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.

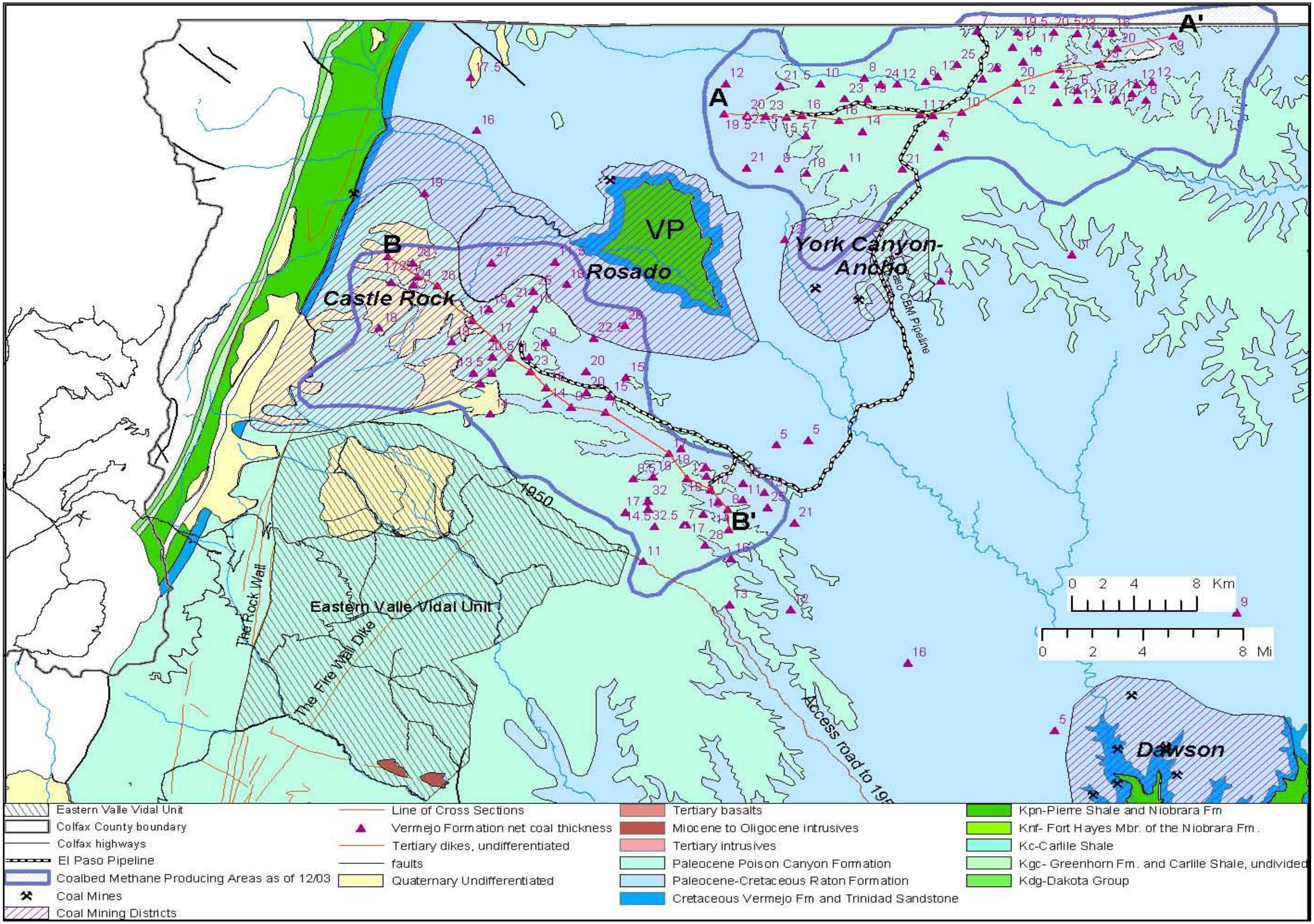

Figure 4.1 Vermejo Formation net coal thickness interpreted from geophysical logs of wells with complete Vermejo section. VP = Vermejo Park.

