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Abstract

The Raton Basin became New Mexico's newest natural gas-producing region in 1999 when a new pipeline allowed production of coalbed methane near Vermejo Park, west of Raton. As of May 2003, 256 wells had been drilled and completed, producing more than 22 billion cubic feet of coalbed methane from coals in the Upper Cretaceous to Paleocene Vermejo and Raton Formations. Less than half of the prospective area as delimited by the presence of thermally mature coal has been developed. An extensive geologic data set exists at the New Mexico Bureau of Geology and Mineral Resources including information from coal mining and coalbed methane production. Study of that data set has resulted in better resolution of basin structure and coal thickness, extent, and quality. In addition, potential for production from Raton Formation sandstone reservoirs is indicated for a large area where coal beds are currently being developed.

Introduction

New Mexico's Raton Basin has long been known for its coal resources. Although coal is not being mined today, a number of surface and underground mines operated in the basin during the past century. In 1999 the basin became New Mexico's newest natural gas-producing region. As of May 2003, 256 wells were actively producing methane (CH_4, the most abundant component of natural gas) derived from coal beds in the Upper Cretaceous Vermejo Formation and Upper Cretaceous to Paleocene Raton Formation. Although there is a large area underlain by these formations, the coalbed methane play covers only a small part of Colfax County where geologic conditions are conducive to methane generation and storage in the coal beds.

An exploration and pilot development drilling project conducted by Pennzoil in 1989–1991 demonstrated that a coalbed methane resource existed, but economics and lack of a pipeline prevented the onset of production until 1999. 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. Both entities have worked closely to make the coalbed methane operation today's model for environmentally responsible energy production.

El Paso Raton LLC has provided the state of New Mexico with an extensive data set of Raton Basin well logs and cores, which reside at the New Mexico Subsurface and Core Libraries at the New Mexico Bureau of Geology and Mineral Resources. There is also a significant body of data and literature devoted to the coal resources of the region stored at the bureau's Coal Library. For this paper we reviewed this public data set with the intent to update and summarize what is known about the coal-bearing formations and their associated methane production.

Basin structure

Baltz (1965) provided a thorough description of the Raton structural basin, paraphrased here. The Raton Basin is an elongate, northerly trending, asymmetric structural downwarp formed during the Laramide orogeny (Fig. 1). On its steeply dipping to overturned western flank lies the Sangre de Cristo uplift. To the north are the Wet Mountains uplift and the Apishapa arch. The eastern flank dips gently (less than 3°) westward off 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 formations of the Raton Basin exist only north of the Cimarron arch. Timing of basin formation is indicated by syndepositional structures in the Late Cretaceous to Paleocene coal-bearing units (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 flank. For the New Mexico portion of the basin, a structure-contour map of the top of the Trinidad Sandstone from outcrop and well data delineates the area of interest for coal and coalbed methane (Fig. 2).

Raton Basin exploration history

Coal mining

In most coalbed methane operations, production of water and accompanying depletion of pressure is the mechanism that causes methane gas to desorb from the coal matrix and migrate through the pore system to a producing well. Thus, the presence of both methane and water during coal mining may be an indicator of coalbed methane potential. Mine records also provide valuable information on the stratigraphic complexity of the coal-bearing formations. Variability in coal seam thickness and extent are critical parameters in coalbed methane operations for determining the number of wells, their spacing, drainage efficiency, and their potential economic viability. There are restrictions on the number of wells that can be drilled per square mile in coalbed methane development. Therefore, data and literature originally designed to describe and support coal mining can be a valuable resource in understanding and developing emerging coalbed methane plays like the Raton Basin.

The Raton coal field is defined as the New Mexico portion of the Raton Basin including Upper Cretaceous and Paleocene coal-bearing sequences in the Vermejo and Raton Formations. This field encompasses a highly dissected plateau region, incised by the Canadian and Vermejo Rivers and their tributaries. The eastern margin of the plateau rises over 1,000 ft above the surrounding plain, and access to the coal-bearing units is through canyons created by the drainage systems. The rugged terrain is conducive to underground mining, starting at coal outcrops in canyon walls and tunneling inward either in a room-and-pillar configuration or more recently by longwall mining methods. Surface mining began in the 1960s and is limited to areas of lesser relief in the upper drainages of the Vermejo River. Locations of historic mining districts are shown in Figure 3.

Lee (1924) outlined the coal resources of the Raton coal field in New Mexico and discussed the early mining districts of the area. Coal was discovered as early as the 1820s (Fig. 4). Coal mining for local domestic use began in the 1870s. Beginning in the 1890s with the arrival of railroad transportation, commercial use of the coal included fuel for steam engines, coke for copper smelters in the Southwest, and eventually fuel for electricity generation. In 1955 Kaiser Steel of Fontana, California, acquired a 530,000 acre mineral estate from St. Louis Rocky Mountain Pacific (Kaiser Steel, 1976) that was eventually incorporated as part of the currently productive coalbed methane area. Following the acquisition, Kaiser began an extensive exploration drilling program that determined that the York Canyon region had the greatest potential for development of both underground and surface mining. These drill hole data are an important addition to the data derived from coalbed methane well records.

From 1888 to 2001, 104 million short tons of coal were extracted from the Raton coal field in New Mexico, which is 7% of the

(Text continued on p. 100)

