Attachment 9
The Raton Basin

The Raton Basin covers an area of about 2,200 square miles in southeastern Colorado and northeastern New Mexico (Figure A9-1). It is the southernmost of several major coal-bearing basins along the eastern margin of the Rocky Mountains. The basin extends 80 miles north to south and as much as 50 miles east and west (Stevens et al., 1992). It is an elongate asymmetric syncline, with 20,000 to 25,000 feet of sedimentary rock in the deepest part. Coalbed methane resources in the basin, which have been estimated at approximately 10.2 trillion cubic feet (Tcf), are contained in the upper Cretaceous Vermejo Formation and upper Cretaceous and Paleocene Raton Formation (Stevens et al., 1992). In 2000, the average gas production rate per well in the Raton Basin was close to 300,000 cubic feet per day, and annual production was 30.8 billion cubic feet (Bcf) (GTI, 2002).

9.1 Basin Geology

The Raton structural basin is an asymmetric synclinal sedimentary basin containing sedimentary rocks as old as Devonian overlying basement Precambrian rocks, with Holocene sediments at the surface. The coal occurs in the Vermejo and the Raton Formations, which overlie the Trinidad Sandstone, a basin-wide regressive marine sandstone (Figure A9-2). The Vermejo and Raton Formations consist of deltaic lower coastal plain and fluvial deposits (Flores and Pillmore, 1987). Numerous discontinuous and thin coalbeds are located in the Vermejo Formation and the Raton Formation, which overlie the Trinidad Sandstone (Figure A9-3). The top of the Trinidad Sandstone forms the lower boundary of the Raton coal basin as shown in Figure A9-1. Development of coalbed methane wells has focused on development of the Vermejo coals rather than the Raton coals because the former are thicker and more abundant. The coalbeds are of limited extent and cannot be correlated over more than a few miles.

Individual coalbeds in the Vermejo Formation range from a few inches to about 14 feet thick, and total coal thickness typically ranges from 5 to 35 feet. An isopach map of total coal thickness in the Vermejo Formation, based on 92 well logs and measured sections, was published by Stevens et al. (1992) (Figure A9-4). Total coal thickness in the Raton Formation ranges from 10 feet to greater than 140 feet, with individual seams ranging from several inches to greater than 10 feet thick. Although the Raton Formation is much thicker and contains more total coal than the Vermejo Formation, individual coal seams in the Raton are less continuous and generally thinner. Additionally, because of extensive erosion of the Raton Formation, particularly in the eastern part of the basin, much of the original coal is no longer present (Stevens et al., 1992). Between 5 and 15 individual coalbeds produce coalbed methane for wells in the basin (Hemborg, 1996).

Middle Tertiary igneous intrusions are present in the central part of the basin (Steven, 1975). Sills and dikes have invaded sediments of the basin including both the Vermejo and Raton Formations. Sills have intruded along the coal seams destroying tremendous quantities of coal (Carter, 1956).

Coal seam depth is an important variable used to estimate gas production potential. Figure A9-5 is a thickness of overburden map from Stevens et al. (1992). The map shows the depth below land surface to the midpoint depth of the coal-bearing interval, using coal thickness as a weighting factor. Overburden thickness ranges from less than 500 feet near the basin perimeter to greater than 4,100 feet in the deep northwestern part of the basin. Many of the differences in thickness of overburden can be attributed to variations in topography and are thus a consequence of erosion and not necessarily subsurface geologic structure.

Stratigraphic cross-sections constructed to illustrate the regional subsurface geologic structure and the distribution of coal seams and igneous intrusions, as well as the areal locations of these cross-sections, are shown in Figures A9-6 through A9-8. The cross-sections use the top of the Trinidad Sandstone as the horizontal datum. The Vermejo Formation has a relatively uniform thickness of about 350 feet throughout the basin. The Raton Formation varies from about 0 to 2,100 feet thick. It grades westward into and is overlain by the conglomeratic Poison Canyon Formation (Flores, 1987; Flores and Pillmore, 1987).

A study of the relationship between coal cleat orientation and the compression stresses due to tectonic forces can indicate areas likely to have increased coal seam permeability and provide increased coalbed methane yield (Stevens et al., 1992). Cleats, or small-scale fractures in the coal, are commonly oriented perpendicularly to the maximum stress. These fractures tend to expand, thereby providing greater permeability and coalbed methane yields on the axes of the anticlines, such as the Vermejo Park anticline. Wells drilled near the axis of the La Veta syncline, in contrast, did not encounter adequate permeability (Stevens et al., 1992). Initially it was thought that sills that intrude along the bedding plane of the coal seams would reduce methane production, but several operators have noted that elevated methane contents have sometimes been measured in coal seams that have been intruded by igneous rocks (Stevens et al., 1992).

9.2 Basin Hydrology and USDW Identification

Regional groundwater flow in the Raton Basin is dependent on geologic structure and topography. Regional flow is generally down-slope from west to east or southeast (Figure A9-9). In the northern part of the basin, however, flow is radial away from Spanish Peaks (Howard, 1982; Geldon, 1990). Additionally, along the eastern margin of the basin, sediments dip to the west and groundwater flow is locally down-dip to the west. While recharge occurs primarily at elevations greater than 7,500 feet, discharge is mainly through streams and by evapotranspiration in the central and eastern parts of the basin.

Principle bedrock aquifers in the basin are the Cuchara-Poison Canyon, the Raton-Vermejo-Trinidad, the Fort Hayes-Codell, the Dakota-Purgatoire, and the Entrada (Geldon, 1990) (Figure A9-3). The pressure regime in the basin is poorly understood. Under-pressured conditions, or hydraulic heads in deep bedrock aquifers that are lower than those in shallow formations, appear to exist throughout much of the basin (Howard, 1982; Geldon, 1990; Tyler et al., 1995). This hydraulic head difference suggests that the deep bedrock aquifers are not in communication with shallow formations. Meteoric circulation, however, is indicated by the regional freshness of the produced waters (Stevens et al., 1992; Tyler et al., 1995).

All of the water produced along with coalbed methane in the Raton Basin has a total dissolved solids (TDS) content of less than 10,000 milligrams per liter (mg/L) (the water quality criterion for an underground source of drinking water (USDW)), and the aquifers from which the gas is produced meet the water quality criterion for a USDW (National Water Summary, 1984). A scatter diagram of potentiometric head versus TDS from coalbed methane wells in the Raton Basin (Figure A9-10) shows little correlation between potentiometric head and water quality. More importantly, this figure shows that all of the water had less than 10,000 mg/L of TDS, nearly all had a TDS of less than 2,500 mg/L, and more than half had a TDS of less than 1,000 mg/L. Two producers used injection wells for disposal, but operating permits issued to one gas producer (Evergreen Resources, Inc.) by the Colorado Department of Public Health and Environment allowed discharge of produced water into streambeds and stock ponds, indicating that the water was not too saline for surface discharge. Hemborg (1998) suggests that the wells yielding larger quantities of groundwater might be connected to the underlying water-bearing Trinidad Sandstone.

9.3 Coalbed Methane Production Activity

Hydraulic fracturing employed for enhancement of coalbed methane production is designed to enable gas within the rock to flow more readily to an extraction well. Coalbed methane well stimulation using hydraulic fracturing techniques is a common practice in the Raton Basin. Records show that fluids used are typically gels and water with sand proppants.

