economically* feasible for highly deviated (or horizontal) wells to be constructed for cell drainage, otherwise this technique would be applied today at the Vermejo Park Ranch where such technology could be beneficial. We cannot predict *if* and *when* such well tech technology (which certainly currently exists but is very expensive) might become economically feasible. However, we acknowledge that it could become potential to do so within a 20-year time frame.

On a total acreage-only basis, if the entire 40,000-acre eastern Valle Vidal Unit were available for development on 160-acre spacing of surface locations for vertical wells, and irregular well placement was allowed for by regulatory approval, there would be 250 reservoir cells available for producing wells. This assumes that the coalbed methane resource is minimally (but sufficiently) economic using lowest-cost vertical wells. It is not the purpose of this RFDS to cause withdrawals of acreage associated with the surface expression of these cells for any reasons other than geologic and customary statutory reasons. Any subsequent analyses by the Carson National Forest would examine interaction and potential conflicts of the development described here on other resources and in terms of overall environmental impacts. Figure 6.1 illustrates the surface projection of 191 subsurface reservoir cells which could be accessed by vertical or slightly deviated wells. This reduced number of accessible cells (from 250) is predicted based on two limiting factors: statutory and geologic. Figure 6.1 was constructed assuming only full 160 acre quarter section surface projection (surface locations) per cell. There are a number of “slivers” of land less than square 160 acres along the boundaries of the area that would normally not be drilled under standard spacing and well location rules. Many of these slivers, particularly along the western and southern boundaries, are also not conducive to physical occupation due to topography (e.g. cliffs, canyon walls). This withdrawal reduces the number of reservoir cells that could be accessed by standard vertical wells by 21. In addition, it is believed that fractured igneous intrusions (dikes) would channel water to producing wells and be undesirable neighbors to wells. A ¼ mile buffer was drawn around intrusions. 160-acre quarter sections that have more than 40 acres covered by the buffer were withdrawn reducing the number of reservoir cells/surface locations able to be occupied by standard vertical wells by another 38. A 300 ft buffer was placed on two major access roads 1914 and 1950 for illustration purposes only.

Of the 191 subsurface reservoir cells remaining, it is clear that some cannot be occupied at the surface due to topography based on rules that require a narrow window for well placement at the center of the quarter section. This is particularly true along the western and north-central margins of the eastern Valle Vidal Unit. However, no withdrawal of area was applied to those locations because flexible well location rules, combined with deviated (not horizontal) drilling, could make those reservoir cells accessible. Again, it is assumed that deeper wells will be drilled with the dual purpose of water disposal and testing deeper plays. These wells can be placed on a pad with a shallow well, but the surface footprint of the pad would cover a larger area.