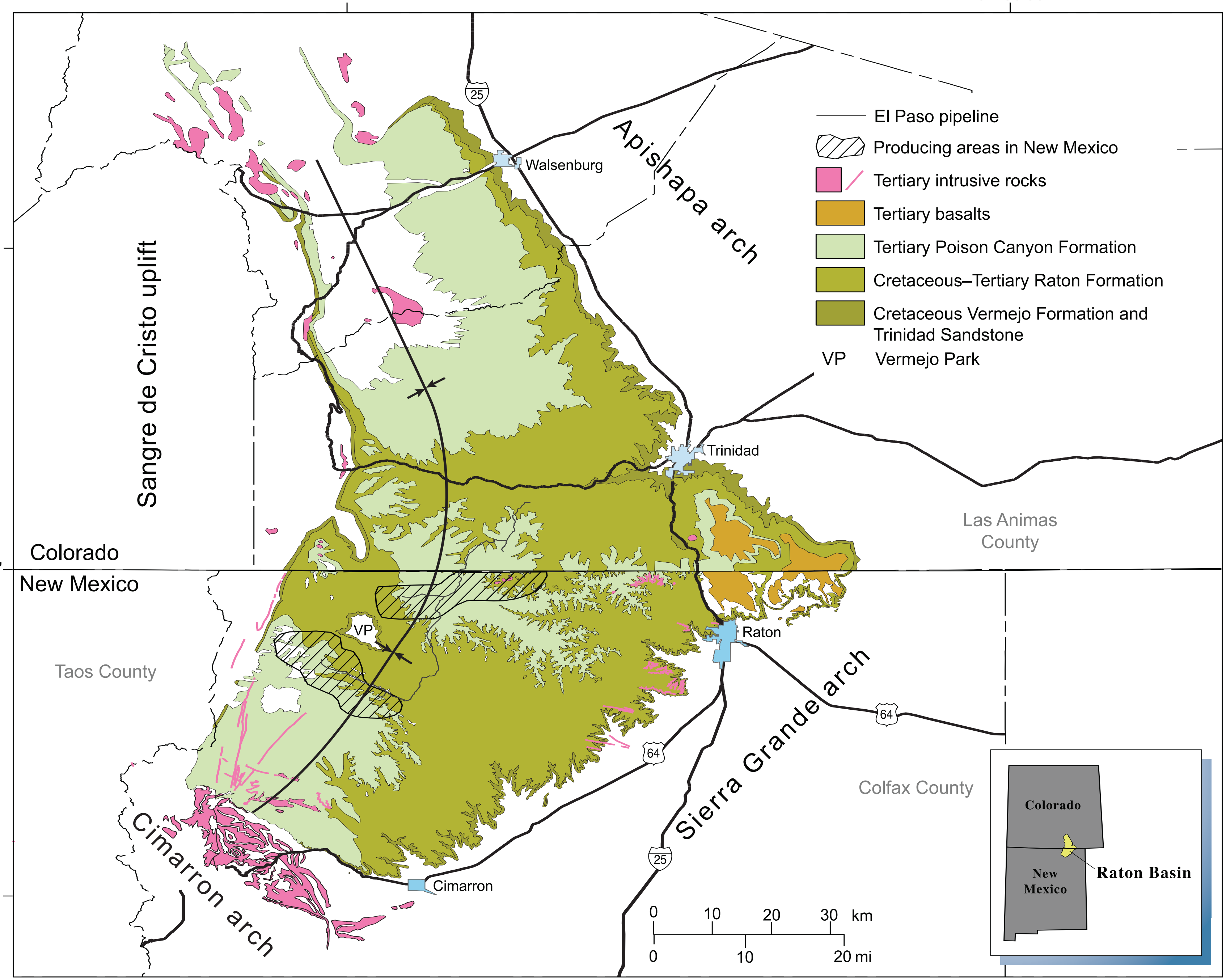

FIGURE 1—Geology and structural features of the Raton Basin, Colorado and New Mexico. Included are coalbed methane-producing areas in New Mexico. Geology derived from New Mexico Bureau of Geology and Mineral Resources (2003) and Tweto (1979).

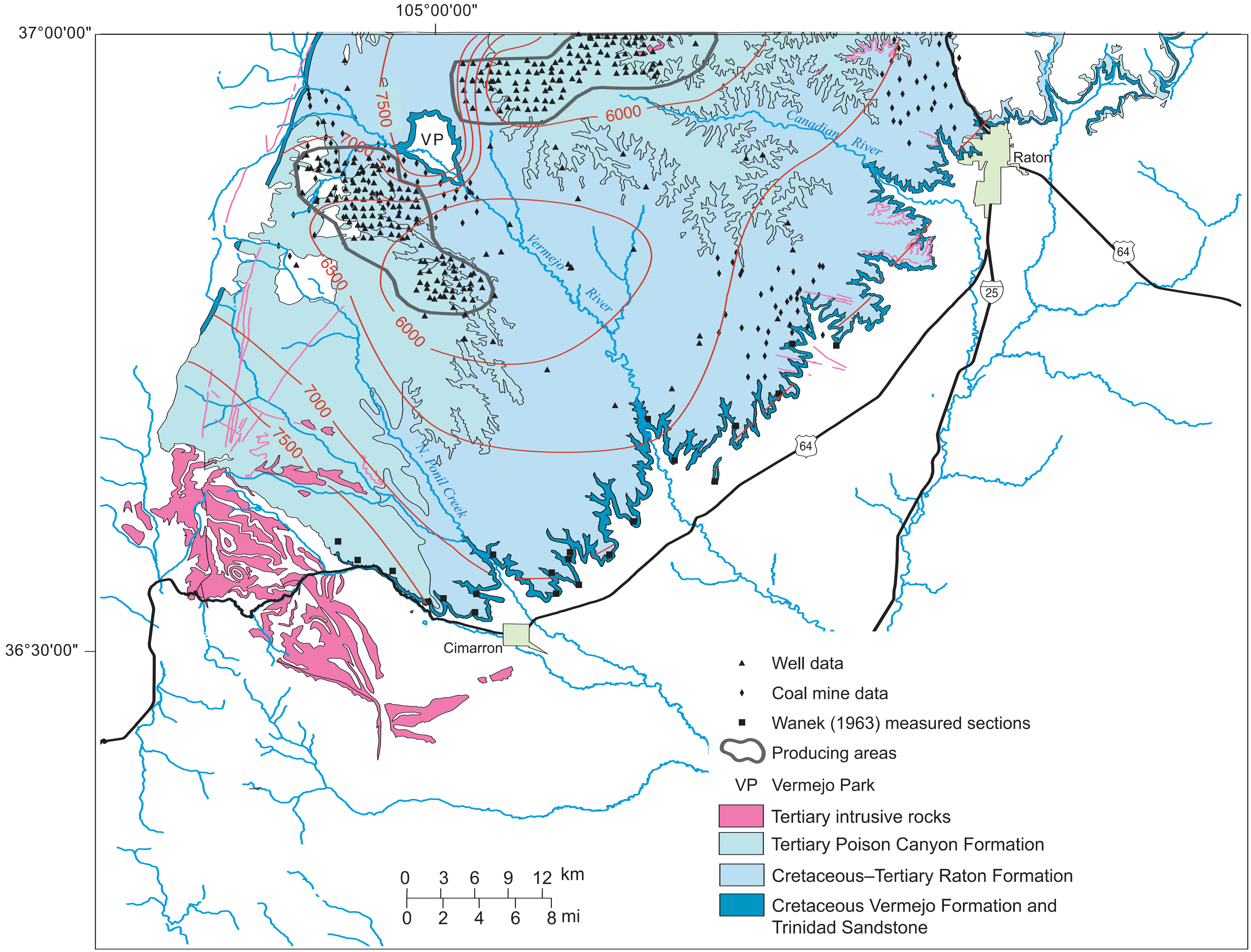

FIGURE 2—Structure-contour map of the top of the Trinidad Sandstone interpreted from well, mine, and surface data. Contour interval = 500 ft.

