Chapter SR

A SUMMARY OF TERTIARY COAL RESOURCES OF THE RATON BASIN, COLORADO AND NEW MEXICO

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INTRODUCTION

The Raton Basin (fig. SR-1) in Colorado and New Mexico contains a large coal resource in the Late Cretaceous and Paleocene Raton Formation. This formation is partly unconformable above the coal-bearing Late Cretaceous Vermejo Formation (fig. SR-2). Late Cretaceous Pierre Shale and Trinidad Sandstone conformably underlie the Vermejo. Coal was first reported in the Raton Basin in 1841. Although these coal deposits have been developed since 1873, their use for the past few decades has been greatly reduced. This situation was exacerbated by the closing of steel plants that used the coal from the basin. Presently, coal mining is gradually being replaced by development of coal-bed methane in the Vermejo and Raton Formations. This report focuses on the geology, occurrence, quality, and production history of the coal resources of the Raton Formation.

The Raton Basin extends over an area of about 4,000 square miles in southeastern Colorado and northeastern New Mexico (see fig. SR-1). The basin is underlain by Upper Cretaceous and Paleocene coal-bearing rocks (fig. SR-2). The basin is a large arcuate structural trough and depocenter that extends from Huerfano Park, Colorado, to Cimarron, New Mexico (see fig. SR-1). The basin is bounded on the west by the Sangre de Cristo Mountains, on the northeast by the Apishapa arch in Colorado, and on the southeast by the Sierra Grande-Las Animas arch in New Mexico and Colorado (Johnson and Wood, 1956). The basin is asymmetrical with the axis located along the western margin. The sedimentary rocks are steeply tilted, overturned, and faulted along the east flank of the Sangre de Cristo Mountains. Anticlines (for example, Vermejo Park) are formed along the western margin of the basin in New Mexico. The sedimentary rocks on the east side of the basin are gently tilted to the west from 1 to 5 degrees. The Las Vegas sub-basin south of the

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Raton Basin in New Mexico was considered by Baltz (1965) to be a part of the structural trough.

Tertiary igneous rocks are common throughout the Raton Basin as exemplified by dikes, sills, and stocks of the Spanish Peaks.   Miocene and Pliocene igneous dikes, sills, plugs, stocks, and laccoliths ranging in age from 6.7 to 29.5 m.y. (D. Miggins, oral commun., 1999) are common intrusions throughout the coal-bearing Vermejo and Raton Formations (Johnson, 1958; 1961). The dikes and sills are mafic to intermediate in composition and the plugs, stocks, and laccoliths are mostly intermediate (Pillmore, 1969). Basalt and andesite flows from 8 to 3.5 m.y. in age are preserved on high mesas in the basin (Johnson, 1969). The dikes exist as dike-like bodies radiating from stocks such as the Spanish Peaks, and as subparallel dikes striking mostly in a northeast direction, and as swarms (Johnson, 1958, 1961). The dikes vary in thickness from a few inches to more than 100 ft and are presumed to be intruded into fracture systems. The dikes cause limited alteration of surrounding coal-bearing rocks; however, sills, which were commonly intruded along coal beds have altered, assimilated, and destroyed the coal. Lee (1924) noted the formation of prismatic coke (for example, graphite in composition) as a result of metamorphism by sill intrusions along coal beds. Pillmore (1969) suggested that hundreds of millions of tons of coal were probably destroyed by sill intrusions along coal beds.

STRATIGRAPHY

Figure SR-2 shows the generalized Late Cretaceous and Paleocene stratigraphy of the Raton Basin (Johnson and Wood, 1956; Pillmore and Flores, 1987). The oldest mapped sedimentary units in the Raton Basin are the Late Cretaceous Pierre Shale and Trinidad Sandstone. The Late Cretaceous coal-bearing Vermejo Formation conformably overlies the Trinidad Sandstone. The Late Cretaceous and Paleocene Raton Formation is partly unconformable above the Vermejo. The Paleocene Poison Canyon Formation overlies and intertongues with the Raton Formation (Johnson and Wood, 1956). The Pierre Shale, Trinidad Sandstone, and Vermejo, Raton, and Poison Canyon Formations were interpreted by Flores (1987) and Flores and Pillmore (1987) as a succession of coarsening-upward megacycles (fig. SR-3). These coarsening-upward megacycles are capped by thin to thick conglomeratic and sandstone-dominated units. For example, the Trinidad Sandstone caps the Pierre Shale. The basal conglomerate of the Raton Formation caps the underlying Vermejo Formation. A sandstone-dominated unit caps the underlying lower part of the Raton Formation. The sandstone-dominated unit of the Poison Canyon Formation caps the upper part of the Raton Formation. Coal of the Paleocene part of the Raton Formation exists in several intervals in the upper part of the formation underlying the sandstone-dominated units; however, the latter interval does not contain economic deposits.

Lee (1917) divided the Raton Formation, in ascending order, into a basal conglomeratic interval, a lower coal-rich interval, a barren or coal-poor, sandstone-dominated interval, and an upper coal-rich interval. Tschudy and others (1984) and Pillmore and Flores (1984) placed the Cretaceous/Tertiary (K/T) boundary near the top of the lower coal-rich interval below the sandstone-dominated interval in the lower part of the Raton Formation. The K/T boundary is based on the discovery of an iridium anomaly at the palynological Cretaceous-Tertiary boundary (Orth and others, 1981; Pillmore and others, 1984). They reported abundant anomalies of iridium and other trace elements coincident with an abrupt disappearance of several taxa of fossil pollen and a sudden change in the ratio of fern spores to angiosperm pollen in 15 sites in the Raton Basin (Pillmore and Flores, 1984; 1987). The geochemical anomalies in these sites are contained in a kaolinitic claystone interbedded with coal and sediments of crevasse splay, swamp, levee-overbank, floodplain, and abandoned-channel environments.

According to Pillmore and Flores (1987) the basal conglomeratic interval is as much as 50 ft thick and consists of interbedded pebble conglomerate and granule, quartzose sandstone. The basal conglomerate consists of pebbles and cobbles of mostly quartzite, chert, and gneiss. The basal conglomerate is laterally discontinuous (Pillmore, 1969). The lower coal-rich zone ranges from 100 to 250 ft thick and is composed of interbedded coal, carbonaceous shale, mudstone, siltstone, and sandstone. The barren or sandstone-dominated interval ranges from 180 to 600 ft thick and includes mainly sandstone and conglomeratic sandstone, subordinate mudstone and siltstone, and sparse coal and carbonaceous shale. The upper coal-rich interval is about 1,100 ft thick in the interior part of the basin but thins to less than 600 ft thick near Raton, New Mexico. It consists of interbedded sandstone, siltstone, mudstone, coal, and carbonaceous shale. These intervals are well developed in the basin center; however, they merge into a thick interval of conglomerate and sandstone of the Poison Canyon Formation along the western margin of the basin (Hills, 1888; Johnson and others, 1966; Pillmore and Flores, 1987). Pillmore (1969) estimated the thickness of the Raton Formation to be from >0 to 2,000 ft.

The coal-rich intervals consist of lenticular coal beds as much as 12 ft thick (Pillmore, 1976; Amuedo and Bryson, 1977; Flores and Tur, 1982; Flores, 1984, 1993; Flores and others, 1985; Pillmore and Flores, 1984). The most abundant rock type in the coal-rich intervals is sandstone, which consist of two types: a fining-upward, scour-based sandstone and a sandstone that caps a thin coarsening-upward

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sequence of carbonaceous shale, mudstone, and siltstone. The fining-upward sandstone is fine to medium grained, and it is composed of single or multiple units separated by thin mudstone and siltstone drapes. These sandstone units are in turn basally erosional, trough and planar crossbedded, and convoluted in the lower part, and rippled and rooted in the upper part. The sandstone that caps the coarsening-upward sequence is fine grained, contains asymmetrical ripple lamination, climbing ripple lamination, and root marks. In addition, the sandstone is tabular and locally incised by basally-scoured sandstone. The mudstone and siltstone that compose the coarsening-upward sequence are burrowed and ripple laminated. The sandstone and coarsening-upward shale, mudstone, and siltstone are commonly interbedded with the coal and carbonaceous shale beds.