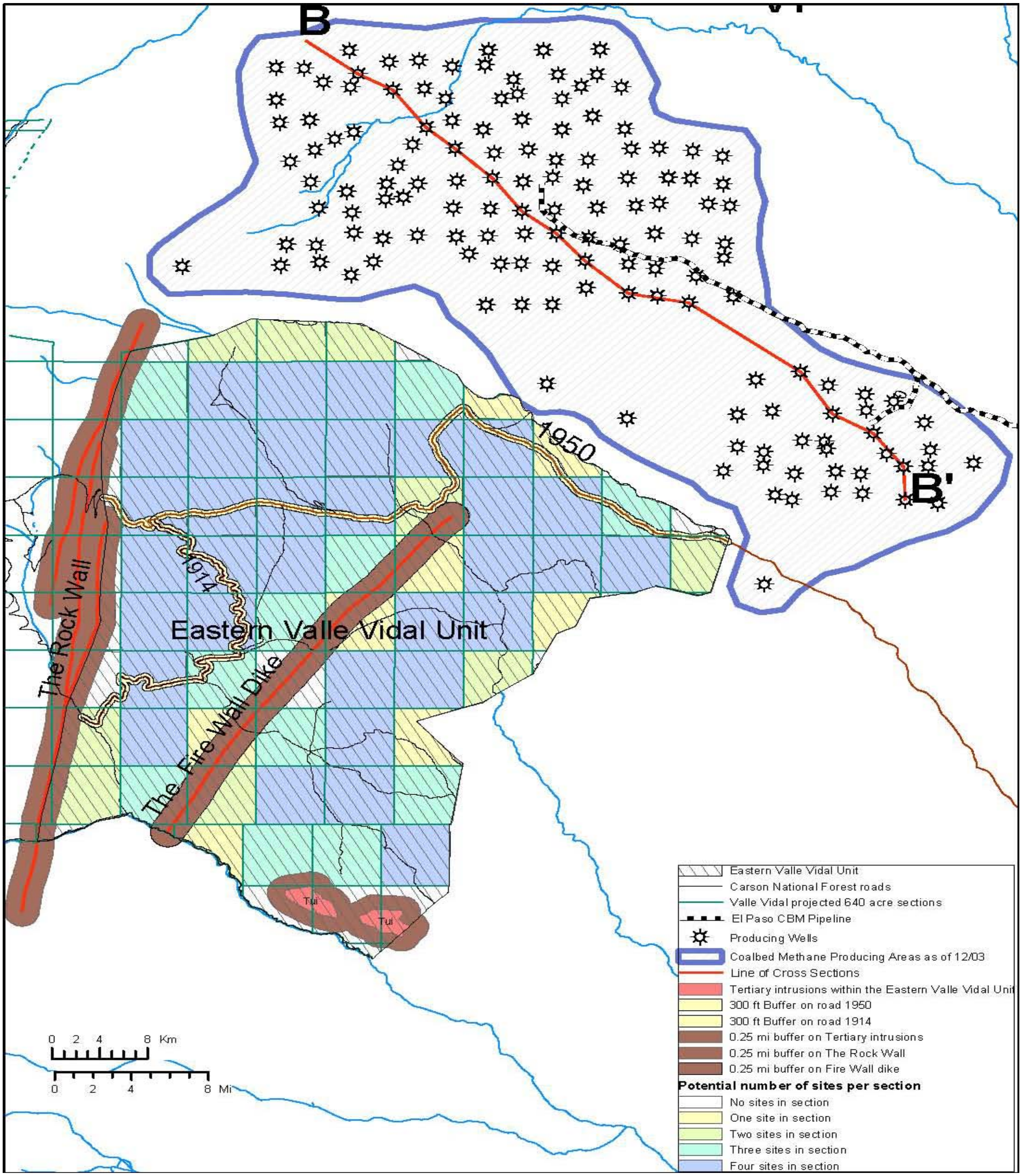


Figure 6.1 Map showing estimated minimum number of well locations for vertical wells for draining subsurface reservoir cells estimated to be likely for coalbed methane development in the eastern Valle Vidal Unit. To our knowledge, highlighted roads 1950 and 1914 are the only roads currently open for public access.

### 6.2 Surface well locations

A square-mile section equals 640 acres of surface area. Four, 160- acre vertical well locations can be placed in each section. Based on the approach outlined in section 6.1, a minimum of 191 surface locations would be required to fully develop the coalbed methane resource on of the eastern Valle Vidal Unit using vertical wells at 160-acre per well spacing. A surface location (well pad) is an area of land that is cleared and leveled to provide an area for temporarily accommodating, moving and storing large equipment for purposes of construction and maintenance of wells. Once wells are constructed, the area required for maintenance can be substantially less than that needed during the drilling and completion stages of construction. This is discussed further below.

An estimated four, deep, vertical, produced-water disposal wells will be required based on statutory regulations and operator practices on the Vermejo Park Ranch. These wells will not cause additional surface locations because they can be “twinned” on pads with producing wells, but the area of disturbance will be larger for surface locations that also accommodate disposal wells.

At this time, it is **not** anticipated that drainage of multiple subsurface reservoir cells will be economically achieved by drilling horizontally. The additional costs associated with horizontal drilling vary greatly depending upon the target the operator is trying to hit, the degree of accuracy that is required (the window of error) to hit the target, depth, reach (distance to terminus) of the well from drill pad, drilling methods (air, mud, foam, coiled tubing, etc.), availability of appropriate equipment, and transportation costs among others. We do not believe that this play is appropriate for horizontal drilling technology. This is due to the shallow depth of the CBM play, thin coal beds separated vertically over hundreds of feet (multiple targets), and potentially long horizontal reach.