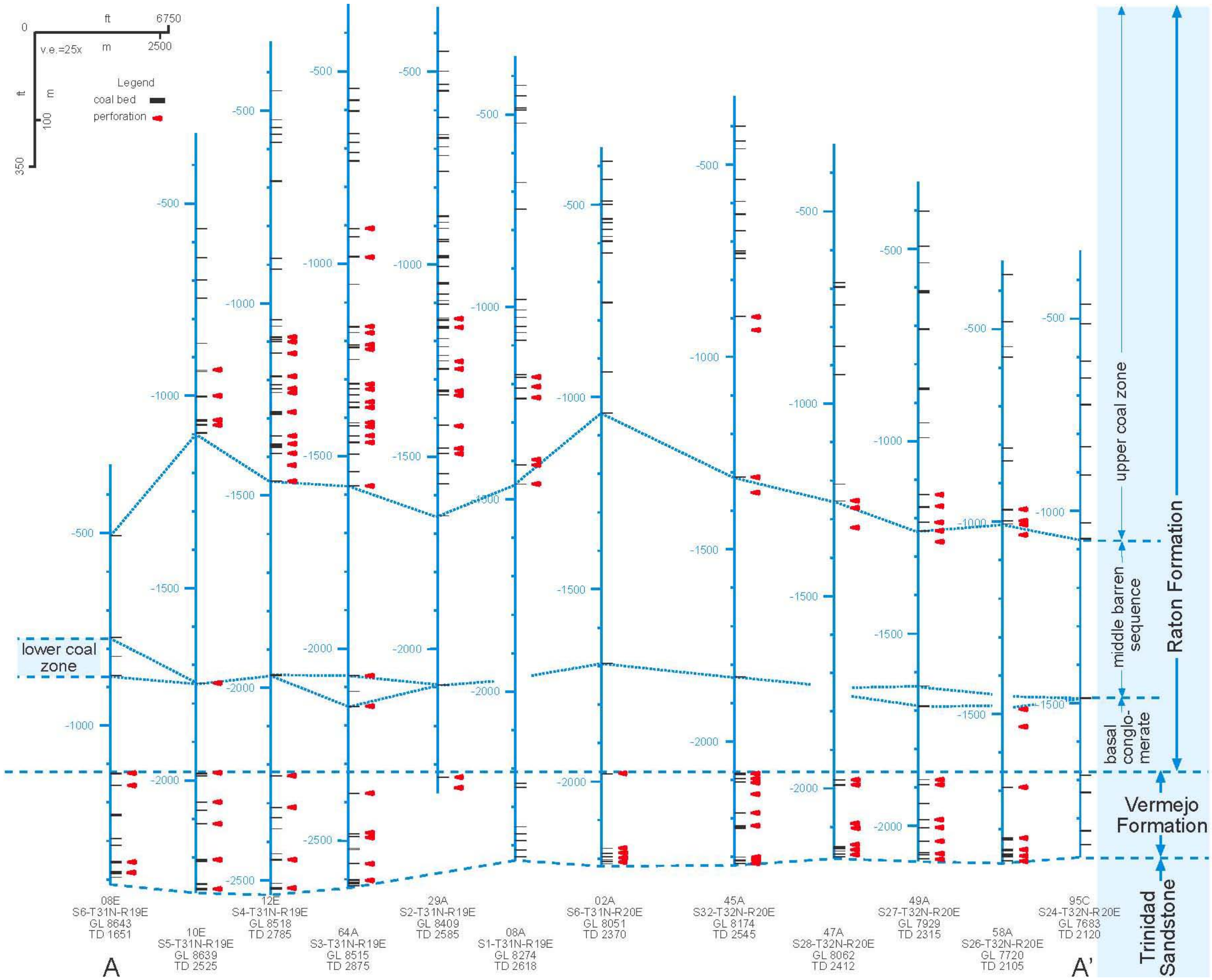

Figure 4.2 Cross-section A-A' (west to east). Approximate spacing between wells is 1 mi. Line of cross section shown on maps in Figs. 4.1 and 4.4. Wells arranged such that the top of the Vermejo Formation is the stratigraphic datum. The top of the Trinidad Sandstone is the base of the well columns. The 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.