The sandstone-dominated intervals commonly consist of multiple stacked bodies of erosionally based, fining-upward sandstone, which laterally grade into mudstone and siltstone units. The sandstone is coarser grained than the sandstone in the coal-rich intervals and is composed mainly of trough crossbeds and convolute laminations. The sandstone bodies are laterally offset or en-echelon, making up a laterally continuous belt.

DEPOSITIONAL ENVIRONMENTS

The depositional environments of the Raton Formation include fluvial channel, overbank-levee, crevasse splay, floodplain lake, and low-lying and raised swamps (Strum, 1985; Flores, 1987; Flores and Pillmore, 1987). The environments formed in alluvial plains with the advent of the Laramide orogeny during the early Tertiary and the withdrawal of the Cretaceous interior seaway (Flores, 1984; 1987). The deposits of these alluvial plains probably grade into deposits of alluvial fans along

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the western basin margin as represented by the Poison Canyon Formation. Prior to the withdrawal of the Cretaceous sea, the Raton Basin consisted of a barred coastline drained by wave-dominated deltas (Billingsley, 1978; Flores and Danilchik, 1978; Flores and Tur, 1982; Flores, 1984; Flores and others, 1985; Flores, 1987). The Pierre Shale represents deposition on the continental shelf and slope of the Cretaceous interior seaway; the Trinidad Sandstone reflects deposition along the wave-reworked, barred nearshore coastlines; and the Vermejo Formation was deposited on active and abandoned (wave-reworked) delta plains.

The coarsening-upward megacycles of the Cretaceous and Paleocene age of the Raton Formation described by Flores and Pillmore (1987) reflect changes in the fluvial-system architecture as controlled by the tectonic uplift of the basin margin and by basin subsidence. These workers suggested that the megacycle in the lower part of the Raton Formation, consisting of the coal-rich interval overlain by the barren, sandstone-dominated interval, reflects deposition from meandering and anastomosed fluvial systems to braided and meandering fluvial systems. Deposition of the coal-rich interval by meandering and anastomosed fluvial systems was influenced by basin subsidence. Allocyclic mechanisms promoted vertical aggradation of the anastomosed streams, which was succeeded by lateral aggradation of meandering streams. Coal was formed in low-lying swamps associated with the anastomosed streams (Smith and Smith, 1980; Smith, 1983; Smith and Cross, 1985) and raised swamps formed on abandoned meander belts (Flores, 1987; Flores and Pillmore, 1987; Flores, 1993). These fluvial systems deposited fluvial channel sandstone, coarsening-upward crevasse splay carbonaceous shale, mudstone, siltstone, and sandstone, and burrowed floodplain lake mudstone and siltstone. In contrast, deposition of the barren, sandstone-dominated interval was controlled by tectonic uplift of the provenance (for example,

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Sangre de Cristo Mountains) along the western margin of the basin. This allocyclic mechanism promoted development of mountain-front alluvial fans that were point sources of bedload sediments of streams. The availability of these sediments and the raising of the stream gradients promoted development of braided streams along the basin margin, which merged with sediment-laden meandering streams in the basin center. Here, the floodplains were choked with sediments that inhibited development of peat-forming swamps.

DESCRIPTION OF COAL ZONES

As shown in figures SR-2 and SR-3, the coal zones are in the lower and upper parts of the Raton Formation; however, they are separated by the barren, sandstone-dominated interval (fig. SR-3). The lower coal zone contains the Cretaceous (Maastrichtian) part of the formation with the K/T boundary near the top of the zone (Pillmore and Flores, 1987). The coal zone ranges in thickness from 250 ft on the western part of the basin to 100 ft on the eastern part. The lower coal zone is overlain by the barren or sandstone-dominated interval. This interval is characterized by sparse coal and is dominated by multiple-stacked channel sandstone. The barren interval ranges from 180 to 600 ft thick. The upper coal zone contains many coal beds less than 3 ft thick, but beds as thick as 12 ft have been mined. A dichotomy of coal occurrence in the upper coal zone of the Paleocene Raton Formation is reflected by the presence of thick coal beds in the basin center (for example, York Canyon and Chimney Divide coal beds) and thinner coal beds in the eastern margin of the basin (Strum, 1985; Flores, 1987; Pillmore, 1991). The vertical and lateral variability of the coal beds in the central and eastern parts of the Raton coalfield in New Mexico are exhibited by the York Canyon, Chimney Divide, Tin Pan, and Potato Canyon coal beds (Pillmore, 1969; 1980; 1991).

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Based on measurement of closely spaced stratigraphic sections, Strum (1985) and Flores (1987) demonstrated the differences in the coal thickness and lateral variability of the coal beds in the upper coal zone in the eastern part of the basin (figs. SR-4 and SR-5). The lateral variability of the coal beds is exemplified in figure SR-4 where the Tin Pan Canyon coal bed splits into three beds within a distance of more than 4,000 ft, which in turn pinch out into a fluvial channel sandstone and associated overbank-levee siltstone and mudstone within a distance of 2,000 ft. In the overlying interval (see fig. SR-4) the discontinuity of the Potato Canyon coal bed was caused by complete erosion by a sand-infilled fluvial channel. The lateral variability of the coal beds in the central part of the basin is exhibited in figure SR-5 where the York Canyon coal bed was completely eroded by a sand-infilled fluvial channel. Another type of lateral variability of the York Canyon coal described by Flores (1993) is splitting by fluvial channel sandstone and crevasse splay sandstone, siltstone, and mudstone of a 12-ft thick coal bed into four coal beds that range from 0.5 to 2 ft thick within a distance of 2.5 miles (fig. SR-6). In the overlying interval (see fig. SR-5) the lateral thinning of the Chimney Divide coal bed was caused by partial erosion by a sand-infilled fluvial channel. Pillmore (1969) indicated that the Chimney Divide coal zone exists throughout an area of more than 50 square miles.

Determining the lateral variability of coal beds in the Raton Formation, according to Strum (1985), depends on the spacing of control points or measured sections. That is, the more closely spaced the control points, the more variable the lateral extent of the coal. This suggests that lateral variability of the coal-bearing rocks can best be ascertained by using closer-spaced stratigraphic sections than far apart sections. In addition, sand-infilled fluvial channel sands that eroded coal beds also caused

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expansion and contraction of intervals between coal beds. This in turn may influence miscorrelation of coal beds especially if the control points are not closely spaced. Flores (1984; 1987) indicated that thicker coal beds resulted from deposition of precursor peat on abandoned deposits of fluvial channel belts and crevasse splays. The abandoned fluvial deposits created a raised platform that protected the swamps from being choked by sediment floods and permitted prolonged peat accumulation.

In addition, the vertical and lateral variability of the coal beds in the upper coal zone of the Raton Formation may have been caused by tectonic control and igneous intrusions. That is, thickening of coal beds may be caused by basin subsidence, which is more rapid in the basin center than in the eastern margin of the basin. In addition, soft-sediment deformation, resulting in intraformational faults (Roehler and Danilchik, 1980) locally controls the thickness and lateral variability of the coal beds. Hasbrouck and others (1980) reported that intrusion by dikes may have interrupted the lateral continuity of Raton Formation coal beds.

COAL QUALITY

Amuedo and Bryson (1977) reported that coal in the Raton Formation in the Colorado part of the Raton Basin ranges from high-volatile, bituminous C to A in rank (on a dry basis). Proximate analyses of Raton coal reported by Amuedo and Bryson (1977) are as follows. Ash content of the Raton Formation coal beds ranges from 7 to 16.5 percent (on a dry basis). Sulfur content of the Raton coal averages from 0.4 to 0.6 percent (on a dry basis). The volatile matter of Raton Formation coal beds varies from 30 to 37 percent and the fixed carbon ranges from 46.5 to 58.7 percent (on a dry basis). The Btu/lb of the Raton Formation coal beds ranges

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from 12,210 to 15,150 (on a dry basis). The Btu/lb and fixed carbon contents increase from the northern to southern parts of the basin. Goolsby and others (1979) indicated a gradational change in coal rank from a high-volatile A bituminous in the southern part of the Raton Basin to a high-volatile C bituminous in the northern part. In the Colorado part of the basin, the U.S. Geological Survey and Colorado Geological Survey (1977) mapped bituminous coal overlain by more than 3,000 ft of overburden and subbituminous coal covered by less than 3,000 ft of overburden.