Hemborg (1996) reported that the average water production from coalbed methane wells in the Raton Basin was 700 barrels per million cubic feet (Mcf), and average daily production for 42 wells in the Spanish Peak Field was 0.309 Mcf (Hemborg, 1998). Conversion of these rates from coalbed methane industry units to those commonly used for water supplies gives an average water production rate for those wells of only 6.3

gallons per minute. These rates are generally not considered sufficient for public water supply or irrigation; however, they meet the water supply volume criterion for a USDW.

Hemborg (1998) showed that in most cases water yield decreased dramatically as coalbed methane production continued over time (Figure A9-11). However, some wells exhibited increased water production as coalbed methane production continued or increased over time (Figure A9-12). Two causal factors were suggested (Hemborg, 1998) for the rise in water production:

1. Well stimulation had increased the well's zone of capture to include adjacent water-bearing sills or sandstones that were hydraulically connected to recharge areas; or

2. Well stimulation had created a connection between the coal seams and the underlying water-bearing Trinidad Sandstone.

The Trinidad Sandstone is a bedrock aquifer confined by the Pierre Shale below and the shales and siltstones of the Vermejo Formation above (Figure A9-2). The Trinidad Sandstone exhibits low vertical and horizontal permeabilities of 0.186 and 0.109 meters per day, respectively, as reported by Howard (1982) in Stevens et al. (1992). One gas company reported that lower water production and improved gas production were achieved by avoiding known water-bearing horizons and by selectively completing the coal zones (Quarterly Review, 1993).

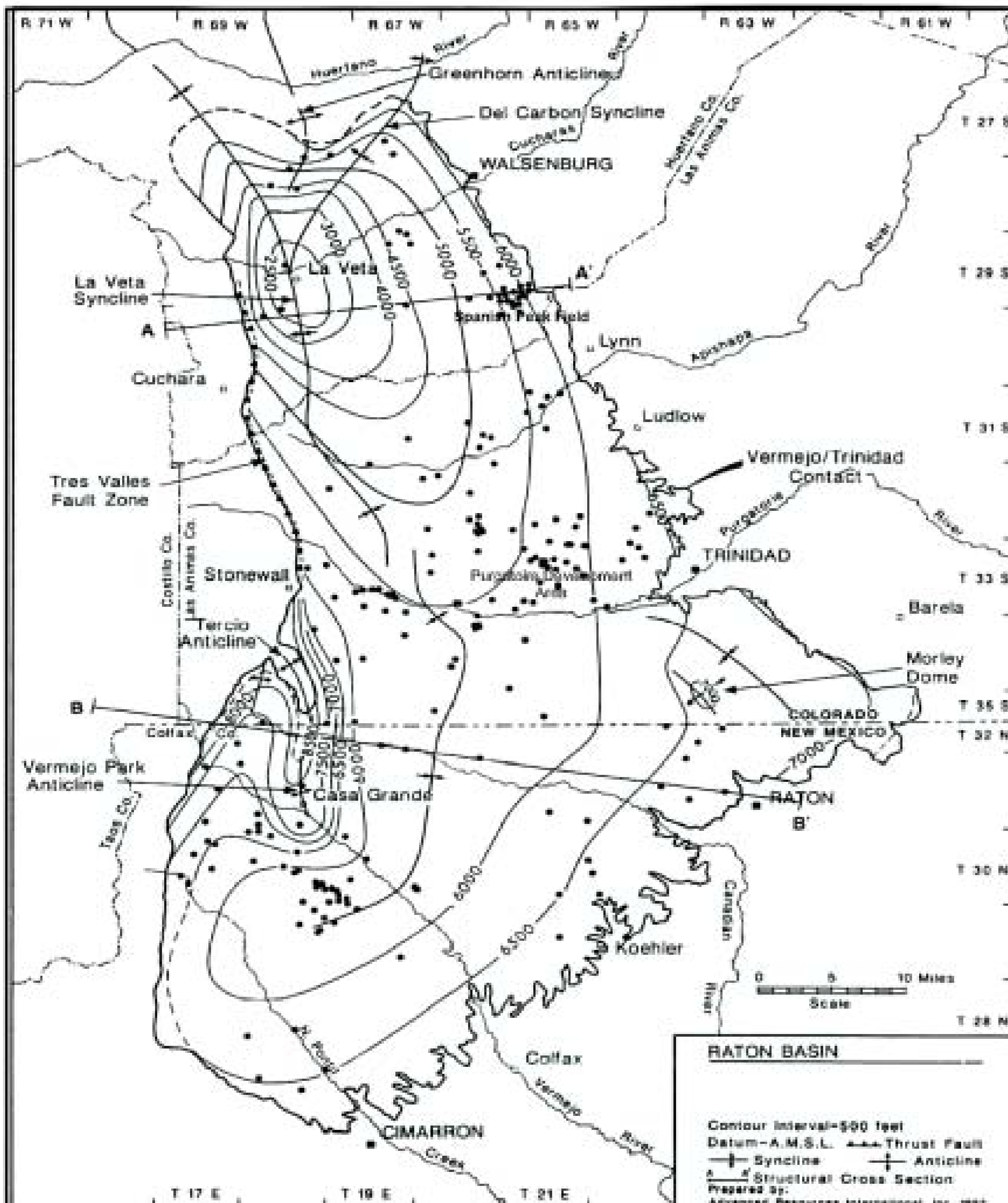
In-place coalbed methane resources in the Vermejo and Raton Formations were estimated by Stevens (1992) to be between 8.4 and 12.1 Tcf with a mean estimate of 10.2 Tcf. As of 1992, 114 coalbed methane exploration wells had been drilled in the basin (Quarterly Review, 1993). Soon after the Picketwire Lateral was constructed to convey gas from the fields to Trinidad and then to markets, gas well development in the basin increased significantly. The Purgatoire River Valley (Figure A9-1), which had been identified as having the highest coalbed methane potential in the basin, up to 8 Bcf per square mile (Stevens et al., 1992), became the focus of development. The Purgatoire Valley area was considered favorable for development because total coal thickness ranges from 5 to over 15 feet, drilling depths are shallow and coalbed methane content is high. The New Mexico portion of the basin was estimated to have methane resources ranging from 4 Bcf per square mile in the southern and eastern margins of the basin to more than 8 Bcf per square mile in the area south of the Vermejo Park anticline. Coal seams in the Vermejo Park area (Figure A9-1) are relatively thick, but shallow and of low rank, making estimates of coalbed methane content relatively low (Stevens et al., 1992).

The Spanish Peak Field, in the Purgatoire River development area in Las Animas County, Colorado (Figure A9-1), had 53 active wells in December 1996. Plans had been announced by Evergreen Resources, Inc. to drill and complete an additional 40 wells in 1997 (Hemborg, 1998). In 1996, the Purgatoire development area was projected to be capable of producing 122-137 Mcf per day in 3 to 4 years (Figure A9-1) (Hemborg, 1996). Total coalbed methane production within the Raton Basin was 30.8 Bcf per year in 2000 (GTI, 2002).