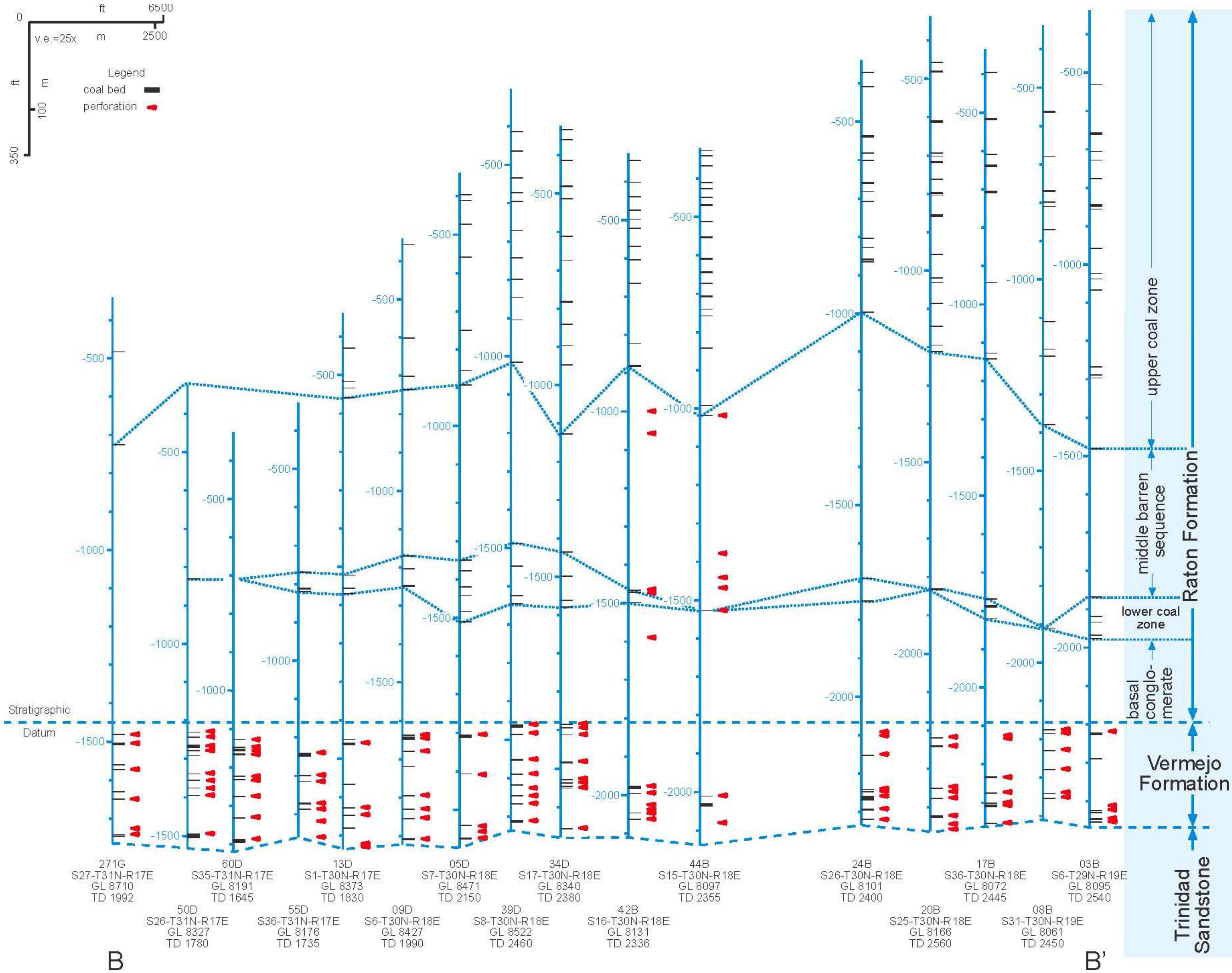

Figure 4.3 Cross-section B-B' (west to east). Approximate spacing between wells is 3/4 mi. Line of cross section shown on maps in Figs. 4.1 and 4.4. See Fig. 4.2 for comments on cross section construction.