Pillmore (1969; 1991) described the Raton Formation coal beds in the New Mexico part (Raton coalfield) of the basin as all high-volatile A to B bituminous rank, and most of it is suitable for manufacturing coke. Proximate analyses of Raton Formation coal beds reported by Pillmore (1969; 1991) are as follows. Ash content of the Raton Formation coal (for example, York Canyon, Chimney Divide, Ancho Canyon, Tin Pan) ranges from 8.8 to 16.5 percent (moisture free). Sulfur content of the Raton Formation coal averages from 0.5 to 0.6 percent (moisture free). The volatile matter of the Raton coal varies from 35.7 to 38.4 percent and the fixed carbon ranges from 46.5 to 58.7 percent (moisture free). The Btu/lb of the Raton coal ranges from 12,470 to 14,340 (moisture free).

In several localities (fig. SR-7), the Raton Formation coal beds in the Raton Basin have been transformed to natural coke by Tertiary igneous intrusions. Heat from regional igneous intrusions in the form of stocks (for example, Spanish Peaks) and laccoliths (for example, Vermejo Park and Morley domes) affected the rank of the Raton Formation coal on a large scale. In addition, the Raton Formation coal beds were locally transformed into bituminous rank by heat from igneous sills. These igneous intrusions (see fig. SR-1) upgraded the quality of Raton Formation coal,

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which averages about 13,000 Btu/lb (on a dry basis). For example, the coal north of a line just south of Spanish Peaks is of steam quality; the coal south of this line is high-quality metallurgical-grade coke. A comparison of the coal quality and geochemistry of the Paleocene Raton Formation coal (for example, York Canyon, Potato Canyon, and Left Fork coal beds) and the Cretaceous Vermejo Formation coal (for example, Raton coal bed found immediately above the Trinidad Sandstone) by Pillmore and Hatch (1976) indicates that the Vermejo Formation coal is higher in Btu, ash, and sulfur contents (on a whole-coal basis). The U and Th content of the Vermejo Formation coal is two to five times higher than in the Raton coal. The Cu content is one-half to one-fourth that of the Raton Formation coal, and the average value for P is about one-fourth to one-third that of the Raton Formation coal.

Numerous ruins of beehive coke ovens, (for example, Cokedale, Dawson, and Gardner; Pillmore, 1980) in the Raton Basin reflect the importance of coking coal in the region’s smelting and locomotive industries. Beehive coking ovens operated in the basin nearly until the mid-20th century (Jones and Murray, 1978; Goolsby and others, 1980). Coke was used in smelting, and to fuel blast furnaces that manufactured steel. Environmental concerns and greater efficiency of by-product coke ovens forced closure of the beehive ovens in the Raton Basin. However, by-product coke ovens owned by Colorado Fuel and Iron (CF&I) Steel Corporation at Pueblo, Colorado, which were active for 30 years, replaced these beehive coke ovens. Coking coal produced in the Raton Basin was utilized for steel manufacturing at steel plants of CF&I at Pueblo, Kaiser Steel Corporation at Fontana, California, and U.S. Steel Corporation at Provo, Utah. With the advent of electric furnaces, coal produced from the Raton Basin in recent years is used mainly for generating electricity.

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ORIGINAL RESOURCES

The total coal resources of the Late Cretaceous and Paleocene Raton and Cretaceous Vermejo Formations in the Raton Basin were estimated by Read and others (1950) and Wanek (1963) to be from 1.5 billion to 4.8 billion short tons. A later estimate of original coal resources of the Vermejo and Raton coal in the basin, based on beds at least 14-inches thick with less than 3,000 ft overburden, is more than 17 billion short tons (Johnson, 1958, 1961; Pillmore, 1969). Amuedo and Bryson (1977) estimated the coal resources of the Raton Formation based on 4-ft thick beds in the Colorado part of the basin, to be about 5 billion short tons. Pillmore (1969; 1991) identified eleven Raton Formation coal beds or zones (for example, Tin Pan, Potato, Rombo Canyon, Savage Canyon, Green, Brown, Left Fork, Cottonwood Canyon, Ancho Canyon, York Canyon, and Chimney Divide coal beds; see figs. SR-4, SR-5, and SR-6) found in eight coal districts in the New Mexico part (Raton coalfield) of the basin that contain substantial coal resources still remaining in the ground. Demonstrated resources of these coal beds or zones, based on aggregate coal thickness in excess of 15 ft, in beds 14-inches thick or greater, were estimated to be 513 million short tons (Pillmore, 1991). Of this resource estimate, the York Canyon coal bed contained measured underground resources of about 30 million short tons in beds 4 ft thick or greater (Pillmore, 1976). Strippable resources of the York Canyon remaining after mining are about 1- to 2 million short tons (Pillmore, 1991). Mining was terminated in York Canyon in 1994 when activities were moved east to Ancho Canyon.

Utilizing a coking-coal classification system, Goolsby and others (1980) estimated that the Raton Basin contains a reserve of more than 1.8 billion short tons of marginal grade (1.1-1.8 percent sulfur, 8.1-12 percent ash) high-volatile A

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bituminous coking coal and more than 216 million short tons of marginal grade high-volatile B bituminous coking coal. These workers further indicated that the total estimated original in-place coking coal reserve base for the Raton Basin is more than 2 billion short tons.

PRODUCTION HISTORY

Mining of coal from the Raton Formation coal zones began in 1873 and reached a peak production of 71 million short tons from 1911 to 1920 (Amuedo and Bryson, 1977). During this period, 5.6 million short tons was produced in the Colorado part of the Raton Basin and 1.5 million short tons was produced in the New Mexico part of the basin. Cumulative production through 1975 for the Raton Basin was estimated by Amuedo and Bryson (1977) to be about 325.5 million short tons; the Colorado part of the basin produced 247.5 million short tons and the New Mexico part of the basin produced 78 million short tons. In 1975, total production was 1.5 million short tons with approximately 600,000 short tons produced from Colorado mines and 1 million short tons produced from New Mexico mines.

Jones and Murray (1976) and Kelso and others (1981) identified 56 underground mines in Las Animas County in the Colorado part of the Raton Basin. These mines developed coal beds in the Vermejo and Raton Formation; the beds vary in thickness from 3.3 to 14 ft. The Allen, Bear Canyon No. 6, Delagua, Primero, and Primrose mines, which produced from Raton Formation coal, yielded a cumulative production of 40,383,282 short tons from 1900 to 1975 (Jones and Murray, 1976). Three of these mines produced coking-quality coal. Fifty-one mines that produced from the Vermejo Formation coal yielded a cumulative production of 158,741,161 short tons from 1884 to 1971 (Jones and Murray, 1976). Eight of these mines produced coking-quality coal. In the New Mexico part of the Raton Basin, Pillmore (1969) reported seven abandoned coal camps (several mines were in each camp) in the Vermejo and Raton Formation coal deposits. No production is included here from these mines, which opened as early as 1870.

Amuedo and Bryson (1977) identified 15 mining districts in the Raton Basin (fig. SR-7). In 1999, only one mine is active in the basin, the P&M York strip mine in New Mexico (see fig. SR-1). The York Canyon mines produced from the York Canyon coal bed (upper Raton coal zone) and yielded about 1 million short tons in 1975. The abandoned Allen underground mine produced from the Allen coal bed (lower Raton coal zone) and yielded about 632,000 short tons during the same year.