Methane production wells have generally been completed with 5.5-inch (outer diameter) casing with two to eight perforations per foot through the casing at the depths of the coal seams. The coal seams are stimulated with hydraulic fracturing treatments of sand and gelled-water, but detailed information on the nature, volumes, and use of hydraulic fracturing fluids in gas well development in this basin are not readily available. Water and gels with 10/40-mesh sand proppant seem to be the fluids of choice for fracturing practices in the Raton Basin. Stevens et al. (1992) report that multiple zones in one well are typically developed with 200,000 pounds of 10/20 or 20/40-mesh sand with 100,000 gallons of cross-linked gel per well. In one series of tests, wells were hydraulically fractured with 283,000 to 532,000 pounds of 12/20 and 20/40-mesh sand as proppant and 110,000 to 769,000 barrels of water or gel. The wells were fractured in two stages, one for a 25-foot thick upper zone and another for a 75-foot thick lower zone (Quarterly Review, 1993). Relatively high rates of water flow in these wells may be the result of fractures penetrating sandstones as well as coal seams. Another set of tests led a different methane producer to conclude that high water production was the consequence of induced fractures that intercept water-bearing sandstone and intrusive rocks. While operators initially assumed that large hydraulic fracture stimulations were necessary to link the thin and widely-spaced coal seams, it was found that such fracturing increased unwanted water production from associated sandstones, sills and water-bearing faults (Quarterly Review, 1993).

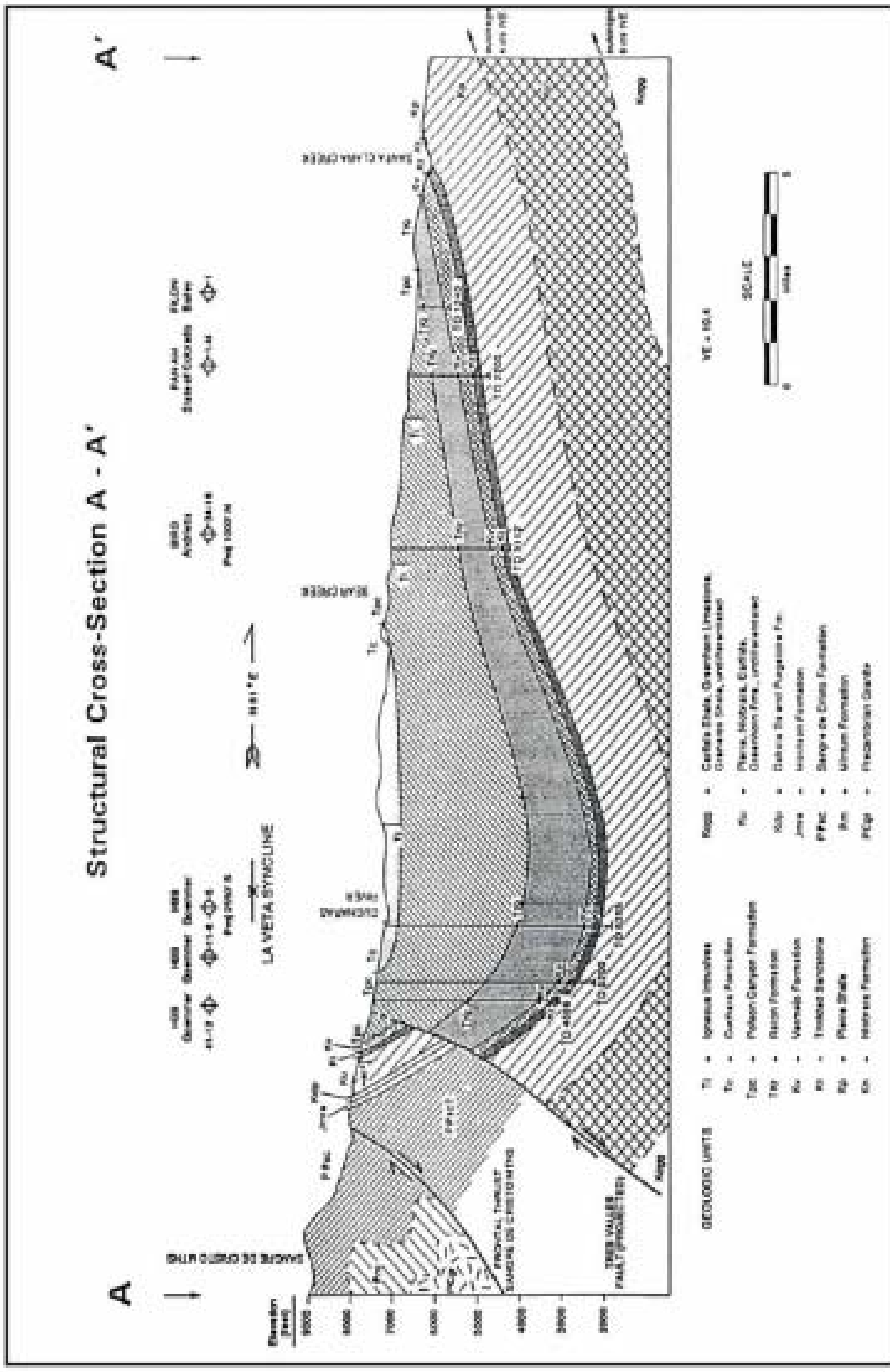
9.4 Summary

There are two major coal formations in the Raton Basin, the Vermejo Formation and the Raton Formation. The Vermejo coals range in thickness from 5 to 35 feet while the Raton coal layers range from 10 to over 140 feet thick. The coal seams of the Vermejo and Raton Formations, developed for methane production, also contain water that meets the water quality criteria for a USDW; therefore, it can be assumed that the Raton Basin coals are located within a USDW. The Cuchara-Poison Canyon, Fort Hayes-Codell, Dakota-Purgatoire, Entrada and Trinidad Sandstone and other sandstone beds within the Vermejo and Raton Formations, as well as intrusive dikes and sills, also contain water of sufficient quality to meet the USDW water quality criteria. Hydraulic fracturing may create connections to the Trinidad Sandstone, as shown by increases in water withdrawal from production wells over time. On the other hand, hydraulic connections to other adjacent water-bearing formations may also account for the increase in water production.



Structure Contour Map On Top Trinidad Sandstone (Stevens et al., 1992)