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.

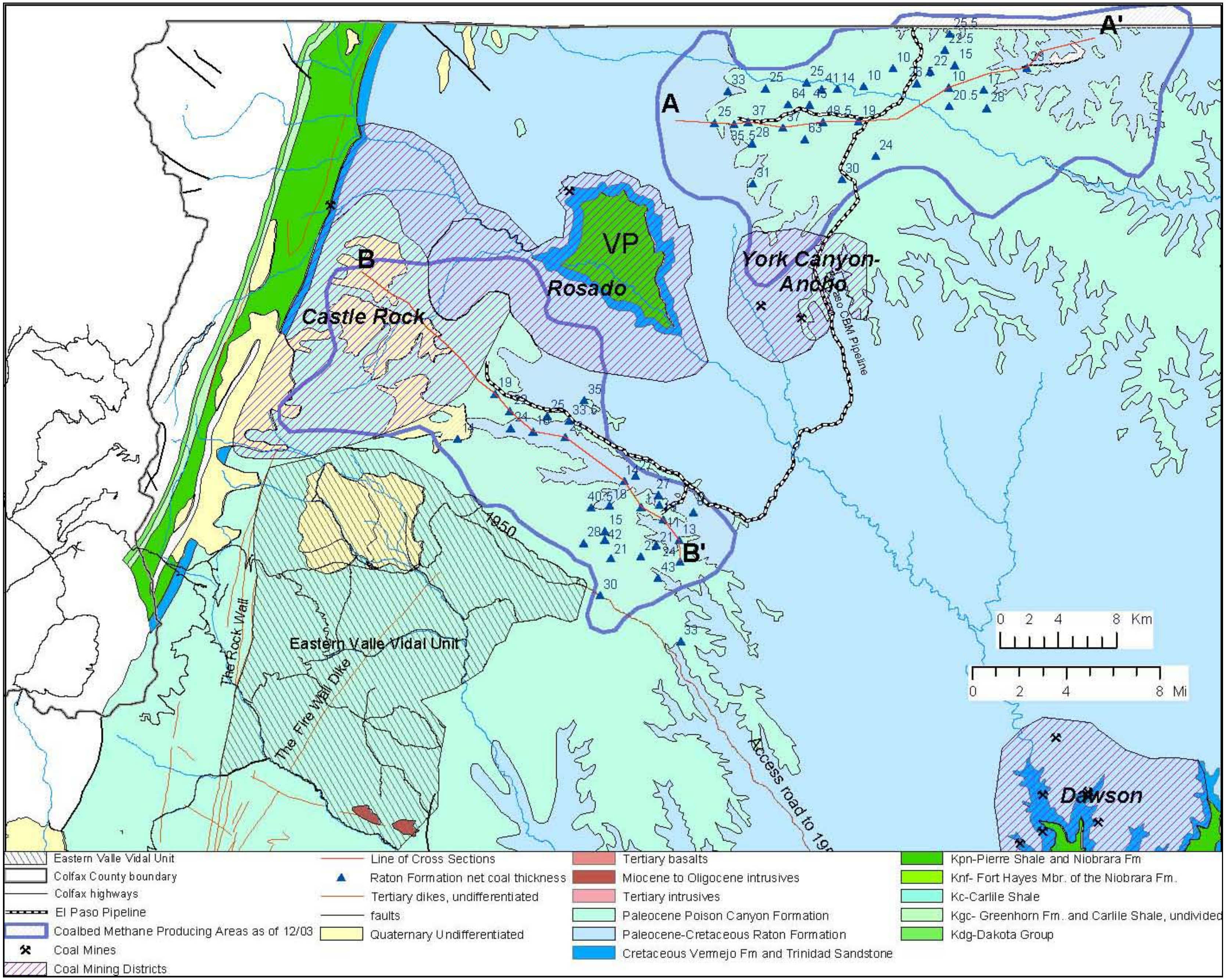

Figure 4.4 Raton Formation net coal thickness interpreted from geophysical logs. Wells included only where 1,400 ft or more of Raton Formation was logged. VP = Vermejo Park.

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.