Production from the York Canyon mines was divided between the underground mine opened in 1966 and the strip mine, which opened in 1972 (Kaiser Steel Corporation, 1980). Total production from the York Canyon mines to January 1969 was about 2.5 million short tons. The underground workings utilized continuous mining and long-wall mining equipment to increase production. In addition, strip mines were opened, which utilized draglines, bulldozers, and front-end loaders to remove loose overburden varying from 30 to 340 ft thick. Both underground and strip mines annually produced as much as 1,500,000 short tons (Kaiser Steel Corporation, 1980). Production from the York Canyon mines during the 1989-1997 period was more than 8.4 million short tons (Resource Data International, Inc., 1997). However, Pillmore (1991) reported that production as of 1991 was about 20 million short tons.

Production from large mines such as the abandoned Allen mine (Raton Formation coal), small underground mines such as the abandoned Morley mine (Vermejo

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Formation coal), and other abandoned mines (Vermejo and Raton Formation coal) along the Purgatoire River valley (see fig. SR-1) was mainly shipped to the steel mills at Pueblo, Colorado. The Morley mine was started in 1906 and reached peak production of 500,000 short tons in the 1920's. Cutbacks in steel production at Pueblo halted coal production of these mines except at the Allen mine in the early 1950's. The Morley mine produced more than 11 million short tons by the time it was closed in 1956.

COAL-BED METHANE

During development of the Morley mine, Colorado Fuel and Iron Company drilled two wells to reduce gas in the coal mines. Additional indication of coal-bed methane emission was found in three coal mines in the basin, which was monitored by the U.S. Department of Labor, Mine Safety and Health Administration, venting more than 2 million cubic ft/day (Jurich and Adams, 1984). Gas shows are commonly encountered during drilling in sandstone of the Vermejo and Raton Formations (Dolly and Meissner, 1977). Since the drilling of the coal-gas relief wells at the Morley mine, coal-bed methane has been explored and developed from the Vermejo and Raton Formations. The Raton Formation coal contains as much as 193 cubic ft/short ton of methane gas (Tyler, 1955). In contrast, the Vermejo Formation coal contains as much as 492 cubic ft/short ton of methane gas (Tyler, 1995). Dolly and Meissner (1977) and Jurich and Adams (1984) estimated that total methane occuring in coal beds of both formations in the Raton Basin is as much as 38.7 trillion cubic ft (tcf). About half (18.4 tcf) of the original coal-bed methane is probably still contained in these coal beds (Dolly and Meissner, 1977; Tyler and others, 1992, 1995).

Tyler (1992) suggested that the coal-bed methane from these coal beds is mainly thermogenic. The origin of the methane was probably controlled by elevated coal rank caused by igneous intrusions (Carter, 1956; Steven, 1975; Dolly and Meissner, 1977; Amuedo and Bryson, 1977). The vitrinite reflectance values of the Vermejo Formation coal vary from 0.57 to 1.57 percent Ro with maximum values in the central part of the basin along the Purgatoire River valley (fig. SR-8). The basin is an area of anomalously high terrestrial heat flow related to the Spanish Peaks and associated underlying magmatic intrusions (Edwards and others, 1978). The presence of high heat flow and low-volatile coal in the Raton Basin indicates the potential generation of substantial amounts of dry methane.

Presently, 85 wells in the central part of the Raton Basin (see fig. SR-9) produce about 17.5 million cubic ft/day. Amoco accounts for about 3.5 million cubic ft/day from 27 wells, Evergreen Resources accounts for 10 million cubic ft/day from 33 wells, and Stroud Oil accounts for 4 million cubic ft/day from 25 wells (Johnson and Flores, 1998). Methane gas is mainly produced from the Vermejo Formation coal beds. Danilchik and others (1979) estimated about 84 billion cubic ft (bcf) of methane gas in a 25-square-mile area in the central part of the basin along the Purgatoire River where gas is currently being produced. This estimate assumed the presence of 7-ft-thick coal beds at depths ranging from 1,500 to 2,000 ft containing 416 cubic ft of gas per ton of coal. Tremain (1980) generated a larger estimate (311 bcf) of coal-bed methane resource for 54 square miles in the same area assuming the presence of 10-ft-thick coal beds. Desorption of coal in this area indicates methane contents ranging from 75 to 510 cubic ft/ton and averaging about 250 cubic ft/ton. Jurich and Adams (1984) defined the west-central part of the basin (310 square miles) as having the greatest potential for coal-bed methane plays in the Raton Basin, with the rest of the basin having a lower potential.

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The Oil and Gas Journal (Anonymous, 1999) reported a resumption of coal-bed methane development in the Raton Basin particularly in the Vermejo Park Ranch area or in the Raton coalfield in northeast New Mexico. A joint venture by PennzEnergy Co. and Sonat Exploration Co. targeted a 700,000-acre area in Colfax County, New Mexico. Pillmore (1991; 1999, pers. commun.) indicated that the rank of the Vermejo Formation coal in the western part of the Raton coalfield ranges from medium– to high–volatile bituminous and the Raton Formation coal is mainly high–volatile bituminous, which are different from that reported by Tyler (1995; see fig. SR-8). The new venture according to the Oil and Gas Journal is expected to "drill a minimum of 35 wells in 1999, followed by 80 wells in 2000, and 150 wells/year until reaching a maximum of about 600 wells."

CONCLUSIONS

Many mines closed in the mid 1950's with the advent of diesel engines. High mining costs and reduced coal utilization in steel making have contributed to decreased and limited development of coal in the Raton Basin. In order to encourage coal exploration and development in the basin, Amuedo and Bryson (1977) suggested potential utilization of the coal by (1) mine-mouth electric generating power plants, (2) creating degasification plants, (3) building a coal-slurry pipeline to transport coal to the Gulf coast, and (4) transporting Raton coal by rail to New Orleans where metallurgical coal is shipped to South America. Fuel for electric power plants and coal degasification probably remains the best potential use for coal in the basin. The low–sulfur content of this coal deposit of increases its potential use as clean and compliant coal for the next 20 to 30 years. In addition, the substantial remaining resource of coking coal in the ground increases the potential for futures of

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Raton Basin coal in domestic and/or international steel plants. Methane has been proven by operators to be a potential source of clean energy for the next few decades. However, the slurry pipeline and marketing of metallurgical coal to foreign markets may not be economically feasible in the immediate future.

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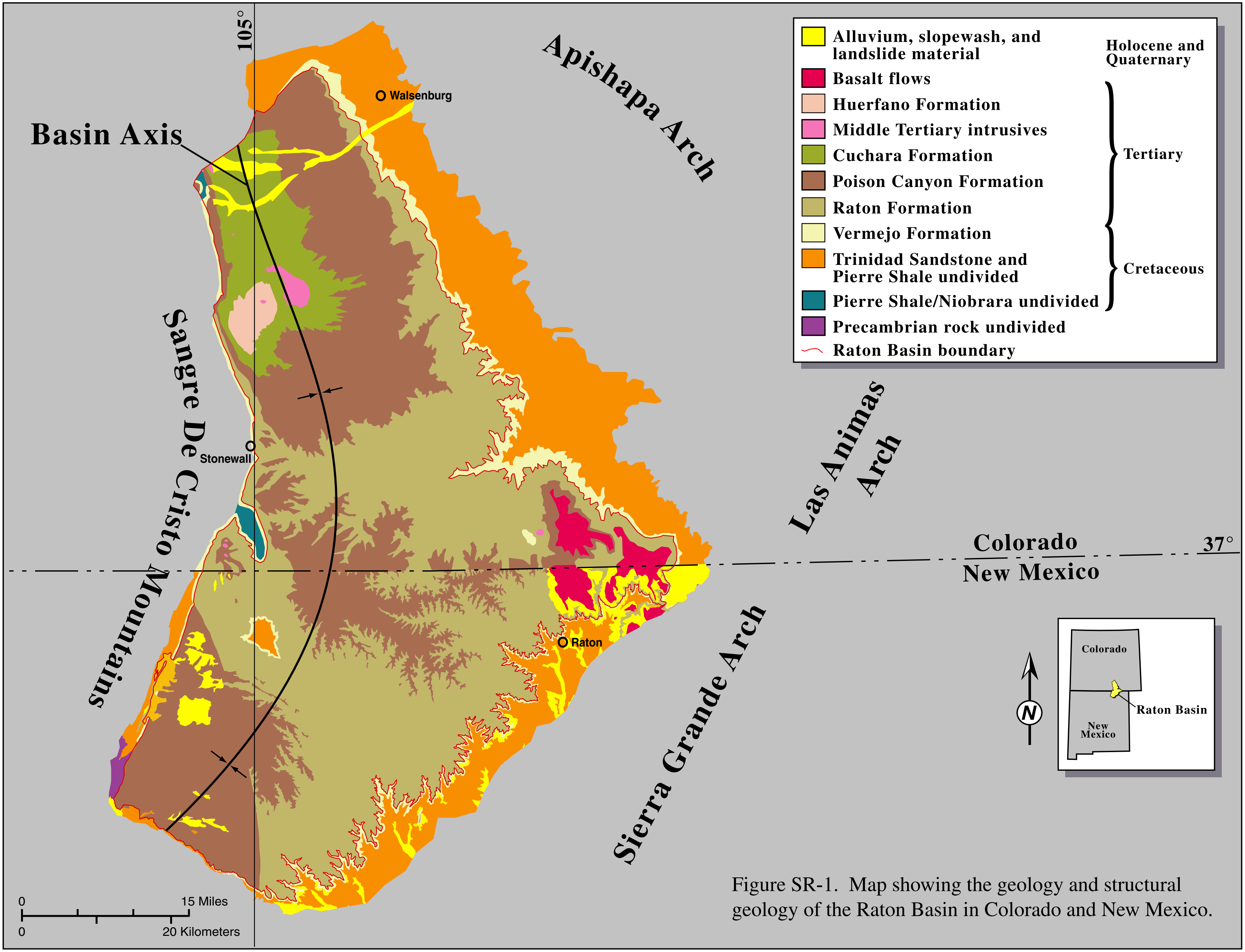