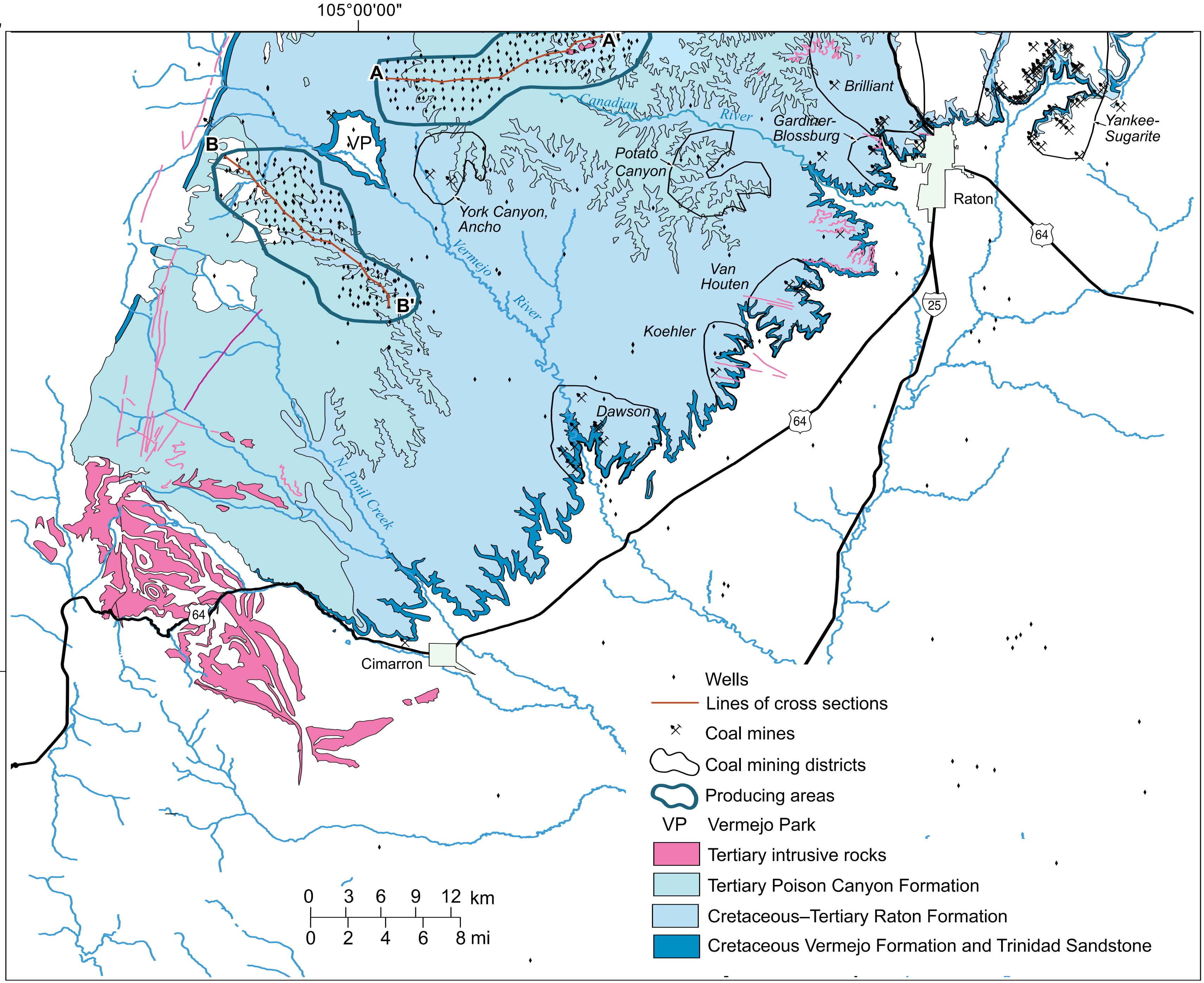

FIGURE 3—Historic mining districts, modified from Pillmore (1991), of the Raton coal field and wells drilled for oil and gas exploration and production. Also shown are lines of cross sections A–A′ (Fig. 6) and B–B′ (Fig. 7).

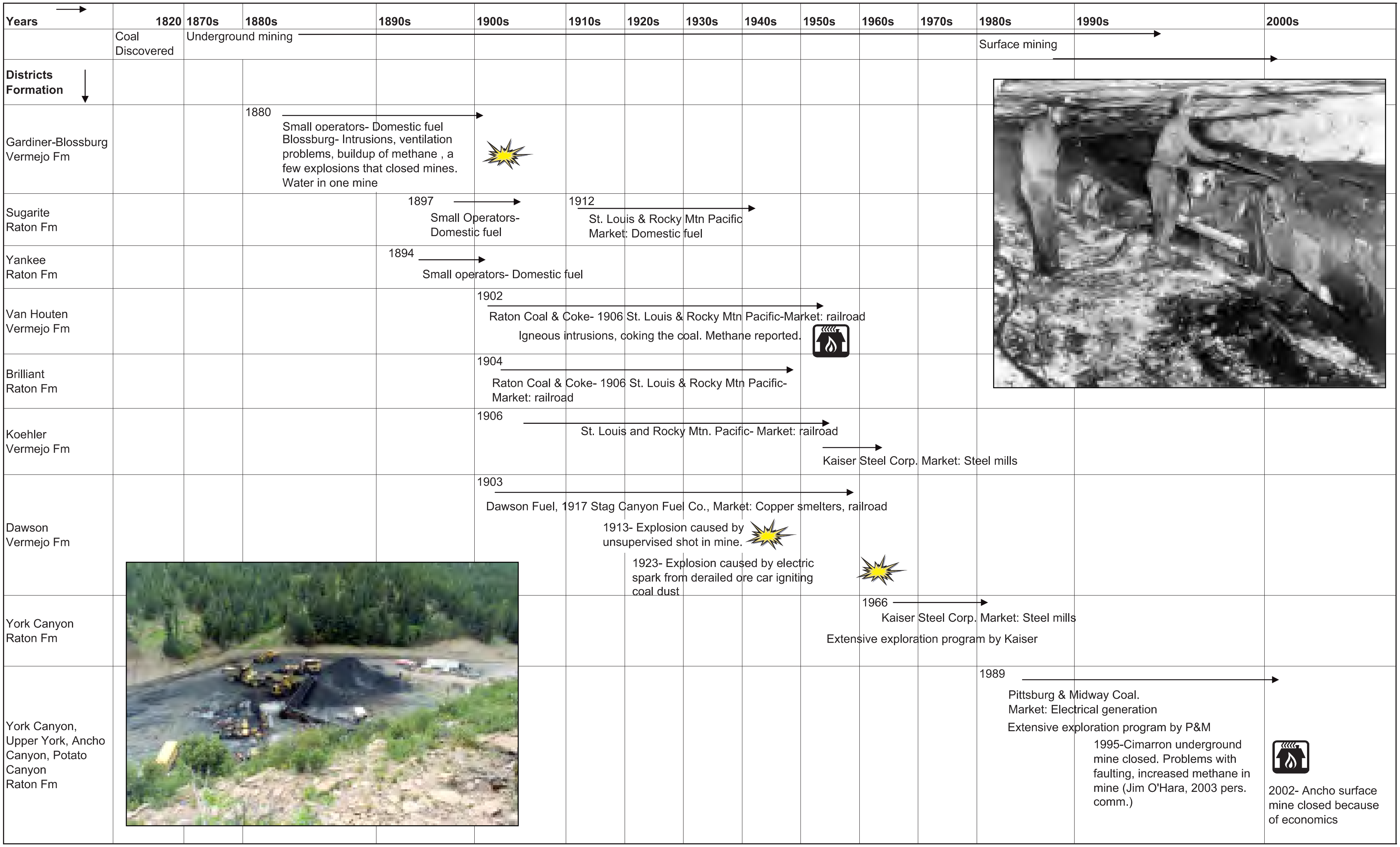

FIGURE 4—Timeline of mining activity and related events in the Raton coal field. **Upper right**—Operator and helper loading coal into shuttle car with joy loader underground at Dawson, New Mexico, ca. 1930. White material is rock dust, applied to roof, ribs, and floor to prevent coal dust explosions. Photo courtesy of Phelps Dodge Corporation. **Lower left**—View from above the longwall entry at Pittsburg and Midway's Cimarron mine (1992). Coal is being brought to the surface by conveyor belt to a small stockpile and transported by truck to the main tipple. Photo by Robert Russell, Energy, Minerals and Natural Resources Department.

estimated 1.5 billion tons demonstrated resource (Pillmore, 1991). Demonstrated resources are based on measured (0–0.25 mi) and indicated resources (0.25–0.75 mi) from a known point, either drill hole or outcrop. Inferred estimates increase the basin resources to more than 9 billion tons. Active mining was suspended in 2002 due to poor economics. Although rail access is available, the cost of mining coal in the area cannot compete with Wyoming coal selling for $5.62/ton (2001). Underground mining has the greatest potential in the Raton coal field; however, the recovery rate for underground operations is less than surface mining, making this method less economic. The coals in the Vermejo and Raton Formations tend to be discontinuous and relatively thin, requiring the mining of multiple seams and further decreasing the economic viability of mining.

There are several important observations to be gleaned from the mining history of the region. With a few notable exceptions, it appears that most mines operated without methane or water production problems. Some of the early mines near Blossburg reported problems with ventilation such that methane accumulating in the mines led to explosions and mine closures. A gas explosion closed another mine located between Brilliant and Blossburg (Lee, 1924). One mine near Blossburg reported problems with water, but pumps were installed and the mine was kept open. Lee (1924) reported methane in some of the Van Houten mines. The underground Cimarron mine was closed because of problems related in part to methane in the mine that would have required overhauling the ventilation system (Jim O'Hara, 2003 pers. comm.).

Dawson had two infamous explosions that killed a sum of 383 miners, but mine inspector reports and Phelps Dodge records suggest ignition of coal dust rather than methane was the cause. Other mining explosions were also attributed to coal dust. An interesting question is, Why were there not more methane problems reported in a basin that would eventually become an important coalbed methane basin? The answer is in part due to the topography and hydrology of the region, which place the outcrop of the Raton and Vermejo Formations in the eastern basin flank well above the regional water table. However, the Cimarron mine and successful coalbed methane production from areas near Vermejo Park are along the water-saturated, deeper axial portion of the basin. Stevens et al. (1992) noted gas contents increase with depth below the potentiometric surface (water table measured in wells) rather than depth from surface. This has negative implications for the viability of coalbed methane development attempts in coal beds within a few miles of their eastern outcrop in the Raton Basin. Thus the area most suitable for the historic mines is the least suitable for current coalbed methane development.