Figure A9-1



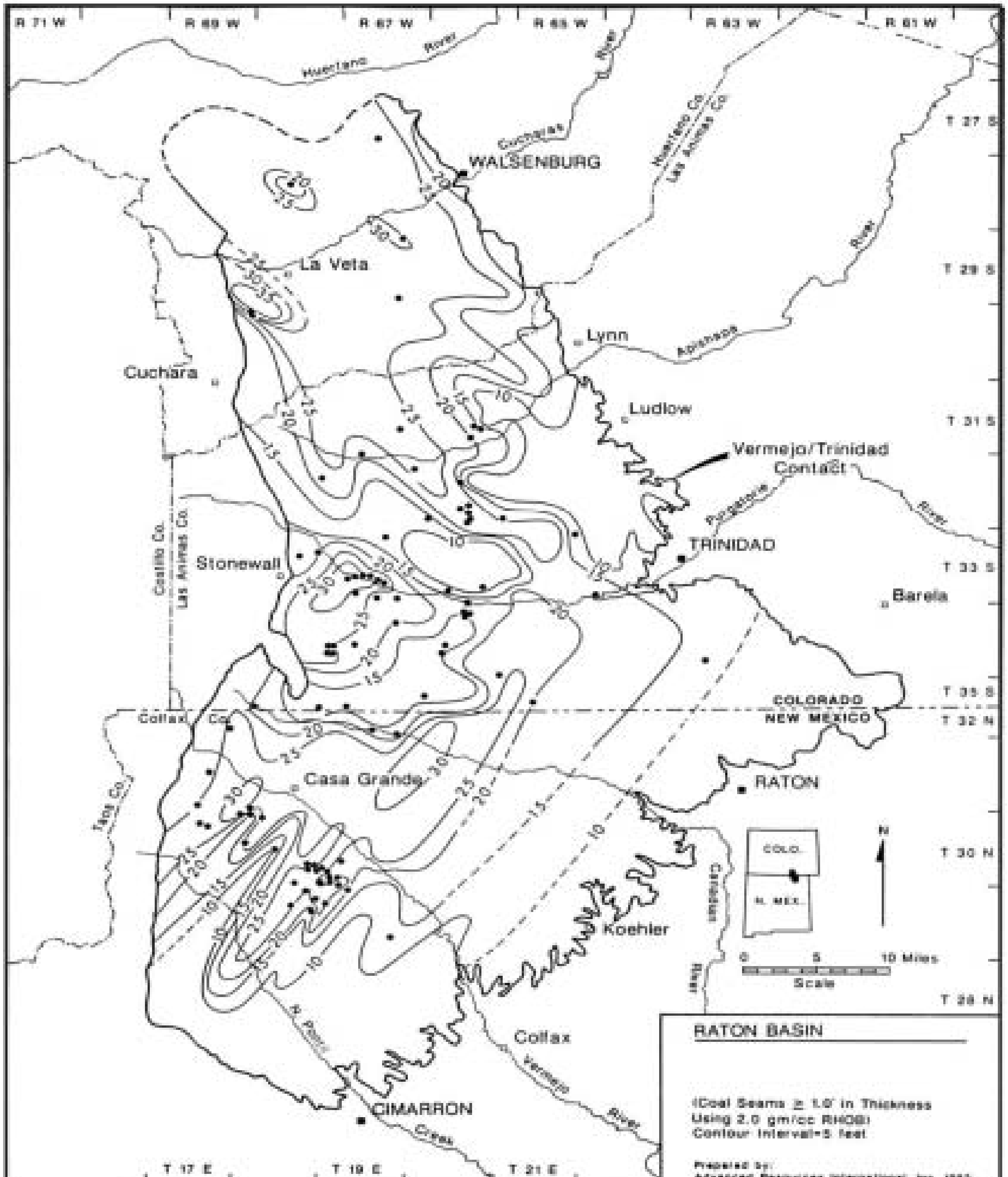
Structural Cross Section (Stevens et al., 1992)

Figure A9-2

ERA	PERIOD / EPOCH	FORMATION	THICKNESS (FT)	LITHOLOGY
CENOZOIC	Recent		0—30	Alluvium, basalt flows
CENOZOIC	Miocene	Devils Hole Formation	25–1,300	Light-gray conglomeratic tuff and conglomerate
CENOZOIC	Oligocene	Farisita Formation	0–1,200	Buff conglomerate and sandstone
CENOZOIC	Eocene	Huerfano Formation	0–2,000	Variegated maroon shale and red, gray, and tan claystone
CENOZOIC	Eocene	Cuchara Formation	0–5,000	Red, pink, and white sandstone, and red, gray, and tan claystone
CENOZOIC	Paleocene	Poison Canyon Formation	0–2,500	Buff arkosic conglomerate and sandstone, yellow siltstone, and shale
CENOZOIC / MESOZOIC	Paleocene / Upper Cretaceous	Raton Formation	0–2,075	Light-gray to buff sandstone, dark-gray siltstone, shale, and coal; conglomerate at base
MESOZOIC	Upper Cretaceous	Vermejo Formation	0–360	Dark-gray silty and coaly shale, buff to gray carbonaceous siltstone, and sandstone beds; coal
MESOZOIC	Upper Cretaceous	Trinidad Sandstone	0–255	Light-gray to buff sandstone
MESOZOIC	Upper Cretaceous	Pierre Shale	1,300–2,900	Dark-gray fissile shale and siltstone
MESOZOIC	Upper Cretaceous	Niobrara Group: Smokey Hill Marl	560–850	Yellow chalk, marine gray shale and thin white limestone; and light-gray limestone at base
MESOZOIC	Upper Cretaceous	Niobrara Group: Fort Hayes Limestone	0–55	
MESOZOIC	Upper Cretaceous	Benton Group: Codell Sandstone	0–30	Brownish sandstone, dark-gray shale, gray limestone and gray shale
MESOZOIC	Upper Cretaceous	Benton Group: Carlile Shale	165–225	
MESOZOIC	Upper Cretaceous	Benton Group: Greenhorn Limestone	30–80	
MESOZOIC	Upper Cretaceous	Benton Group: Graneros Shale	185–400	
MESOZOIC	Lower Cretaceous	Dakota Sandstone	100–200	Buff sandstone, buff conglomerate sandstone, and dark-gray shale
MESOZOIC	Lower Cretaceous	Purgatoire Formation	100–150	
MESOZOIC	Jurassic	Morrison Formation	150–400	Variegated maroon shale, gray limestone, red siltstone, gypsum, and gray sandstone
MESOZOIC	Jurassic	Ralston Creek Formation	30–100	
MESOZOIC	Jurassic	Entrada Sandstone	40–100	
MESOZOIC	Triassic	Dockum Group	0–1,200	Red sandstone, calcareous shales, and thin limestones
PALEOZOIC UNDIVIDED			5,000–10,000	Variegated shales, arkose, conglomerates, and thin marine limestone

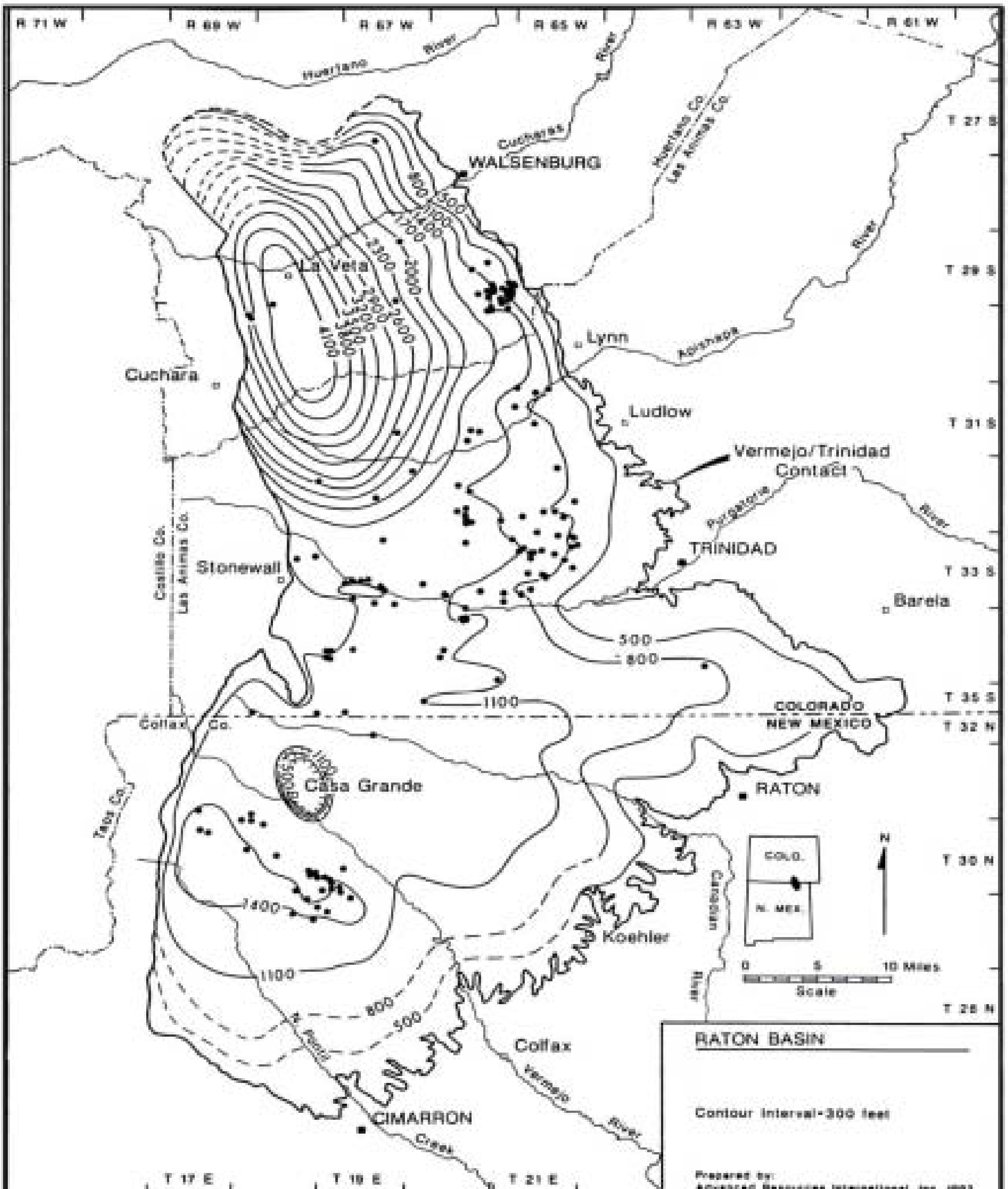
Generalized Stratigraphy of Cenozoic and Mesozoic Units (Hemborg, 1998)