### 6.3 Lease infrastructure

Lease infrastructure required includes natural gas- and water handling-related facilities and access roads. Natural gas infrastructure includes a trunk pipeline for transporting gas to market, a central compressor facility for compressing lease gas to required pipeline pressures, a gathering pipeline system that branches to the individual wells, and well pad equipment including wellheads and wellhead separators. It is assumed that the trunk pipeline would enter the property from the east, either connecting to the existing El Paso pipeline or following the right of way for Forest Road 1950 to connect to a pipeline paralleling Highway 64. Gas gathering pipelines could be laid beside access roads to individual wells. The central gas compression facility could be powered by combustion of lease gas or by electricity (the power source used at the Vermejo Park Ranch). If electricity is used, a power line would need to be strung or buried along the right of way accommodating the trunk gas pipeline.

Water handling-related infrastructure includes pump jacks to remove water from wells, flow lines to deliver water from wells to a storage tank battery, filtration equipment, injection pumps, and water disposal wells. Pump jacks could be powered by lease gas or by electricity (they are powered by electricity at the Vermejo Park Ranch). As many as four disposal sites may be required, each equipped with tanks and equipment houses. Flow lines between wells and disposal facilities can follow well access roads along with gas gathering lines. Electric lines, if used, could be strung or buried beside flow lines (lease power lines are buried at the Vermejo Park Ranch). .

## 6.4 Footprint of drilling and production operations

The surface disturbance normally associated with drilling and production operations is two acres per well pad plus an additional acre of right-of-ways for associated roads and pipelines. For 191 surface locations, this is 573 acres. Water disposal and central compression facilities would expand the footprint of a limited number of locations. Four water disposal facilities and one compressor site each having 3 acres of added area contribute an additional 15 acres for a *total infrastructure disturbance of 588 acres*. Additional surface disturbance would result if right-of-ways are not limited to roadways or if roadways are not placed optimally to reduce total surface area.

Of course the footprint of drilling and production operations is variable dependent upon the needs of the operator and the mutual goals set by the operator and land owner/manager. There are certainly alternative scenarios that could apply to the eastern Valle Vidal Unit. It is not the purpose of this RFDS to determine specific environmental impact of oil and gas operations, yet there are some obvious development alternatives that the land management agency could consider relative to oil and gas production options. The authors would encourage the Carson National Forest to consult with both the operator and surface owner of the Vermejo Park Ranch wells to consider potential working alternatives to standard oil and gas development practices. At the Vermejo Park Ranch, well pads have a much smaller (than standard) surface footprint, greatly reduced visual impact, reduced exhaust emissions, and reduced environmental impact overall due to specially negotiated conditions on timing and method of operations. As example, well locations take up only 0.5 acres. Roadways and right-of-ways are combined to a 30 ft wide path, but right-of-ways are immediately reclaimed to reduce the path to 20 ft. These measures alone reduce the surface disturbance attributable to individual wells by almost two-thirds. As described above, the assumption made to determine surface disturbance associated with individual well completions in this RFDS is the standard 2 acres per well pad plus an additional 1 acre of right-of-ways for associated roads and pipelines.

# Chapter 7 Responses to Operator Survey

## 7.1 Summary of responses

The objective of the industry survey (example in Appendix 1) was to solicit informed opinions from coalbed methane operating companies and other companies familiar with the Raton Basin. See Chapter 2 for the methods applied. Four responses were provided; three were from coalbed methane operators in the Raton Basin. The following list of base assumptions was provided to the operators:

- There is a "shallow" (generally less than 2000 feet depth) petroleum system play that yields coalbed methane from coal and sandstone beds in the Raton and Vermejo Formations in the Raton Basin. Much or all of the RFD study lies within a moderate to high probability area for production from this system. Exploration and production activity associated with this play will dominate the RFD scenario.
- There is a "mid-depth" (generally between 2000 feet and 8000 feet depth) petroleum system play that could yield oil or natural gas from Mesozoic sandstone and shale formations ranging from the Trinidad Sandstone to the Morrison Formation. There has been no commercial production to date from this system, but the number and quality of oil and gas shows from these formations suggests that the play would be an attractive target for future exploration, conducted through drilling of wildcat wells. The RFD scenario will consider a limited number of such wells.
- There is potential for a "deep" (generally greater than 8000 feet depth) play in Paleozoic rocks that may cause seismic exploration activity to be conducted with the possibility of one or more exploratory wells.