Figure SR-1. Map showing the geology and structural geology of the Raton Basin in Colorado and New Mexico.

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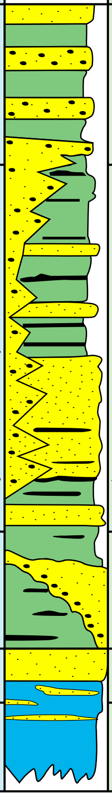
AGE		FORMATION NAME	GENERAL DESCRIPTION	LITH-OLOGY	APPROX. THICKNESS IN FEET
TERTIARY	PALEOCENE	POISON CANYON FORMATION	SANDSTONE–Coarse to conglomeratic beds 13–50 feet thick. Interbeds of soft, yellow-weathering clayey sandstone. Thickens to the west at expense of underlying Raton Formation		500+
		RATON FORMATION	Formation intertongues with Poison Canyon Formation to the west UPPER COAL ZONE–Very fine grained sandstone, siltstone, and mudstone with carbonaceous shale and thick coal beds BARREN SERIES–Mostly very fine to fine grained sandstone with minor mudstone, siltstone, with carbonaceous shale and thin coal beds LOWER COAL ZONE–Same as upper coal zone; coal beds mostly thin and discontinuous. Conglomeratic sandstone at base; locally absent		0?–2,100 ← K/T Boundary
MESOZOIC	UPPER CRETACEOUS	VERMEJO FORMATION	SANDSTONE–Fine to medium grained with mudstone, carbonaceous shale, and extensive, thick coal beds. Local sills		0–380
		TRINIDAD SANDSTONE	SANDSTONE--Fine to medium grained; contains casts of *Ophiomorpha*		0–300
		PIERRE SHALE	SHALE--Silty in upper 300 ft. Grades up to fine grained sandstone. Contains limestone concretions		1800-1900

Figure SR-2. A generalized stratigraphic column of the Cretaceous and Tertiary rocks in the Raton Basin. Adapted from Pillmore (1969), Pillmore and Flores (1987), and Flores (1987).

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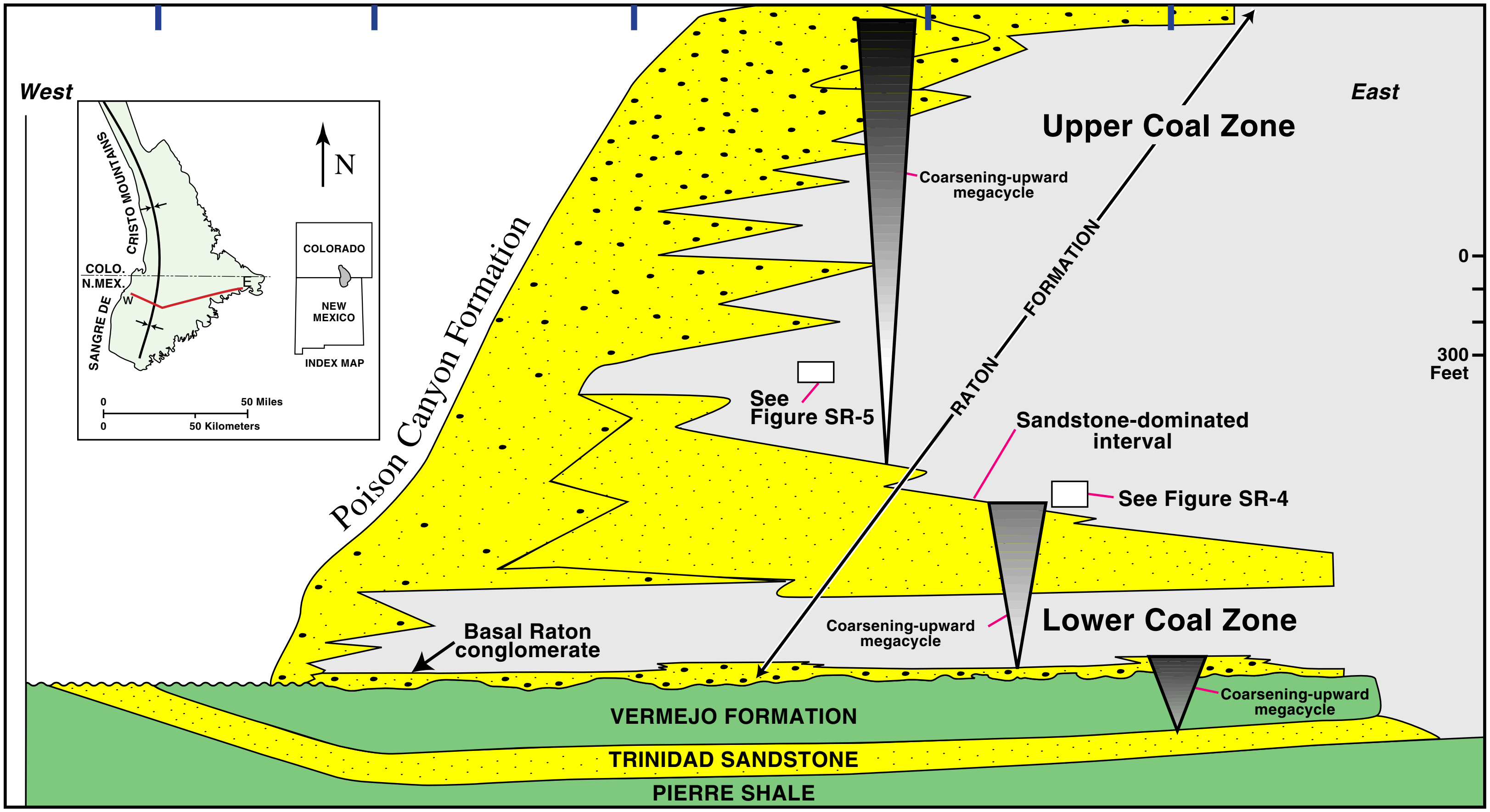

⬜ Coal

🟨 Sandstone

🟩 Siltstone and mudstone

▍ Measured section

〰 Cross section

Figure SR-3. Stratigraphic cross section (west to east) across the southern part of the Raton Basin showing vertical and lateral variations of the Cretaceous and Tertiary rocks. The vertical variation is demonstrated by the succession of coarsening-upward megacycles that divide the Cretaceous and Tertiary rocks. Modified from Flores (1987).