Figure A9-3



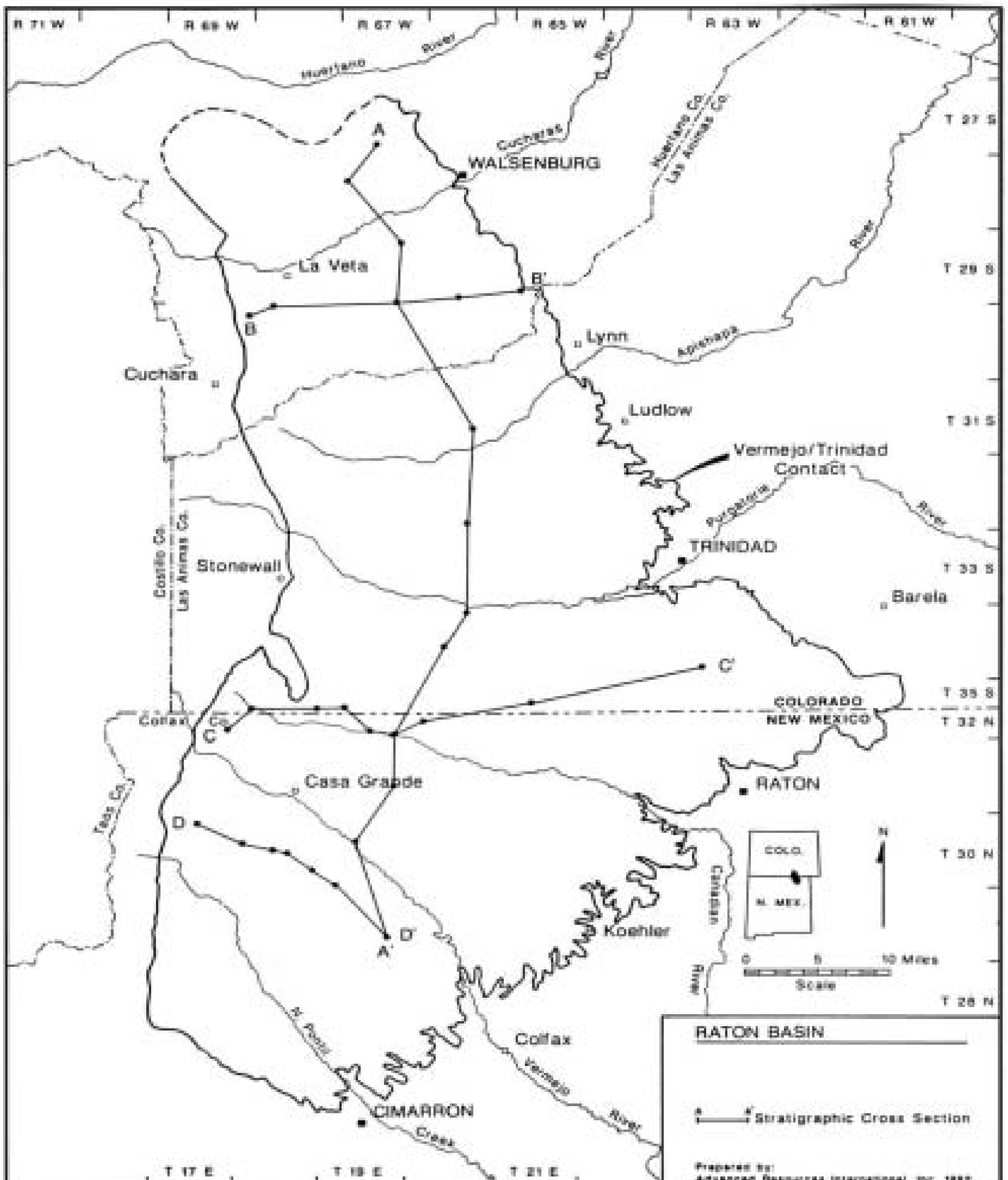
Vermejo Formation - Total Coal Isopach (Stevens et al., 1992)