Another lesson learned is that some mines had limited extent because coal bed thickness tends to be highly variable over short distances. Kaiser's and (later) Pittsburg & Midway's extensive exploration drilling programs yielded successful underground and surface-mining operations targeting thick coals over several square miles. This suggests that coalbed methane development in the Raton Basin might benefit from an exploratory phase focused on locating areas of thick coal and perhaps avoiding less-economic blanket-like development of large areas typical in basins with thicker and more extensive coal beds.

Oil and gas exploration

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; 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 in 1991. 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.

Coalbed methane-related literature

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 1 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. A new Raton Basin characterization project is underway at the NMBGMR that includes a GIS-linked digital database. That data will be available as an open-file report in early 2004.

Coal-related stratigraphy

Coal was first reported in the Raton Basin region in 1820 by the Long expedition (Pillmore, 1976). Orestes St. John was one of the earliest geologists to look at the coal resources in the Raton Basin as part of the Hayden survey, later assessing the coal resources for the Maxwell land grant in the 1870s (Pillmore, 1976). Willis T. Lee, employed by the U.S. Geological Survey, did extensive geologic work in the basin, as reported in his 1917 and 1924 publications. Knowlton (1917) investigated the fossil flora in the Vermejo and Raton Formations, helping to define the ages of these formations. Wanek (1963) published a map with text on the coal resources of the southern Raton coal field. Pillmore began mapping several quadrangles in the Raton field in the 1960s and published a comprehensive paper (1969) on the coal deposits, drawing on previous work and access to coal data from Kaiser Steel. He defined significant coal beds or zones in the Vermejo and Raton Formations within the coal field and specified geographical areas where these coal zones exist. Pillmore and Flores (1987) published several papers together, separately, and with other co-authors through the 1980s on the sedimentology of the Raton Basin and the location of the Cretaceous–Tertiary boundary within the lower coal zone of the Raton Formation.

See Baltz (1965) for a comprehensive summary of the stratigraphy of the region. The coal-bearing sequence in the Raton Basin is underlain by the Trinidad Sandstone. As thick as 130 ft (40 m), 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 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 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 (107 m) 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 unconformably overlies the Vermejo Formation. 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 (3- to 9-m-thick) pebble conglomerate to granule quartzose sandstone eroded into the Vermejo Formation. Overlying the basal conglomerate, the 100- to 300-ft-thick (30- to 91-m-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 (50 to 183 m 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), in part because of vegetative cover, but also 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.

Flores (1987) recognized three upward-coarsening megacycles in the Vermejo, Raton, and Poison Canyon Formations. The Vermejo Formation to the basal Raton conglomerate represents the first megacycle; the lower coal zone and middle barren sequence in the Raton represent the second, and the third megacycle consists of the upper coal zone of the Raton and the Poison Canyon Formation. These megacycles apparently record local Late Cretaceous to Paleocene tectonic pulses affecting the basin and adjacent uplift.

Coal thickness and continuity

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. For this study, we examined well logs throughout the area at a density of one well per square mile where available, recording thickness of coal beds ≥ 1 ft (0.3 m) 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 evaluation 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 entire Raton Formation was not recognized in the open-hole geophysical logs because wells are cased to the 300-ft (91-m) 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 (0.3 m) to > 10 ft (3 m) from these same data indicates 84% of Raton coals are 1–3 ft (0.3–1 m) thick, whereas 73% of Vermejo coals are in this same thickness range. Vermejo coals 5 ft (1.5 m) thick or greater make up about 8% of the data set, and Raton coals 5 ft (1.5 m) thick or greater account for 3% of the data set.

Vermejo Formation

Because the Vermejo Formation contains some of the thickest coals in the Raton

TABLE 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 1,400 ft (427 m) of section from base of Raton. Vermejo coal picks from logs with base of Raton and top of Trinidad.

	Total coal thickness ft (m)		Number of seams		Average seam thickness per well ft (m)	
Formation	**Raton**	**Vermejo**	**Raton**	**Vermejo**	**Raton**	**Vermejo**
Average	27 (8.2)	17.47 (5.32)	15	7	2 (0.6)	2.5 (0.76)
Maximum	66 (20)	41.50 (12.6)	30	17	3.2 (0.9)	5.5 (1.7)
Minimum	8 (2.4)	4 (1.2)	4	2	1.2 (0.4)	1.5 (0.4)
Well count	59 (18)	133 (40.5)				

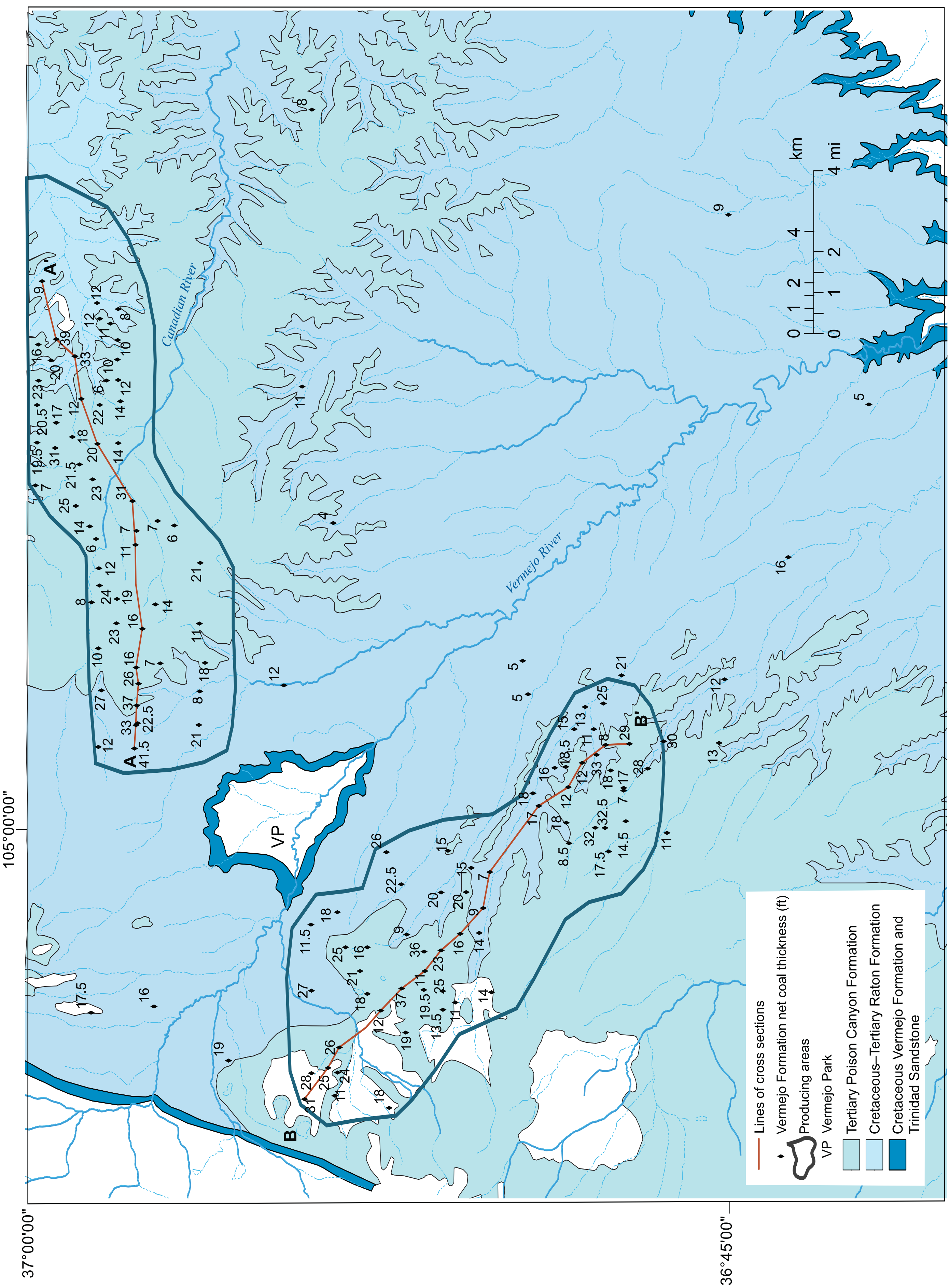

FIGURE 5—Vermejo Formation net coal thickness interpreted from geophysical logs of wells with complete Vermejo section.