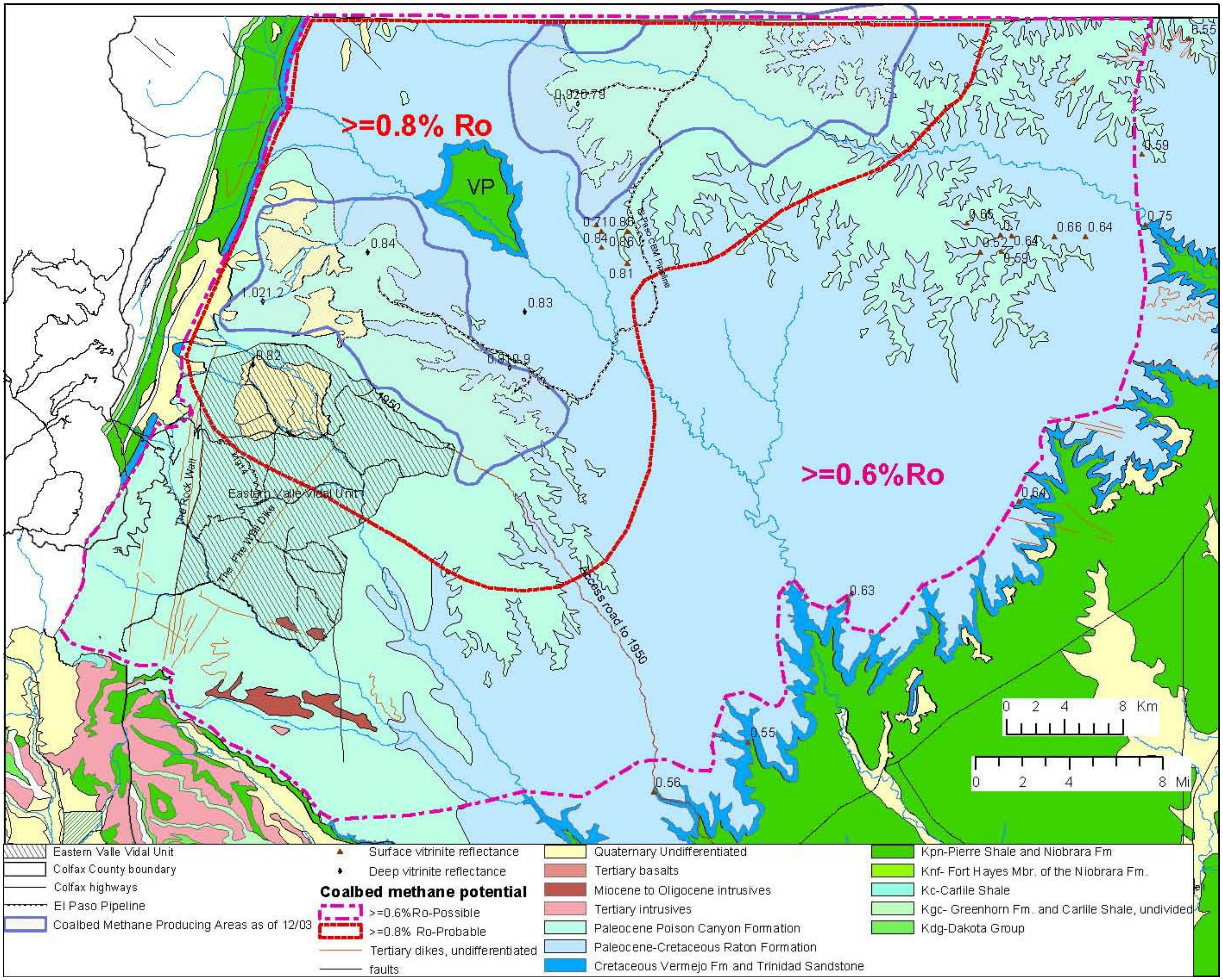

Figure 4.5 Map of vitrinite reflectance (%Ro), a source rock thermal maturity indicator. Area of probable coalbed methane productivity is suggested by thermal maturity contour value ≥0.8 % Ro; area of possible potential for coalbed methane production is suggested by thermal maturity contour value ≥0.6%Ro. 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.