Figure A9-4



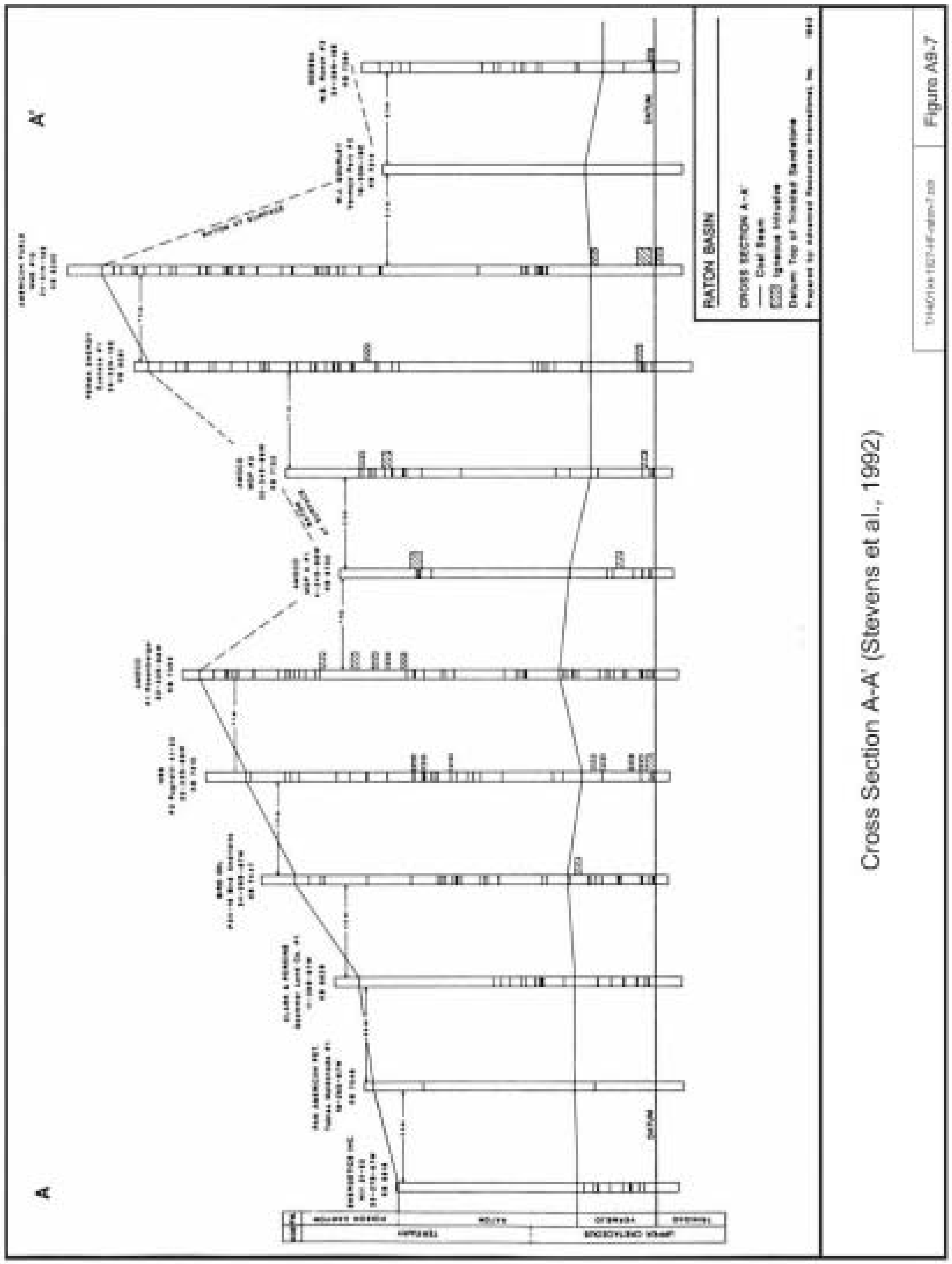
Overburden to Coal Interval (Stevens et al., 1992)

Figure A9-5

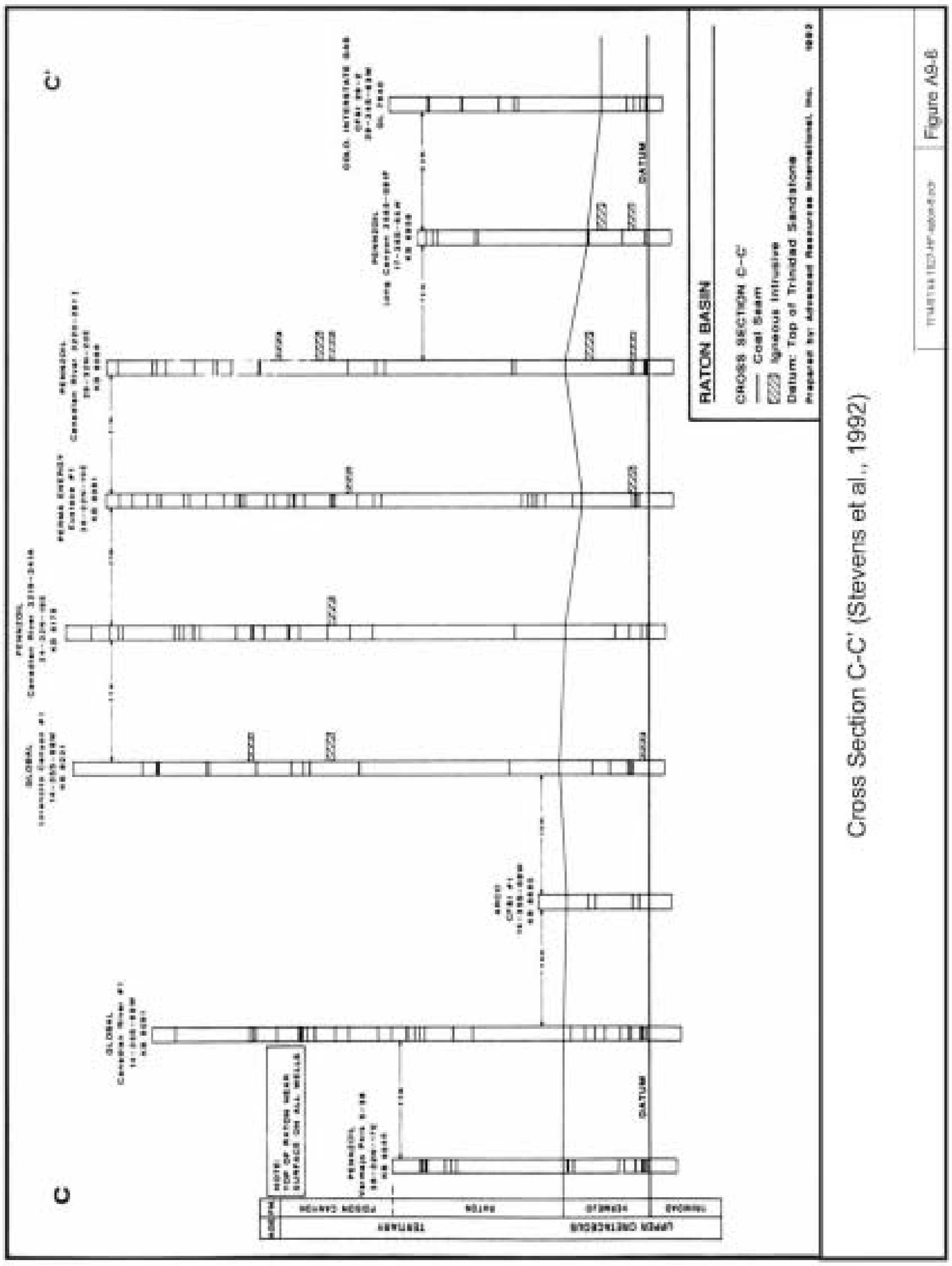


Location of Stratigraphic Cross Sections (Stevens et al., 1992)