Basin, these were the predominant coals being mined in the early period of mining along the eastern edge of the basin. Figure 5 is a map of net Vermejo Formation coal derived from well log interpretation (sum of Vermejo coal beds ≥ 1 ft [0.3 m] thick, wells with complete section of Vermejo). In the wells examined, net Vermejo coal ranges from 4 to 41.5 ft (1.2 to 12.6 m) supporting observations from surface work and mining that describe lenticularity of coal beds and associated variability in individual coal bed thickness. Figure 5 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 19 ft (5.8 m) net thickness for the southwestern area (62 wells) and 18 ft (5.5 m) net thickness for the northeastern area (57 wells). Several wells on the map fall outside the producing areas (thus 133 wells total).

Figures 6 and 7 are stratigraphic cross sections based on wells spaced approximately ¾ to 1 mi (1.2 to 1.6 km) 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 ½ mi (0.8 km) spaced wells. 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 and was an obvious target for past mining.

Raton Formation

The lower coal zone of the Raton Formation has several thin lenticular coals of little importance for mining; however, a lower-zone coal was mined at Sugarite in the eastern part of the coal field. These lower-zone coals have been completed in many coalbed methane wells. The upper coal zone has more economic potential for mining and coalbed methane as it tends to have some lateral continuity. The York Canyon coal bed in the upper coal zone averages 5–6 ft (1.5–2 m) thick and was the principal bed mined at the York Canyon complex. In the Upper York or Left Fork district where the Cimarron underground mine operated (Fig. 3), there are two coals that range in thickness from 3.5 to 11 ft (1–3.4 m).

Figure 8 is a map of net Raton Formation coal from well log interpretation (sum of Raton coal beds ≥ 1 ft [0.3 m] thick, wells with a minimum of 1,400 ft [427 m] 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 66 ft (2.4 to 20 m) thick. Wells examined that are encompassed by the two producing areas average approximately 24 ft (7 m) net thickness for the southwestern area (29 wells) and 29 ft (9 m) 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 6 and 7 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.

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 (%R_o—a method to estimate thermal maturity) increases to 0.6–1.0, and the moisture content of the coal decreases.

Some unpublished %R_o data are available for the Raton Basin in addition to the published data. 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 9 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 %R_o. Given that coal is primarily a gas-prone source rock and that thermogenic gas generation becomes significant at approximately 0.8 %R_o, these areas probably have little potential for coalbed methane as they are relatively thermally immature and above the water table. The northwest corner of the Raton coal area has the greatest coalbed methane potential, because %R_o is greater than 0.8 and much of the coal lies below the water table.

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. There is evidence from fission track studies that approximately 1 km (0.62 mi) of denudation has occurred in the Vermejo Park region since the Miocene (Hemmerich, 2001). 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 fluids (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.

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 where vitrinite reflectance exceeds 1.1 %R_o. However, all of the gas producing wells have a lesser %R_o in the two producing areas that we have examined, and many of these show evidence of gas saturation in some sandstone beds, most commonly in the basal part of the Raton Formation. 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 10 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 (2 m) in thickness and coal beds ≥ 1 ft (0.3 m) thick, and indicates which sands have the well log gas effect. These wells are spaced only ½ mi (0.8 km) 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.

Summary of current coalbed methane operations

Coalbed methane wells in the Raton Basin in New Mexico produce from three statutory pools: Stubblefield Canyon (Raton–

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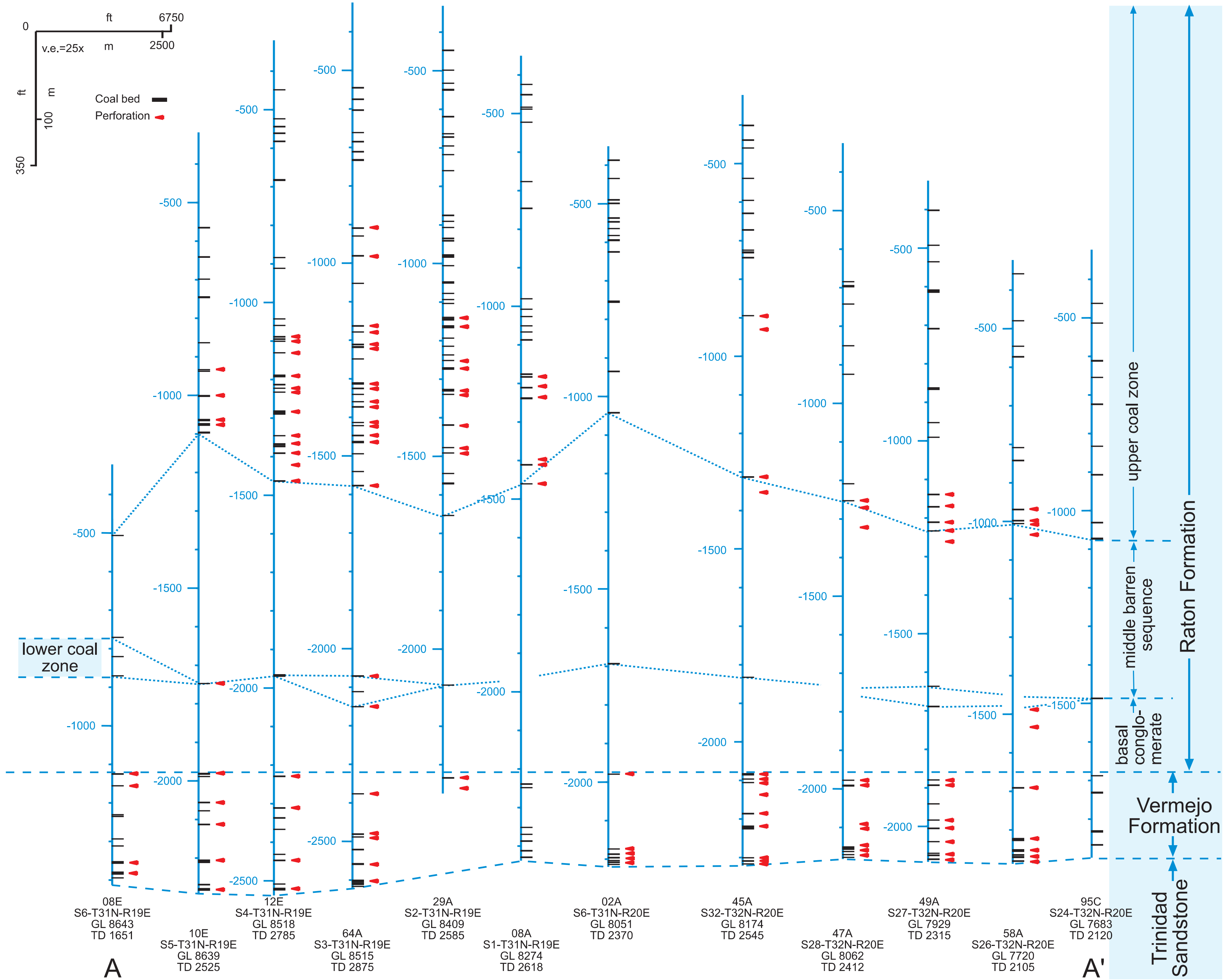

FIGURE 6—Cross section A–A′ (west to east). Approximate spacing between wells is 1 mi (1.6 km). Line of cross section shown on maps in Figs. 3, 5, and 8. Wells arranged such that the top of the Vermejo Formation is the stratigraphic datum. The top of the Trinidad Sandstone is the base of the well columns. 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 in the well that have been targeted for production.