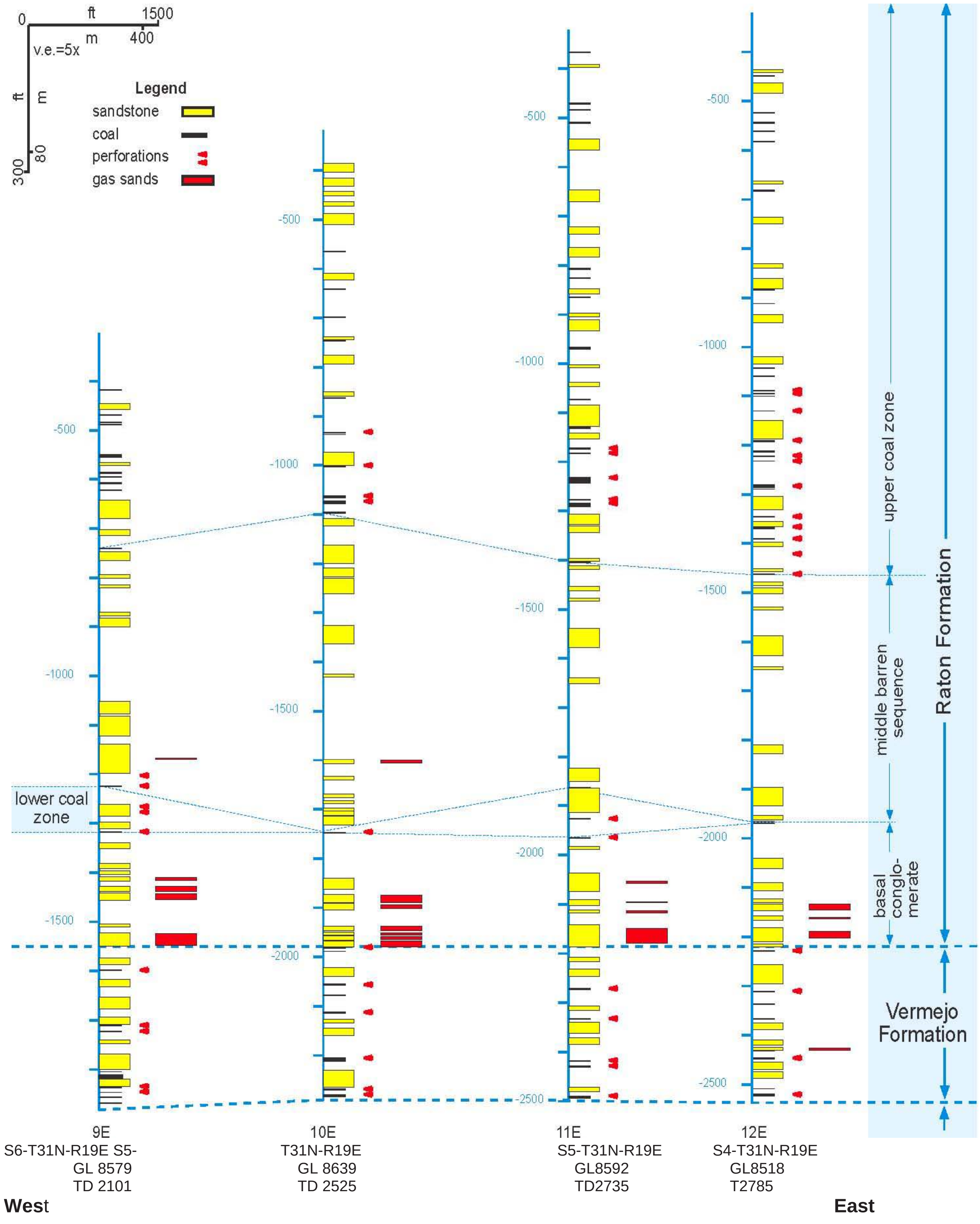

Figure 4.6 Cross section that provides a closer spaced view of the western part of cross section A-A' (Fig. 4.2). Sandstone beds interpreted to be gas charged are indicated by red rectangles. Approximate spacing between wells is ½ mi. See caption for Figure 4.2 for other comments on cross section construction.