The Following questions were asked. Responses are noted.

**7.1.1** Do you agree with the base assumptions?
YES: 4
NO: 0

**7.1.2** Do you currently operate CBM wells in the Raton Basin?
YES: 3
NO: 1

**7.1.3** Do you currently operate CBM wells in other basins but not Raton Basin?
YES: 2
NO: 1
No response:1

**7.1.4** Current CBM well spacing in the Raton Basin is 160 acres per well. Considering the 20-year timeframe of the RFD, do you anticipate an increase in well density to 80 acre spacing?
YES: 3
NO: 1

**7.1.5** Current CBM wells in the Raton Basin are vertical wells. Do you anticipate horizontal drilling becoming a viable option for such shallow reserves in the coming 20 years?
YES: 1
NO: 3

**7.1.6** Noise and exhaust emissions from production and transportation equipment could be a critical consideration for allowing/denying development. On the Vermejo Park Ranch, buried electric power is used to run pumpjacks, compressors, and other motors. Would you consider this to be an acceptable alternative to lease-gas powered equipment if necessary?
YES: 2
NO: 2
Additional comment from one respondent stated “terrain too rugged-would also limit economic viability. Current technology can reduce noise and exhaust emissions to acceptable limits.”

**7.1.7** What gas compression option would you prefer for this type of production?
Wellhead**:** 0
Centralized**:** 4

**7.1.8** What water disposal options would you prefer for produced water less than 2000 ppm total dissolved solids?
Surface disposal: to settling pits, then to natural drainages**:** 4
Subsurface injection into deep saline aquifers**:** 0
Trucking (at minimum 30 miles) to off-site approved disposal facilities**:** 0

**7.1.9** If productive, mid-depth Mesozoic targets will most likely yield gas with producing wells spaced 320 acres per well.
YES: 2
NO: 2
Additional comments from two respondents with NO answer: “Shale gas potential may require wells closer than 320s to drain the tight gas source” and “160 acres required as would be tight gas”

**7.1.10** Seismic exploration methods in the area will likely be:
2-D: 0
3-D: 4

Probable spacing between lines/cross-lines: One respondent replied “~1000 ft”. Another respondent replied “900 ft shot lines, 300 ft receiver lines, but use existing roads as much as possible”.

### 7.2 Implications of responses to RFDS

The survey responses generally support the base assumptions presented to the respondents with some exceptions.

In question 7.1.4, three of four respondents favored 80-acre well spacing for development. We do not have enough data to demonstrate a need for 80-acre spacing at this time. Justification for infill drilling to this density would need to be supported by modeling and analysis of more years of production than are available in wells adjacent to the eastern Valle Vidal Unit. The degree of stratigraphic complexity of the Vermejo and Raton Formations does suggest to us that evaluation of 80-acre well spacing might be justified at some point in the future when sufficient production data is available. We provide two scenarios in the RFDS, one based on 160-acre and 80 acres well spacing.

In question 7.1.8, all of the four respondents preferred a surface discharge option for produced waters. The Carson National Forest is encouraged to consider a surface discharge option as part of any further analysis of field development. Currently the State of New Mexico requires subsurface disposal for produced waters.

# Chapter 8 Impacts of future technology

## 8.1 Technology impacts on the RFDS

Advances in technology and research have played an important role in improving gas recovery from unconventional plays of the Rocky Mountain region. Several key areas likely to impact Raton Basin development are directional/horizontal drilling, well stimulation, and the remediation of produced water. Each of these may eventually have an impact on development of the eastern Valle Vidal Unit. The technologies listed below, if successfully applied to the Raton Basin, could increase the economic viability of production of individual wells and/or increase the effectiveness of draining reservoirs as a whole. However, given the current level of deployment, these technologies are *not considered to be alternative scenarios* to that recommended in the conclusions of this RFDS, *but rather potentially desirable future possibilities*.