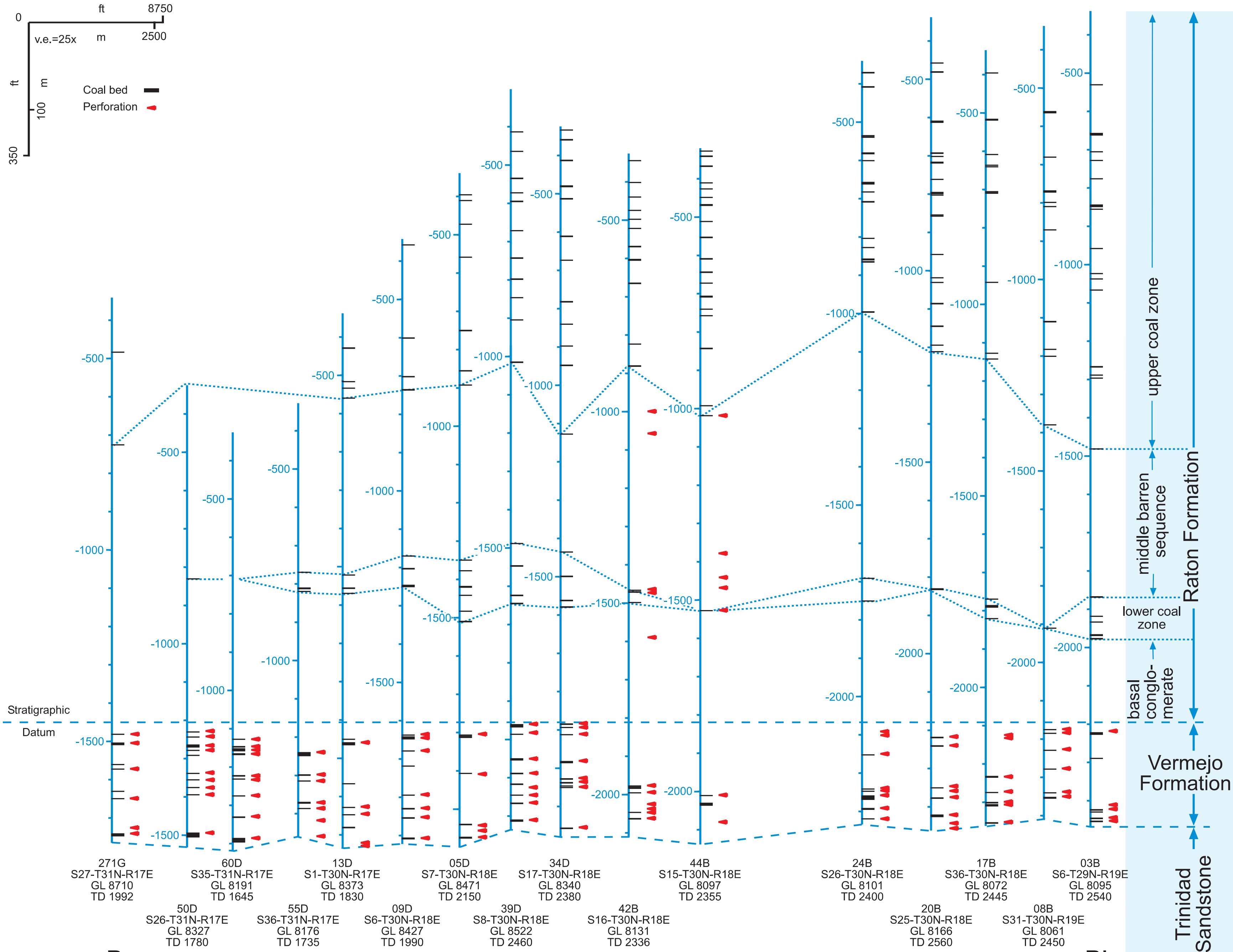

FIGURE 7—Cross section B–B′ (west to east). Approximate spacing between wells is ¾ mi (1.2 km). Line of cross section shown on maps in Figs. 3, 5, and 8. See caption for Fig. 6 for comments on cross section construction.

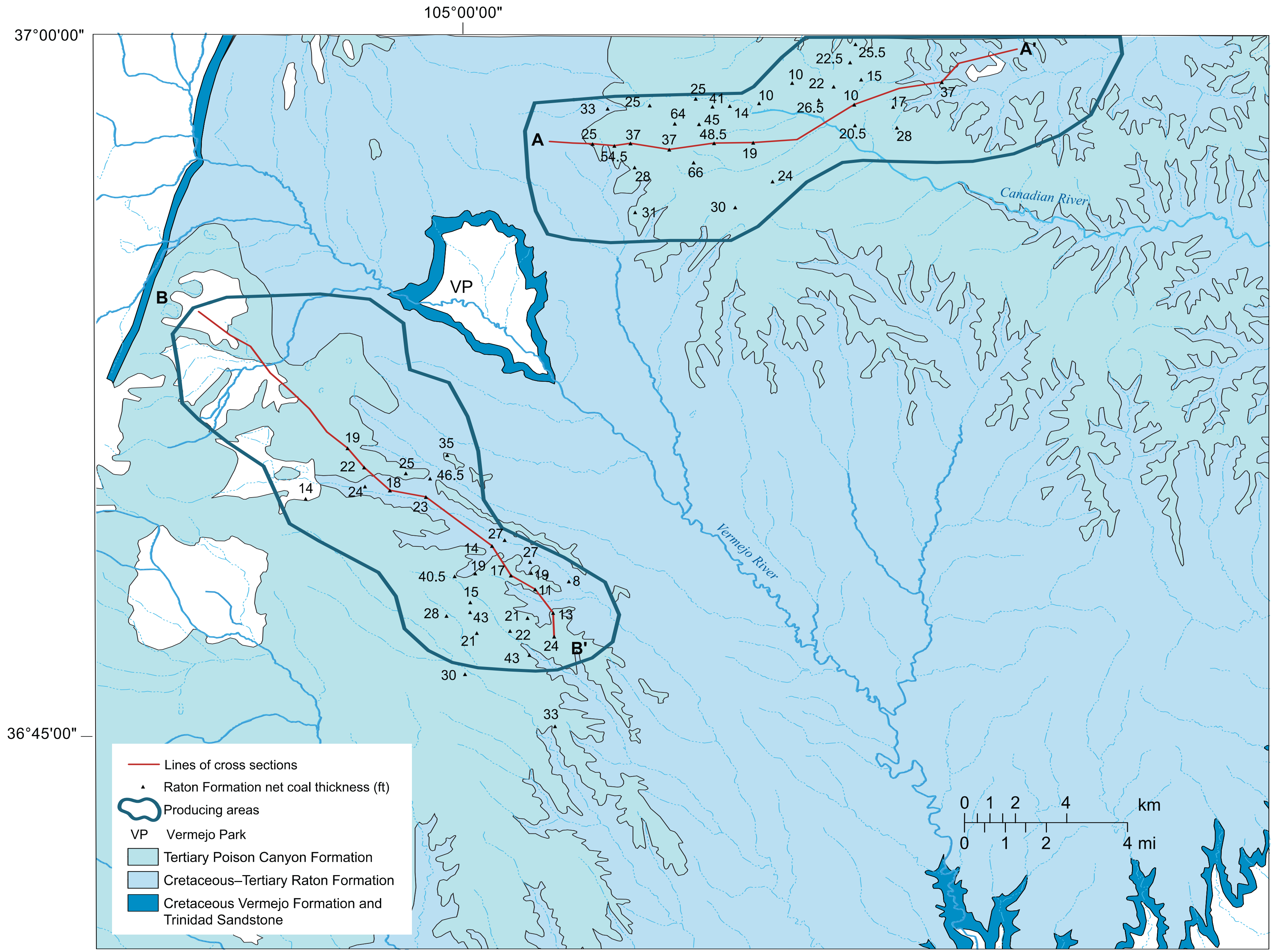

FIGURE 8—Raton Formation net coal thickness interpreted from geophysical logs. Wells included only where 1,400 ft (427 m) or more of Raton Formation was logged.