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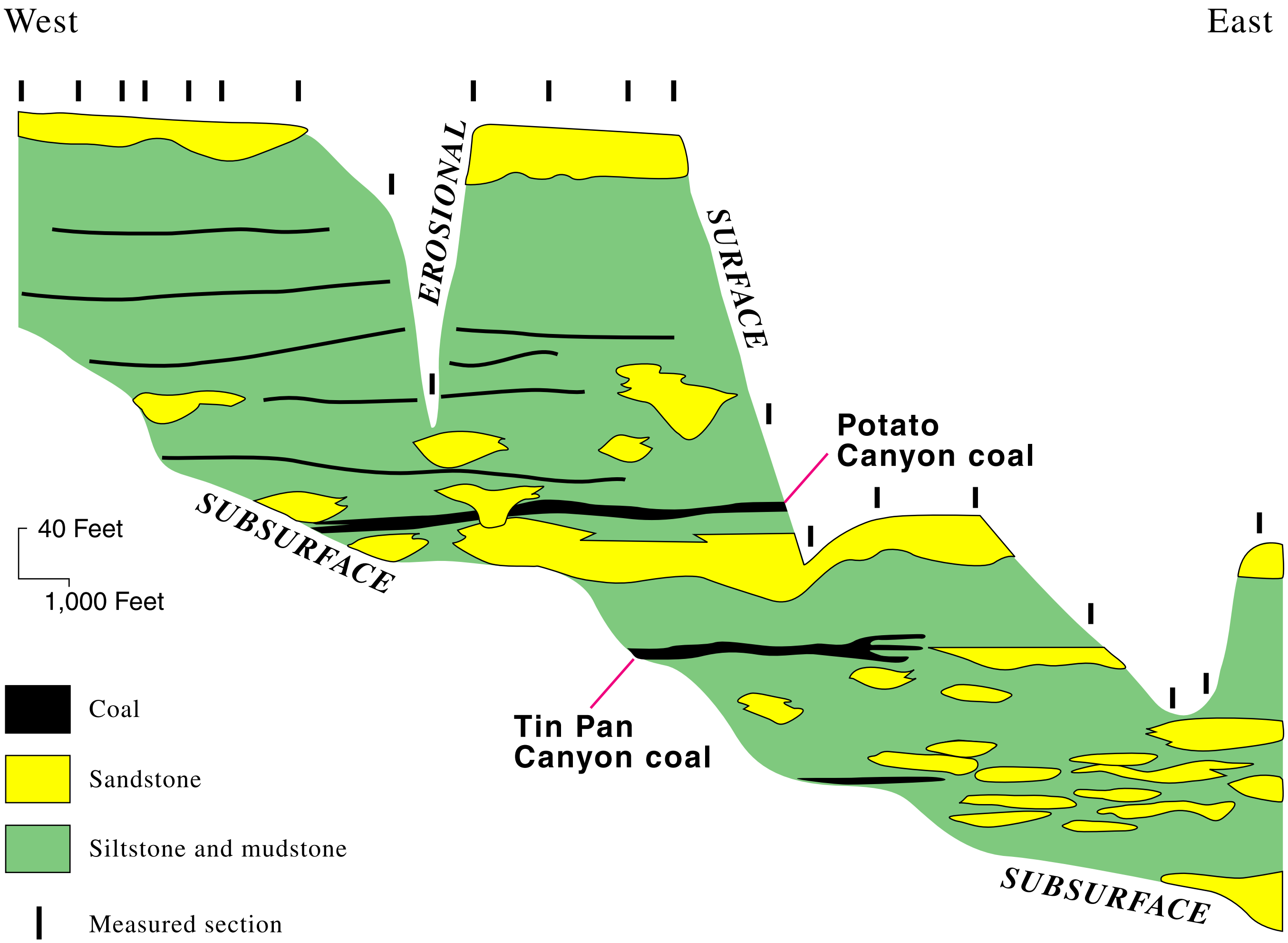

Figure SR-4. Lateral and vertical variations of coal-bearing rocks in the lower part of the upper coal zone of the Raton Formation in the southern part of the basin. Modified from Strum (1984).

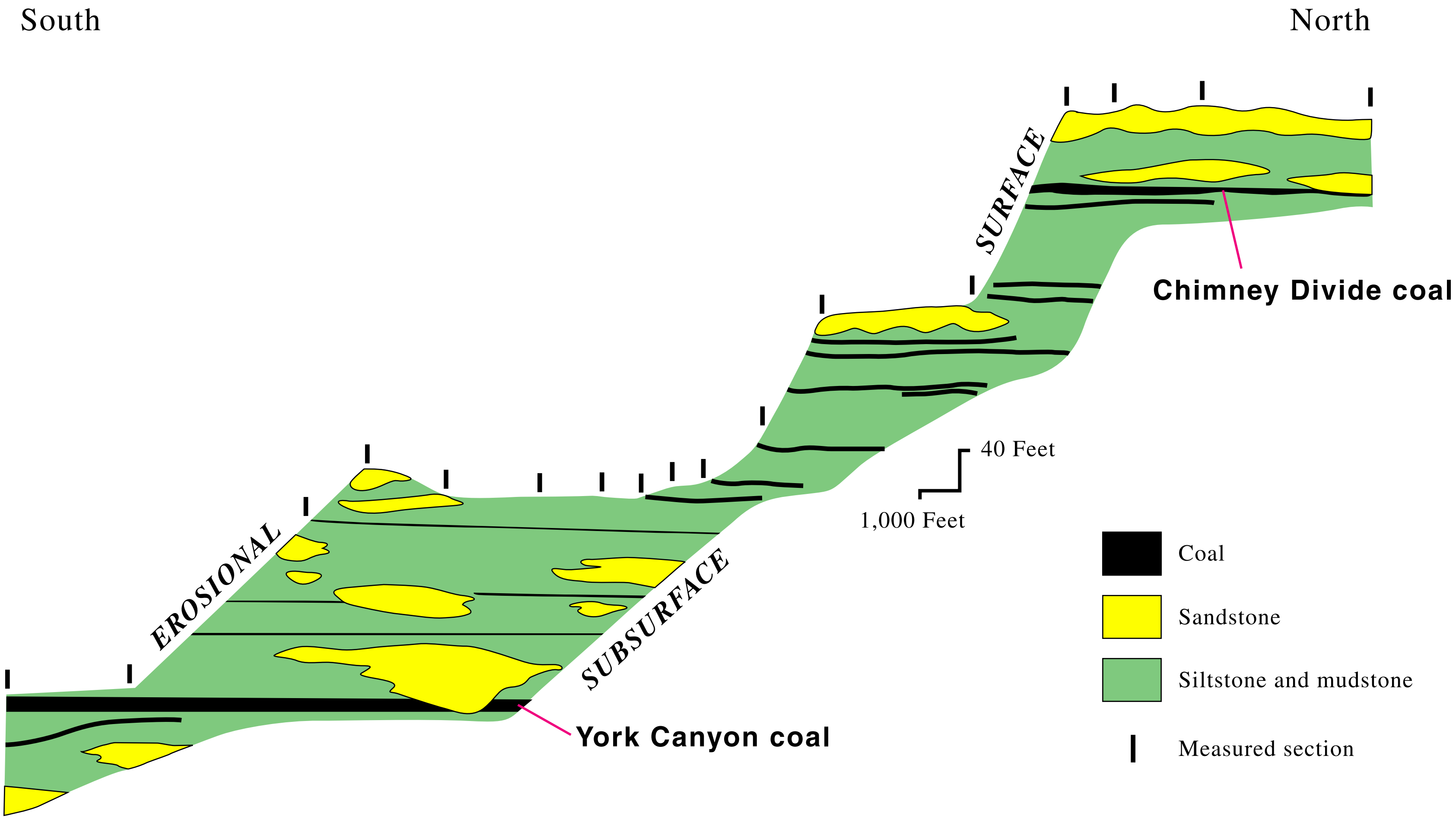

Figure SR-5. Lateral and vertical variations of coal bearing rocks in the upper part of the upper coal zone of the Raton Formation in the southern part of the basin. Modified from Strum (1984).