## 8.2 Directional and horizontal drilling

The objectives of directional (purposely deviated) and horizontal drilling are typically related either to avoiding surface occupation or to increasing production efficiency. These two objectives are not always compatible. Avoidance of surface occupancy is typically due to topographic or environmental concerns. In this case, a drilling location will be selected as near as possible to the subsurface target and a well bore will be constructed in such a manner as to minimize cost while achieving the subsurface target. The goal is to capture the same reserves that would have been achieved from a vertical well, had one been drilled. In terms of economic efficiency, such wells are less efficient due to increased cost (approximately 20%) and higher operating expenses with no change in producible reserves. Such wells can present difficulties in operation, particularly when artificial lift is required because inexpensive rod pumps (driven by pumpjacks) cannot operate when the borehole has “doglegs” or bends.

Application of horizontal well technology in the onshore United States has been increasing in recent years. For example, horizontal well activity in the San Juan Basin has increased lately in the Fruitland Coal, as industry realizes the benefits of such practices. However, not all reservoirs are candidates for this type of completion. A first step in selecting appropriate reservoirs is to screen the key parameters for commercial success. For example, natural fracture orientation and intensity, net pay and vertical permeability, susceptibility to formation damage, reservoir pressure, anisotropy, and drilling/completion costs need to be understood in the context of penetrating the reservoir with a horizontal well.

Fractured reservoirs such as coals may be more suitable for horizontal drilling because of the ability to intersect fractures (cleats). However, where artificial lift is required, this drilling technology often proves impractical. We believe that the thin and discontinuous coalbeds in the eastern Valle Vidal Unit, and the relatively low net coal existing over a large gross vertical interval, are conditions that are not conducive to horizontal drilling. The shallow depth of the CBM reservoir would make horizontal well construction excessively expensive compared to vertical wells. We do not recommend horizontal drilling as a viable method during the 20-year life of the RFDS.

### 8.3 Completion technology

Hydraulic fracture techniques have evolved over the years with improvements in fluids, proppants, and design. Hydraulic fracturing is achieved by pumping large volumes of fluid (typically fresh water or a fresh water-nitrogen-soap foam), under pressure, with viscosifying additives (guar gum is typical) and quartz sand. The purpose is to cause the formation of interest to fracture under pressure, with the sand propping open the fractures to allow reservoir fluids to flow through the newly opened conduits. Advances in hydraulic fracturing of low permeability formations will have, perhaps, the greatest potential impact on future development; particularly, to improve the effectiveness in thin, multiple pay zones. Currently identified issues that require further improvement are:

- Cost reduction of all stimulations is a priority among all operators. The goal is to increase fracture efficiency while reducing cost per application in future well completions.
- Research is required to achieve more effective hydraulic fracturing of naturally under-pressured or semi-depleted formations.
- There is currently a need to improve multi-zone or multi-formation stimulations within a single well bore.
- All stimulations tend to cause some degree of formation damage (pore network plugging) such that the efficiency of the stimulation is less than ideal; therefore there is a need for better identification of sensitivity of formations to fluid interaction-related damage and need for research into optimal, non-damaging fluid systems
- There is a regional shortage of availability of better-engineered liquefied $CO_2$ delivery systems. This limits the application of, and increases the cost of, less damaging liquid $CO_2$ fracturing.

Hydraulic fracturing techniques were applied to all wells that are currently producing gas at the Vermejo Park Ranch. This stimulation technique appears to be a critical element in economic production of the CBM reservoir. There, economic improvements in a 20-year time frame would likely result from improved stimulation methods.