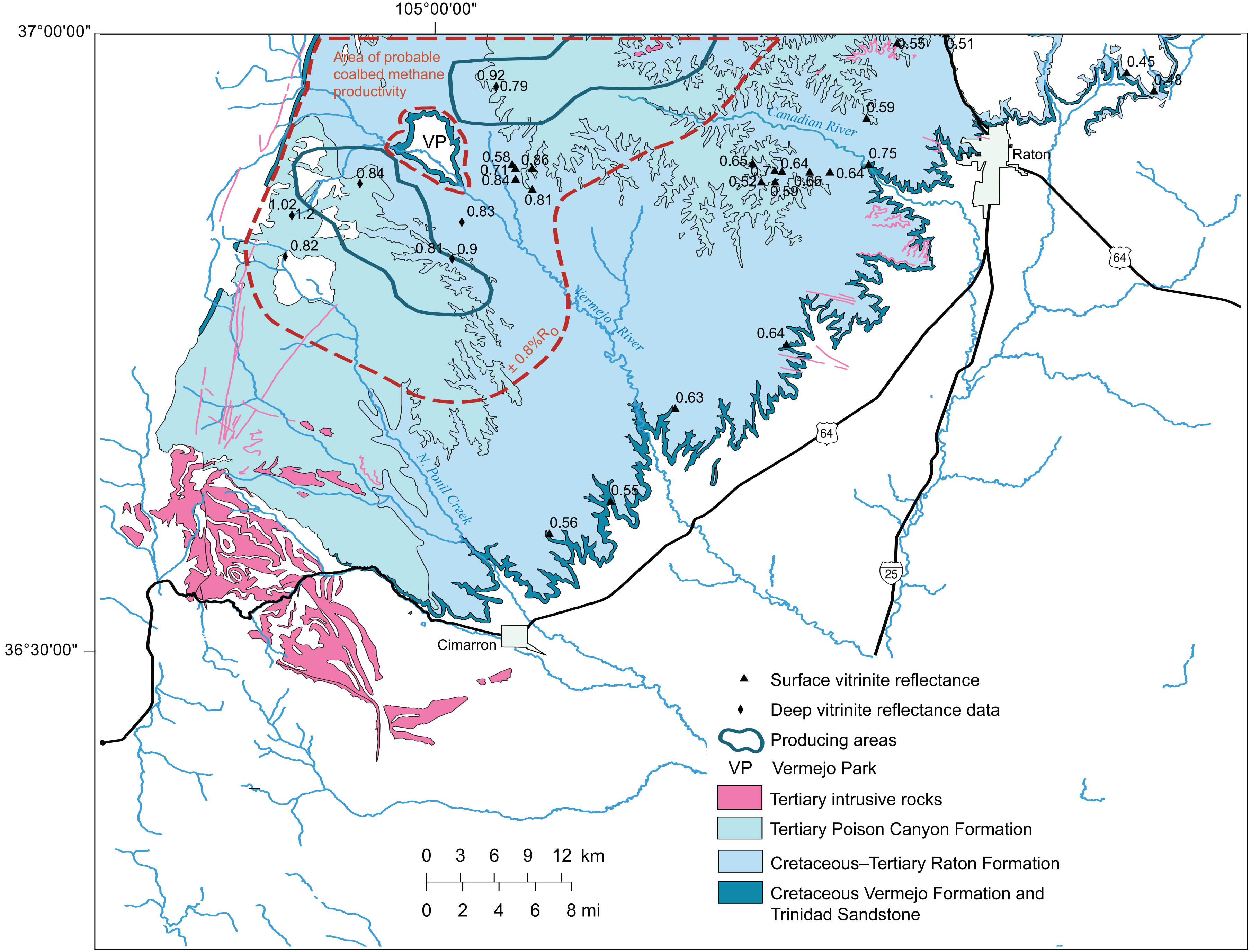

FIGURE 9—Map of vitrinite reflectance (%R_o), a source rock thermal maturity indicator. Area of probable coalbed methane productivity is suggested by contour value ± 0.8%R_o. Points depicted include only raw data that have not been adjusted for depth.

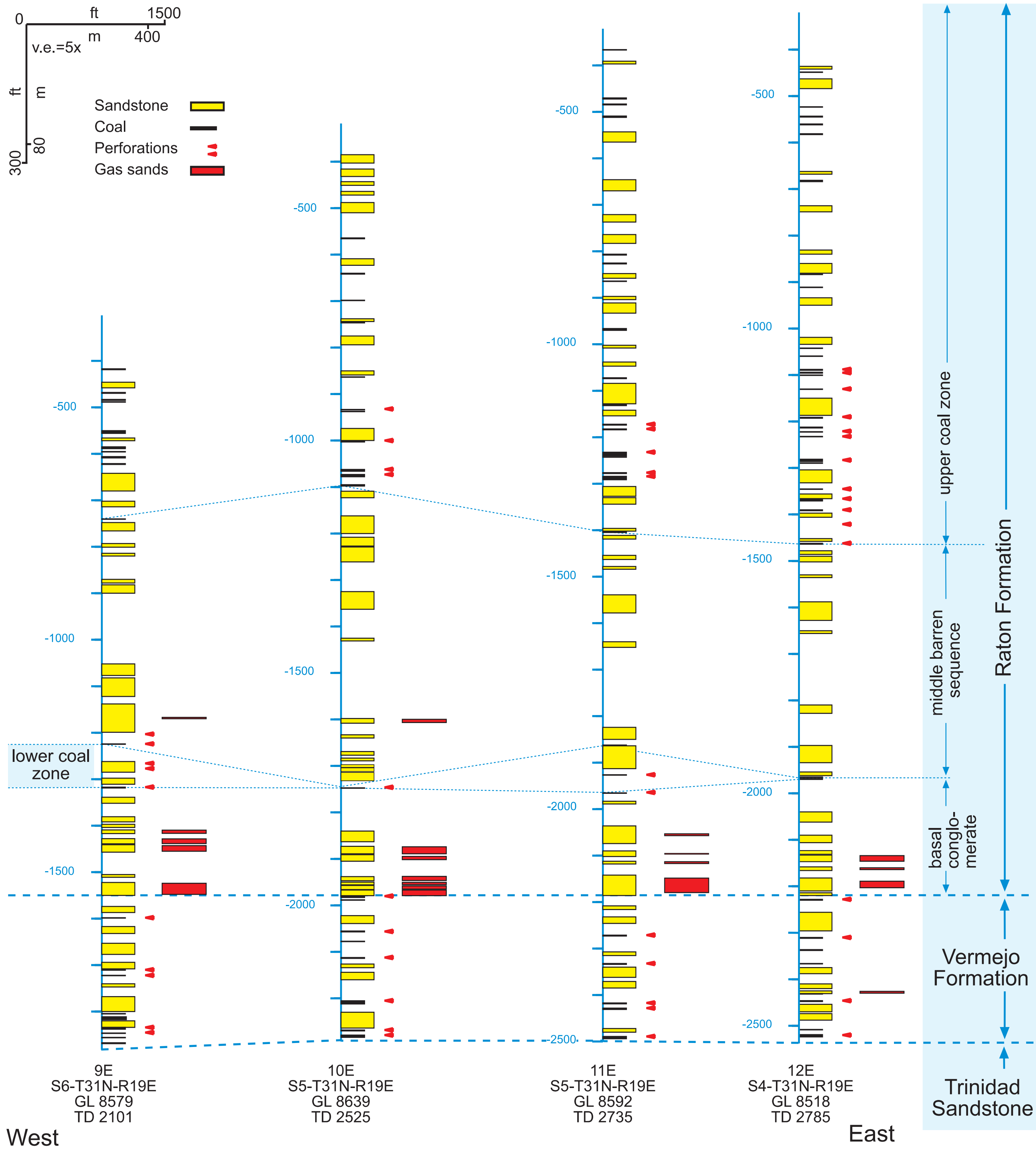

FIGURE 10—Cross section that provides a closer spaced view of the western part of cross section A–A′ (Fig. 6). Sandstone beds interpreted to be gas charged are indicated by red rectangles. Approximate spacing between wells is ½ mi (0.8 km). See caption for Fig. 6 for other comments on cross section construction.