Fence diagram of the York Canyon Coal

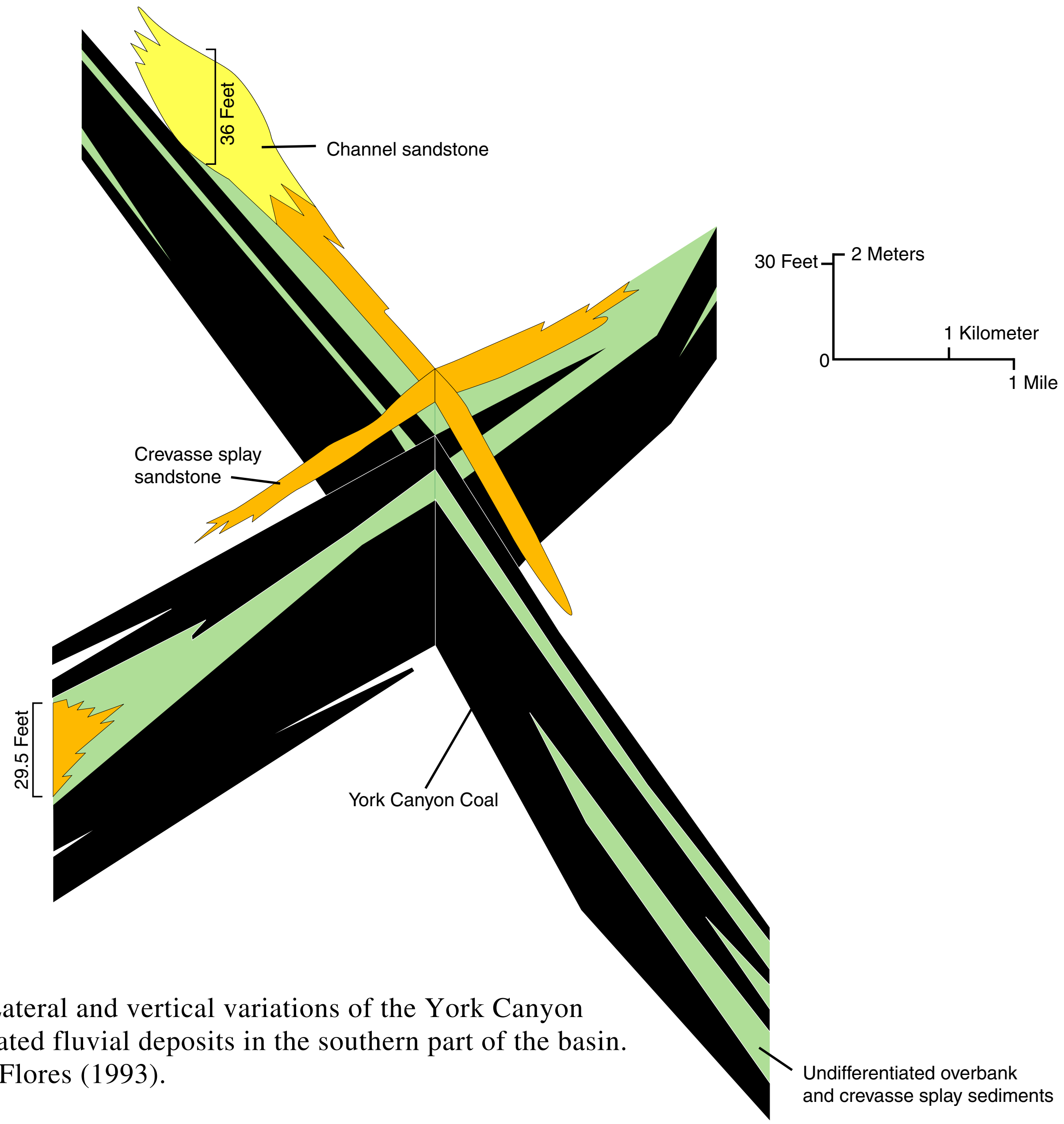

Figure SR-6. Lateral and vertical variations of the York Canyon coal and associated fluvial deposits in the southern part of the basin. Modified from Flores (1993).

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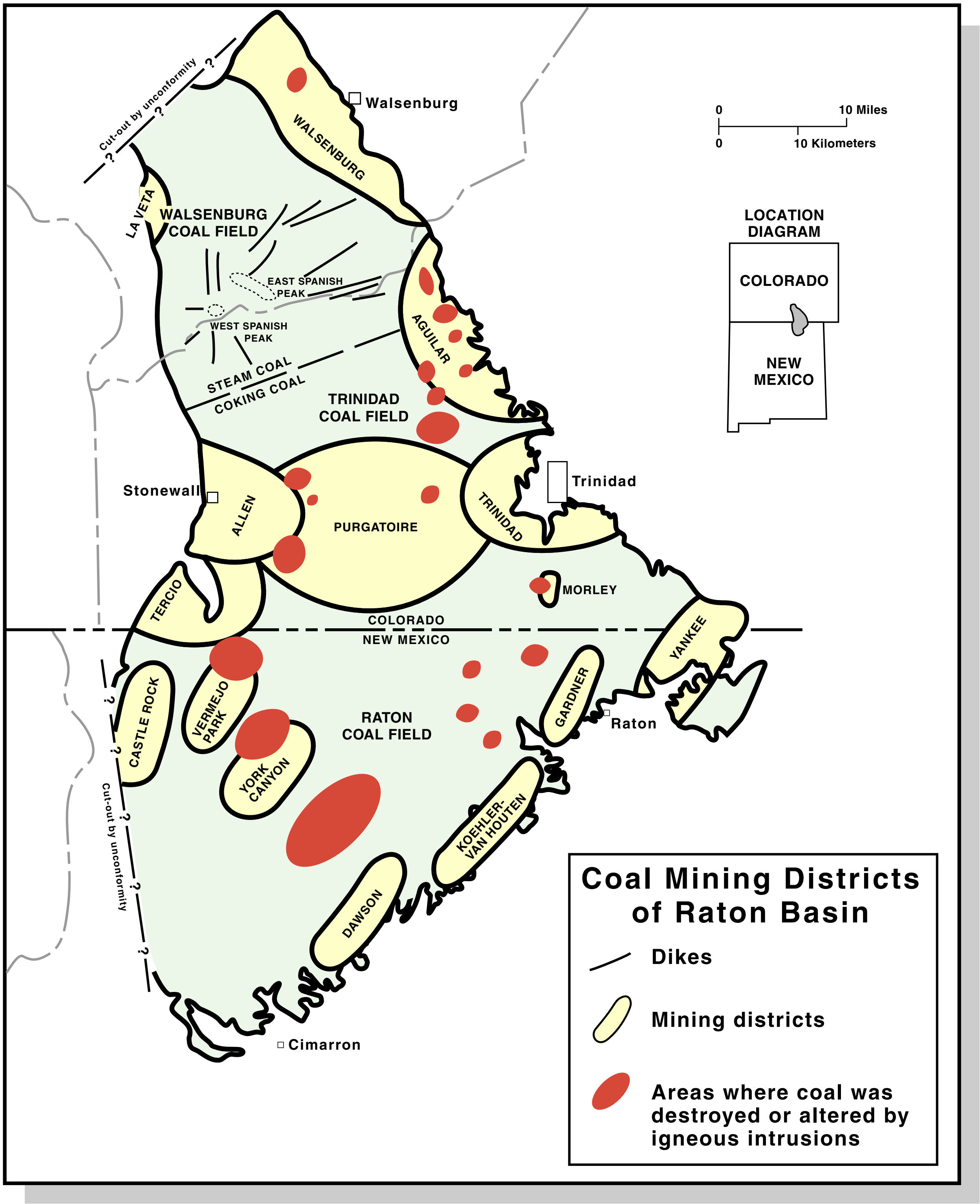

Figure SR-7. Map showing the coal mining districts in the Raton Basin in Colorado and New Mexico. Modified from Pillmore (1969), Amuedo and Bryson (1977), Jurich and Adams (1984), and Pillmore (1991).