## 8.4 Produced water treatment and filtration

Production of formation water is a necessary requirement for production of coalbed methane. Much of the gas content of coals is in the form of molecules of methane physically adsorbed on organic particles in the coal matrix. By producing formation water from the coal porosity system, formation pressure is reduced. Reduction of formation pressure is the primary mechanism for the desorption of methane from the coal matrix. Water produced as a byproduct of pressure reduction cannot be disposed of by returning it back into the formation from which it was produced because this would replenish the pressure and halt the production process. Therefore, produced waters must be disposed of in an approved fashion. Generally, this can be done by surface discharge if the water quality is suitable, or disposal by injection into a deep disposal zones if the water quality is poor, however, requirements differ according to State regulation. In the Colorado part of the Raton Basin, produced waters of sufficient quality are pumped to a surface pit for settling of coal fines, then transferred to surface drainages, adding volume to larger rivers. In New Mexico, Raton Basin produced water is required to be injected into state-approved deep disposal zones.

An argument can be made that discharge to the surface allows water of acceptable quality to be reused by adding to local stream flow. There may be beneficial uses of the water downstream in agriculture, manufacturing, and municipal applications. However, if fresh water is pumped into a saline aquifer for disposal, it is essentially permanently removed from reuse and thus wasted.

Water produced at the Vermejo Park Ranch is best classified as brackish, in the range of 2,000 to 10,000 mg/l total dissolved solids. Current methods to improve the quality of brackish water for beneficial use tend to be excessively expensive compared to the option of deep saline aquifer injection. There are many ongoing collaborative research efforts underway in New Mexico and elsewhere to produce useable, even drinkable water from brackish aquifers. One pilot project seeks to aid the City of Alamogordo and Holloman Air Force Base by adding significantly to the drinking water supply through application of innovative filtration technology (Allan Sattler, Sandia National Laboratories, 2003, pers. comm.). Another effort being conducted by Sandia National Laboratories, New Mexico Institute of Mining and Technology, and others is focusing on chemical treatment of coalbed methane produced waters in the San Juan and Raton Basins. An initial conclusion of the water quality evaluation stage of that project is that some Raton Basin produced waters already meet EPA surface discharge requirements. Those that do not meet discharge requirements would qualify with minimal treatment.

As stated above, it is not the purpose of this RFDS to determine specific environmental impact of oil and gas operations. There are, however, obvious development alternatives that further analysis should consider relative to optional oil and gas operation methods. Given a supportive regulatory environment and growing commercial availability of treatment and filtration technology already available, produced water could be effectively and economically improved at either the wellhead or at centralized facilities to meet reasonable requirements for a surface discharge option in the eastern Valle Vidal Unit should that option be found desirable. A surface discharge option for produced water would not significantly reduce the footprint of coalbed methane operation if a lease-centralized treatment facility would be required, such a facility being similar in size to a subsurface disposal facility. It is important to note that as the coalbed aquifer is depleted over time, the volumes of water being produced will likely decrease.

# Chapter 9 Conclusions: Reasonable Foreseeable Development Scenario

## 9.1 Potential for occurrence: High

The overall potential for occurrence of oil and gas resources in the eastern Valle Vidal Unit is high using the ranking method described in this report. This rank is based on geologic conditions predicted to be present at the site relative to that of adjacent lands being actively and economically developed. The primary play of interest is the areally-extensive, shallow (less than 2000 ft deep) coalbed methane and low permeability sandstone natural gas play associated with the Vermejo and Raton Formations. There is some uncertainty as to the quality and economics of this play due to lack of coal quality data in the southern part of the study area. However, there is no negative evidence. The potential for igneous-influenced, increased coal maturity in this area is encouraging.

Another high potential occurrence play using the ranking method described in this report is the fractured “shale” blanket-type Pierre-Dakota play. There is also a lesser possibility of conventional reservoir traps in the Dakota Sandstone. A third play based on postulated presence and source rock potential of the Pennsylvanian Sandia Formation is assigned a low potential due to uncertainty and lack of positive indicators such as oil or gas shows nearby.