Vermejo), Van Bremmer Canyon (Vermejo), and Castle Rock Park (Vermejo). The formation names that are a part of the official pool names do not accurately reflect the formations from which coal beds are producing in all wells in these pools. For this paper, pool boundaries are artificial subdivisions. All currently producing pools are located on the Vermejo Park Ranch in Colfax County.

To date 256 producing wells have been drilled and completed as coalbed methane gas producers. However, drilling is continuing, and the field is expected to expand rapidly beyond the producing areas shown on our maps. The ultimate density of wells and the areas developed on the Vermejo Park Ranch are limited by con-

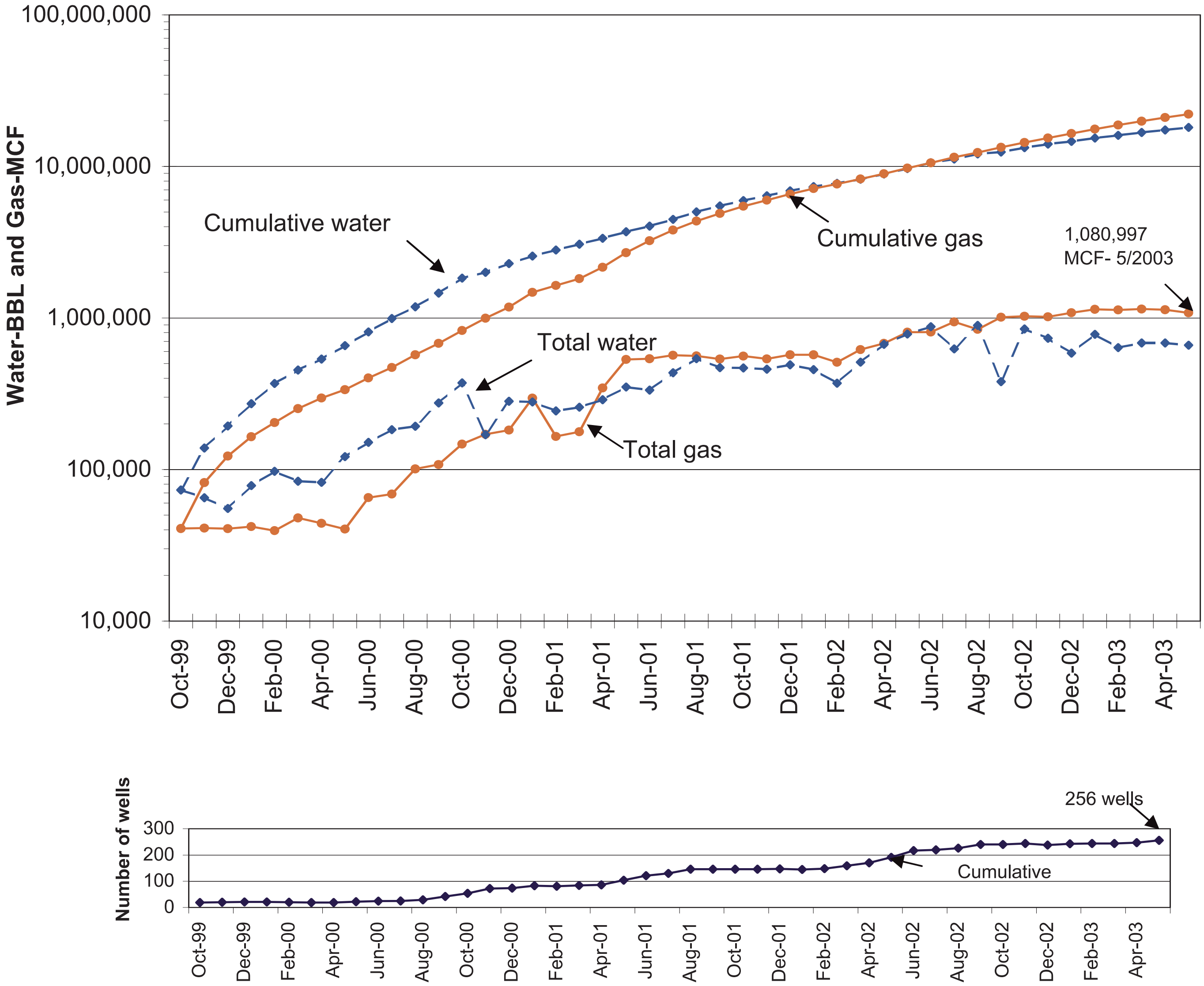

FIGURE 11—Graph of gas and water production for Colfax County, New Mexico, current through May 2003. Data include cumulative production, monthly production, and cumulative number of active wells versus date.

tractual agreement between the mineral and surface owners in the interest of environmental preservation. Operations are coordinated carefully with the Vermejo Park Ranch and the New Mexico Oil Conservation Division, which has regulatory jurisdiction over drilling on privately owned lands within the state. Drilling and other operations are planned so that they lessen the impact on other surface activities of the Vermejo Park Ranch. Spacing of wells is approximately 160 acres per well, equating to approximately ½ mi (0.8 km) between wells. The footprint of well pads is about ½ acre (2,024 m^2). Large areas with coalbed methane reserves are left undeveloped to preserve critical habitat for elk and bison herds. Wells are rarely noticed when driving the main roads on the ranch. Wells, roads, pipelines, and other infrastructure are located and constructed to minimize surface impacts, and pipeline right-of-ways are quickly reclaimed. Water and gas are piped to central facilities where gas is compressed for pipeline transport and water is disposed of by deep saline aquifer injection, a manner approved by the New Mexico Oil Conservation Division. Wells and gas compressors are equipped with electric motors to minimize noise and emissions.

In general, the coalbed methane wells are drilled to the top of the Pierre Shale (at a depth of approximately 2,200 ft [670 m]). The casing and cementing program is designed to protect shallow ground water (to approximately 300 ft [91 m]), yet allow most of the Raton and Vermejo coal beds to be completed together. Following geophysical logging, steel production casing is run to total depth and then cemented into place. The casing is then perforated at each coal bed below 1,000 ft (305 m; for many but not all wells), and the coals are stimulated by hydraulic fracturing, a procedure to create and prop open fractures that typically uses more than 100,000 lb (45,000 kg) of quartz sand carried by nitrogen and fresh water-based foam. Sandstone beds, even those with gas shows, have been mostly avoided to date, perhaps because of concerns about excess water production. However, at least one sandstone test is now producing, and others are likely to follow.

Figure 11 depicts total production of methane and related water for Colfax County, New Mexico. As of May 2003 the field was producing more than 1 billion cubic feet (Bcf) per month. More than 22 Bcf has been produced since inception in October 1999. This activity benefits the economy of Colfax County and the state of

New Mexico through severance (and other) taxes and employment. As the play matures it will continue to have a growing economic impact.

Conclusion

It is too early to predict the life span and ultimate recovery of the current coalbed methane development efforts in Colfax County, New Mexico. The longest-producing wells (since October 1999) have accumulated 0.12 Bcf on average per well to date or an average of approximately 0.5 Bcf per square mile. At present, the developed acreage covers about half of the area where production potential appears to be favorable.

Increases in production volume have been tied closely to stages of development drilling. Future volume increases will require some development of private and public lands not drilled to date. Given the geologic complexity of the coal-bearing sequences, it seems unlikely that the current density of wells is the most efficient for reserve recovery. Therefore, reserves may eventually grow through targeted infill drilling of vertical or horizontal wells. It is clear that initial coalbed methane development in the New Mexico portion of the Raton Basin has been successful in terms of both technical and economic benchmarks and that development will continue to expand in the coming decade.

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