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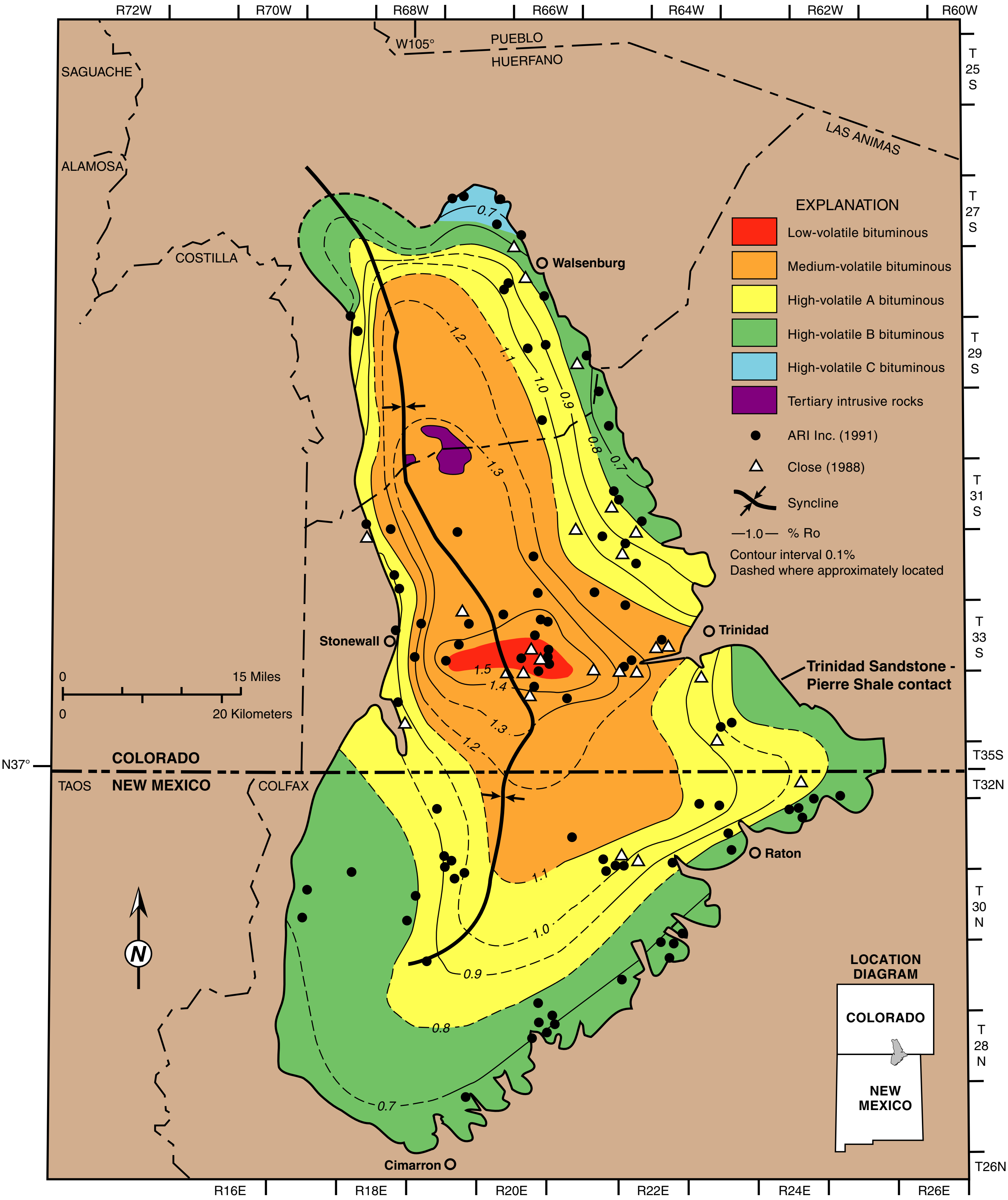

Figure SR-8. Coal rank map of the lower part of the Upper Cretaceous Vermejo Formation. Variations in vitrinite reflectance are also shown. Modifed from Tyler and others (1995).

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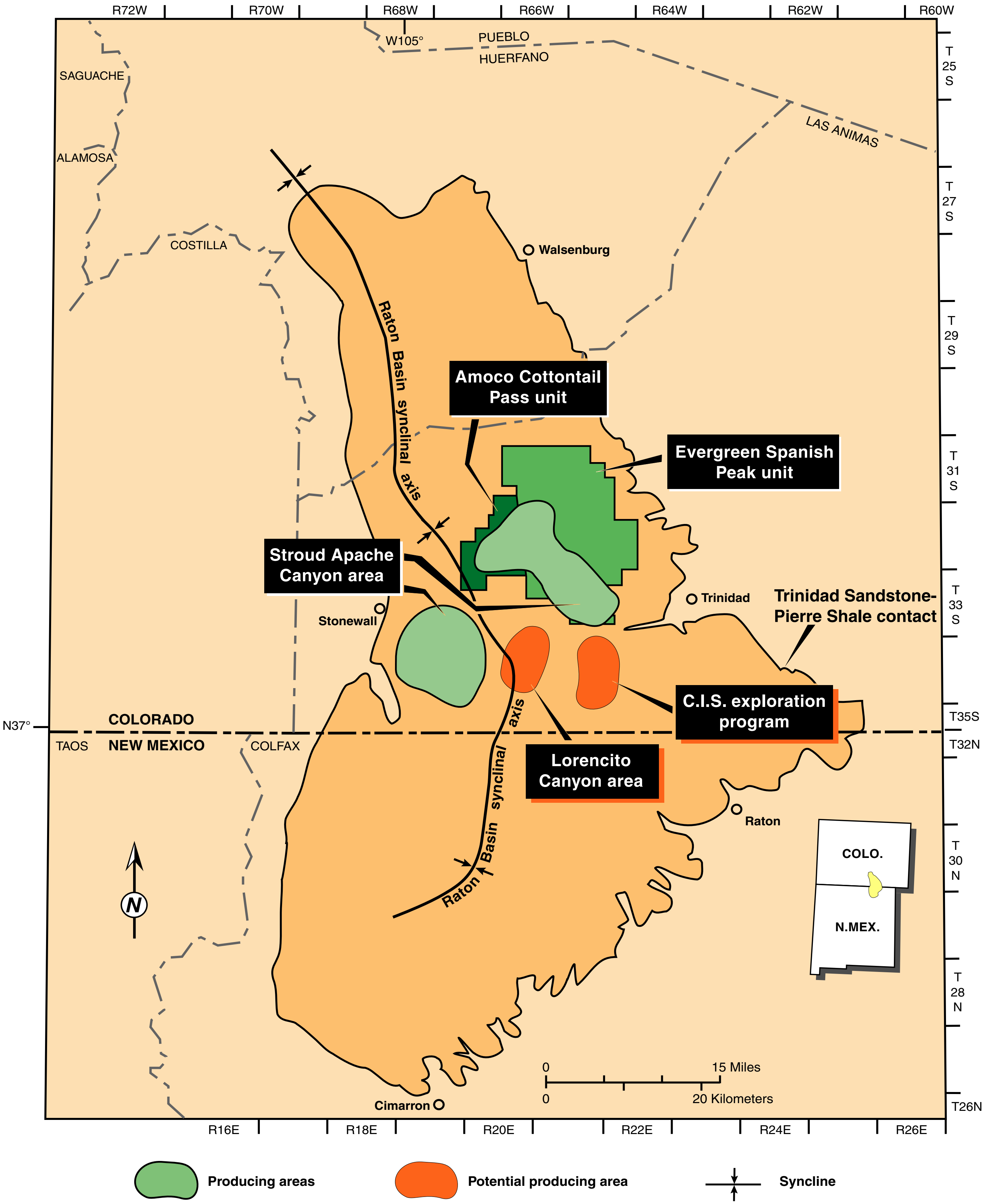

Figure SR-9. Map showing areas of current and potential coal-bed methane production in Raton Basin. Adapted from Hemborg (1996).