## 9.2 Potential for development: High

The potential for development of oil and gas resources at the eastern Valle Vidal Unit is high based on the ranking scheme described in this report. If allowed to lease the eastern Valle Vidal Unit, oil and gas operators will be primarily interested in the immediate economic benefit of developing the coalbed methane resources. Development will proceed from an initial phase of testing 5 to 10 selected sites to evaluate geologic and economic conditions, primarily gas-in-place and net coal thickness in the Vermejo Formation for comparison with productive gas wells on the adjacent Vermejo Park Ranch. A second phase will focus on bringing in the proper infrastructure to produce the area as a whole. This phase involves construction of a pipeline that will require negotiation to be successful and therefore not evaluated here as to economic feasibility. Other infrastructure development will be gas compression and water handling and disposal facilities. A third phase will involve drilling every allowed location on 160 acre spacing where feasible using conventional vertical drilling technology. A fourth phase might involve drilling problematic locations using deviated (not horizontal) wellbores if economics prove to be sufficient. Deep targets will be tested as a side benefit of drilling water disposal wells and may not require additional locations.

### 9.3 Drilling activity and surface use forecast

Development of the coalbed methane resource is not likely to require reflection seismic data. Evaluation of deeper plays would benefit from such data. Operators in the region have expressed interest in 3-D seismic data with lines/cross-lines spaced closer than ¼ mile. No evidence of existence of 3-D seismic data or current acquisition activity was found in the vicinity. If acquired later in the RFDS, seismic acquisition by vibroseis source (trucks) may be able to take advantage of existing lease roads to minimize disturbance.

Over the 20 year life of the RFDS, it is predicted that a minimum of 195 total wells would be drilled on a total of 191 surface locations at 160-acre per well spacing. Four wells will be drilled as water disposal wells/deep tests and could be placed on an existing well pad for a shallow coalbed methane well. The area of disturbance for each location need not be large because the shallow depth and minimal required equipment would allow for small locations. Innovative and environmentally progressive development practices could significantly reduce impacts to alternative land uses while promoting maximum economic benefit. Flexibility in spacing rules and better-than-anticipated geologic conditions could allow expansion to a total of 254 wellbores on 250 surface locations.

Approval for 80-acre infill (increased density) drilling locations may be needed to produce the resource within the 20-year time frame. Presently there is insufficient evidence to determine the possibility that downspacing will occur. Some operators believe that there will eventually be sufficient justification for this. If 80-acre per well spacing is approved, this would essentially double the number of locations. Therefore, a range of between 191 and 500 surface locations (well pads) is possible within the 20-year life of the RFDS.

Coalbed methane plays benefit from planned dewatering of coal over a large area. If the Carson National Forest allows oil and gas leasing and development, it is worth considering leasing the eastern Valle Vidal Unit as a contiguous block of acreage in order to drain the natural gas reserves most efficiently, economically, with the least disturbance, and to prevent duplication of infrastructure.

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### Appendix 1

# Industry Survey of Exploration and Development in the Valle Vidal Unit, Carson National Forest, Colfax County, New Mexico

The Carson National Forest (NFS) has requested from New Mexico Tech an estimation of the *Reasonable Foreseeable Development* (RFD) for the eastern Valle Vidal Unit, Colfax County, New Mexico. The study begins with an effective date of January 1, 2005 with a duration of 20 years. The RFD characterizes potential oil and gas resources, describes options for subsurface development needed to access and drain reservoirs, and estimates the probable surface disturbance that would result from subsurface development. The final RFD will be used to support an environmental analysis through an Environmental Impact Statement (EIS) that will lead to a leasing decision and amend the Carson National Forest's Forest Plan. Industry's participation is solicited to better develop a plan that is mutually beneficial to all concerned.

## Description of study area

The eastern Valle Vidal Unit is located approximately 24 miles northwest of Cimarron, New Mexico and 17 wiles east of Costilla, New Mexico in the Sangre de Cristo Mountains on Forest System Road 1950. The area of study encompasses 40,000 acres within the Forest Service boundary east of a linear geologic feature (an igneous dike) called the Rock Wall. The area falls within the geologic boundaries of the Raton Basin, a region of current coalbed methane (CBM) development activity.