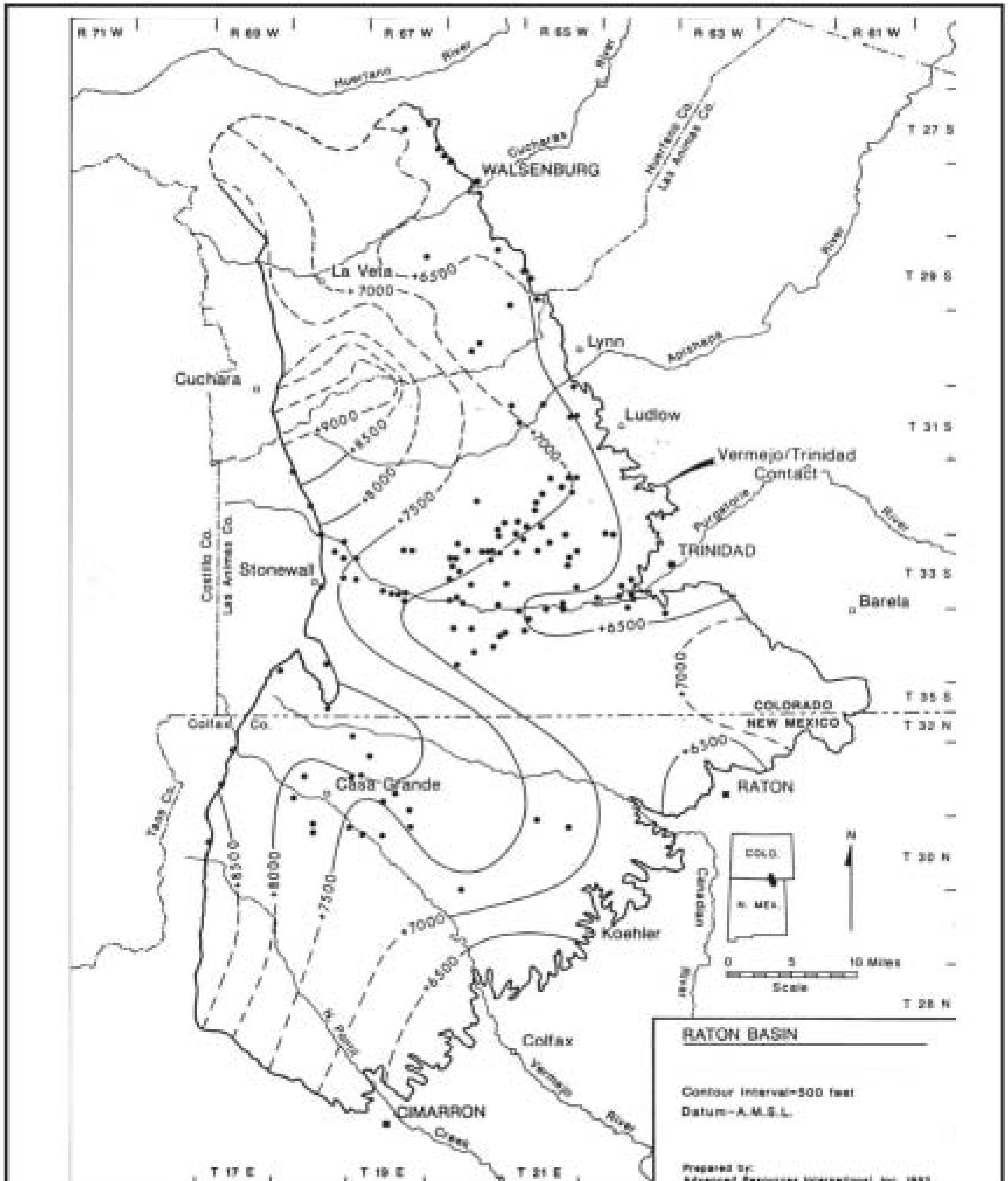
Figure A9-6



Cross Section A-A' (Stevens et al., 1992)

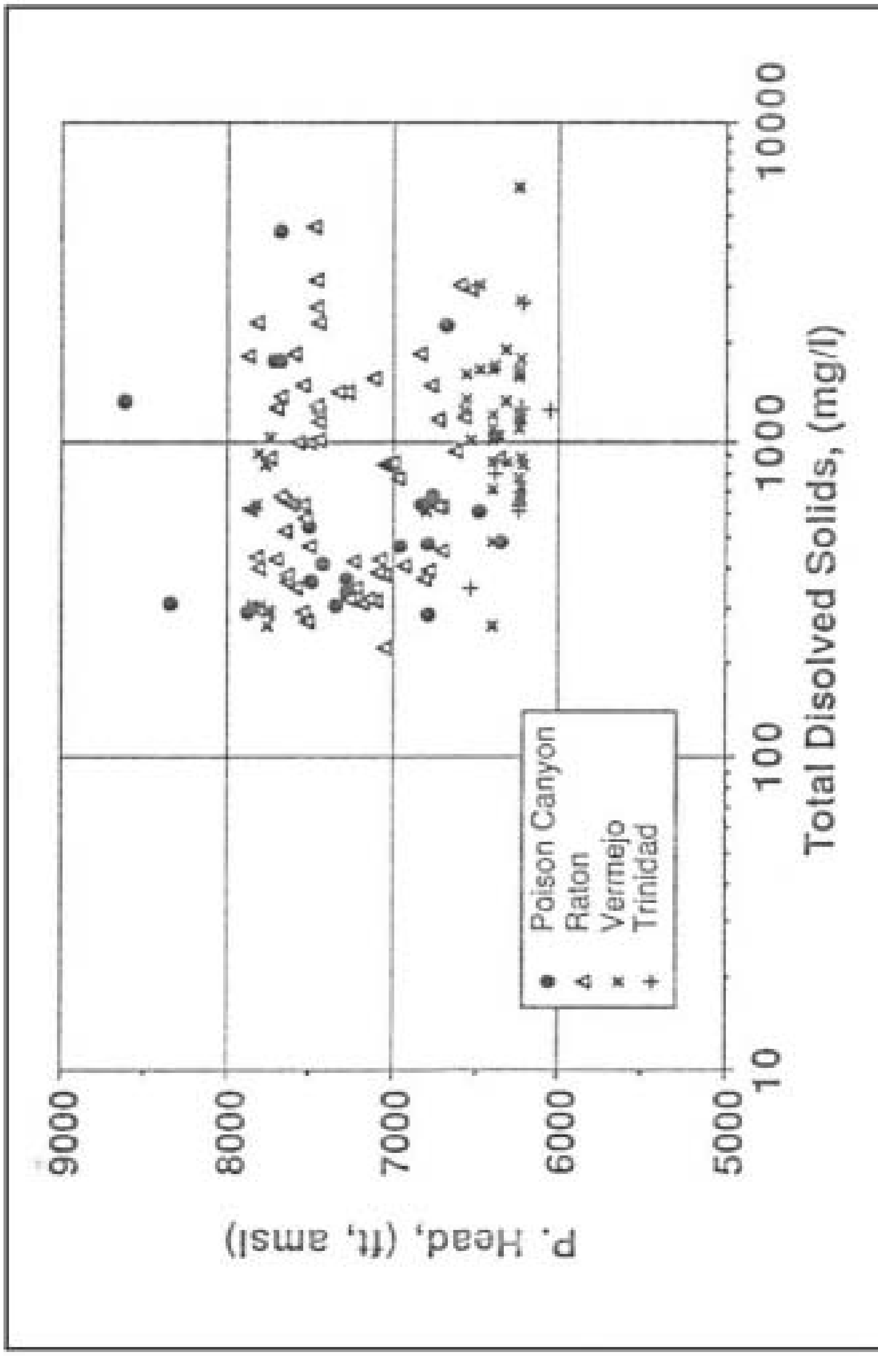


Cross Section C-C' (Stevens et al., 1992)