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.

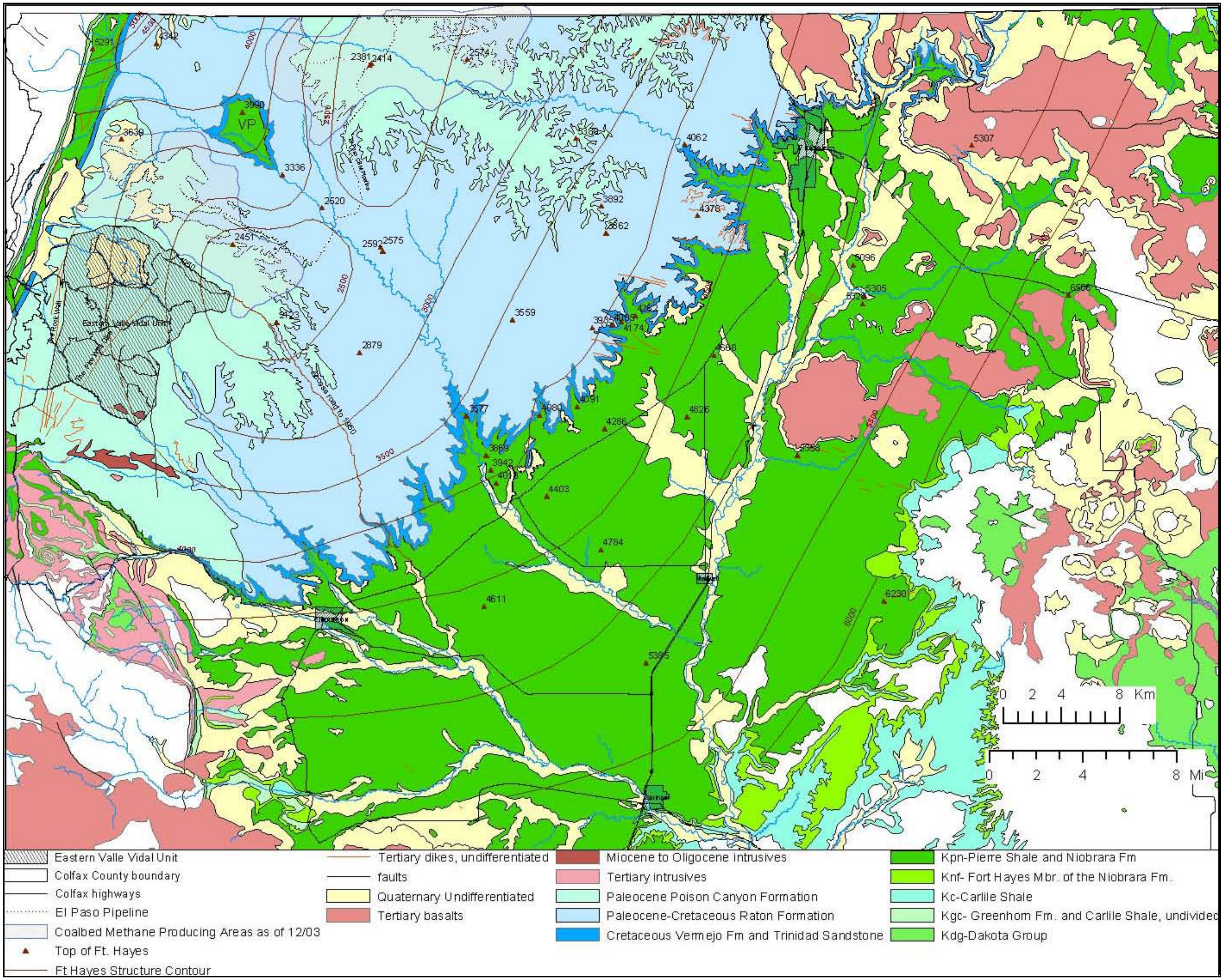

Figure 4.7 Structure-contour map of the top of the Fort Hays Limestone interpreted from well data. VP = Vermejo Park.

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