## Summary of current management and oil and gas development of the Valle Vidal Unit

Prior to 1999, there was no commercial oil or gas production from the New Mexico part of the Raton Basin. From 1999 to May, 2003 some 256 wells have been drilled that produce CBM at the Vermejo Park Ranch in Colfax County, New Mexico. The Vermejo Park Ranch is adjacent to the northern and eastern boundary of the Valle Vidal Unit. Currently there is no oil or gas production from the Valle Vidal Unit. In addition, there is no infrastructure (pipelines, electric power) other than access roads to support production. Historically, exploration there has been limited to drilling to evaluate the coal and water resources. The federal oil and gas (including CBM) mineral estate encompassed by the Valle Vidal Unit is not currently leased. Recent adjacent coalbed methane development coupled with industry requests for leases has prompted the Carson National Forest to consider amending the Forest Plan to include oil and gas development.

## Development potential base assumptions

The following list of general constraints is provided as a baseline for answering the following questions.

- There is a "shallow" (generally less than 2000 feet depth) petroleum system play that yields coalbed methane from coal and sandstone beds in the Raton and Vermejo Formations in the Raton Basin. Much or all of the RFD study lies within a moderate to high probability area for production from this system. Exploration and production activity associated with this play will dominate the RFD scenario.
- There is a "mid-depth" (generally between 2000 feet and 8000 feet depth) petroleum system play that could yield oil or natural gas from Mesozoic sandstone and shale formations ranging from the Trinidad Sandstone to the Morrison Formation. There has been no commercial production to date from this system, but the number and quality of oil and gas shows from these formations suggests that the play would be an attractive target for future exploration, conducted through drilling of wildcat wells. The RFD scenario will consider a limited number of such wells.
- There is potential for a "deep" (generally greater than 8000 feet depth) play in Paleozoic rocks that may cause seismic exploration activity to be conducted with the possibility of one or more exploratory wells.

## Confidentiality Statement

*Information gathered in this survey to be used solely by New Mexico Tech for the purposes of the RFD and the identity of the person or company responding to the survey will not be disclosed to or used by any other party.*

**Survey**

Please answer each question below by circling your choice. Please feel free to attach a narrative answer or further discussion on a separate sheet.

**Question 1: Do you agree with the base assumptions?**
YES
NO (important to attach a narrative explanation).

**Question 2: Do you currently operate CBM wells in the Raton Basin?**
YES
NO

**Question 3: Do you currently operate CBM wells in other basins but not Raton Basin?**
YES
NO

**Question 4: Current CBM well spacing in the Raton Basin is 160 acres per well. Considering the 20-year timeframe of the RFD, do you anticipate an increase in well density to 80 acre spacing?**
YES
NO

**Question 5: Current CBM wells in the Raton Basin are vertical wells. Do you anticipate horizontal drilling becoming a viable option for such shallow reserves in the coming 20 years?**
YES
NO

**Question 6: Noise and exhaust emissions from production and transportation equipment could be a critical consideration for allowing/denying development. On the Vermejo Park Ranch, buried electric power is used to run pumpjacks, compressors, and other motors. Would you consider this to be an acceptable alternative to lease-gas powered equipment if necessary?**
YES
NO

**Question 7: What gas compression option would you prefer for this type of production?**
A) Wellhead
B) Centralized

**Question 8: What water disposal options would you prefer for produced water less than 2000 ppm total dissolved solids?**
A) Surface disposal: to settling pits, then to natural drainages
B) Subsurface injection into deep saline aquifers
C) Trucking (at minimum 30 miles) to off-site approved disposal facilities

**Question 9: If productive, mid-depth Mesozoic targets will most likely yield gas with producing wells spaced 320 acres per well.**
YES
NO

**Question 10: Seismic exploration methods in the area will likely be:**
A) 2-D
B) 3-D
Probable spacing between lines/cross-lines:____________________

We would appreciate any further comments or suggestions pertaining to future development plans.

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

Name: _________________________

Company: ______________________

**Confidentiality Statement**

*Information gathered in this survey to be used solely by New Mexico Tech for the purposes of the RFD and the identity of the person or company responding to the survey will not be disclosed to or used by any other party.*

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# Appendix 2

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