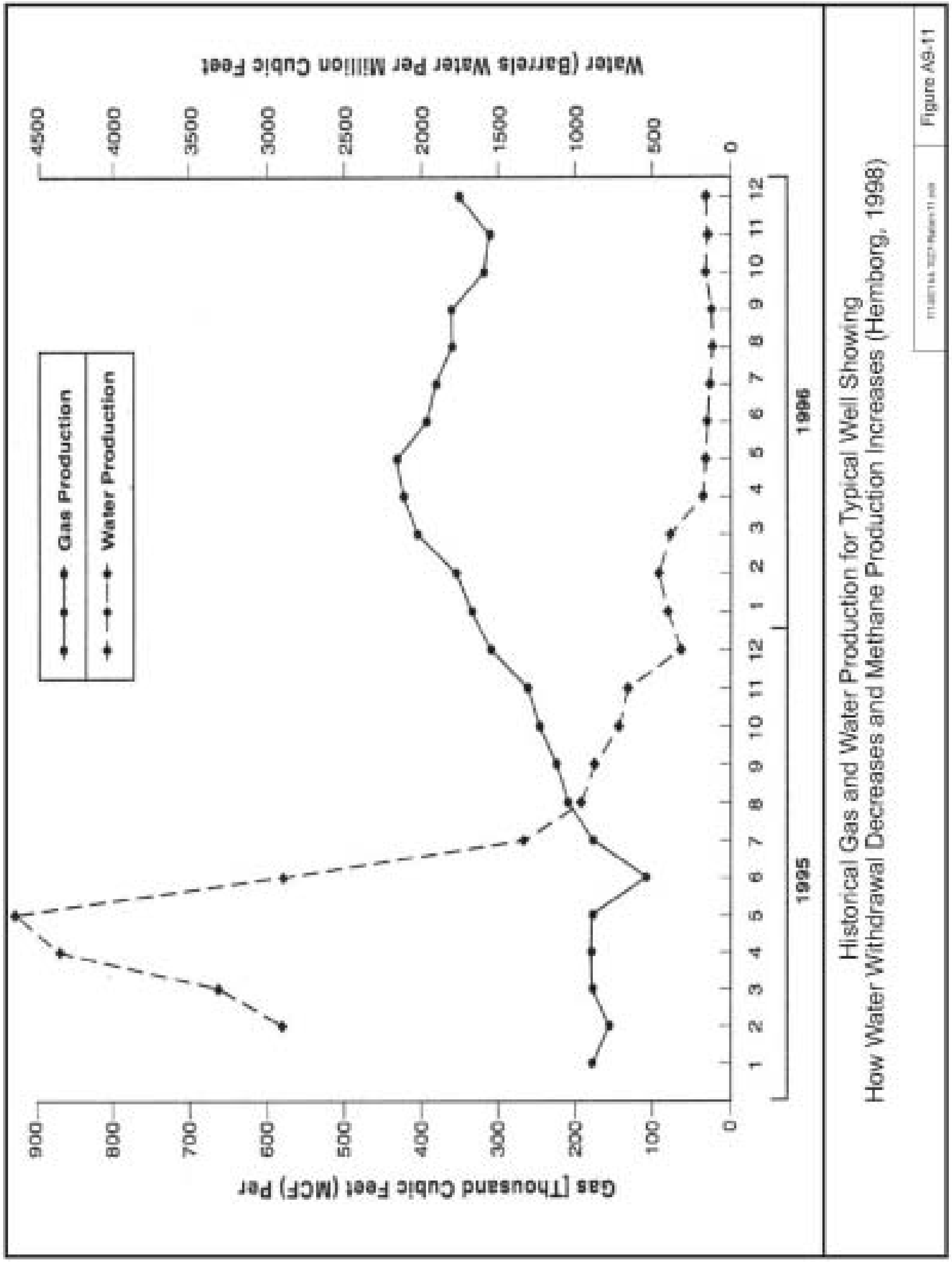
Potentiometric Surface Map for Raton Basin (Oldaker et al., 1993)

Figure A9-9



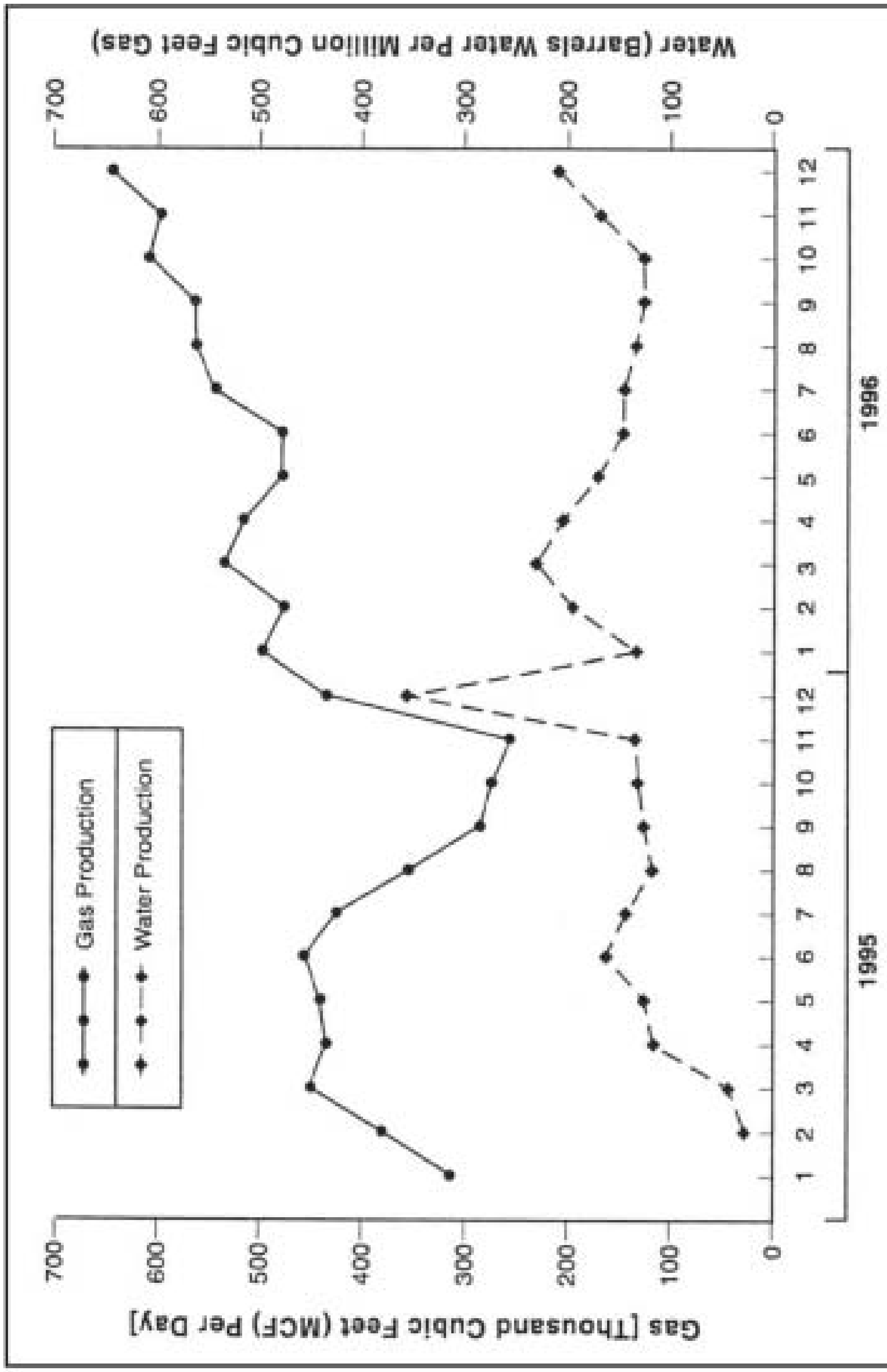
Relationship Between Gas Content and Depth Below Pontentiometric Surface for Two Groups of Coal Rank
(Oldaker et al., 1993)

Figure A9-10



Historical Gas and Water Production for Typical Well Showing
How Water Withdrawal Decreases and Methane Production Increases (Hemborg, 1998)

Figure A9-11



Historical Gas and Water Production for Ozzello 42-1 Well Showing
Water Withdrawal Increasing with Gas Production (Hemborg, 1998)

Figure A9-12

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