PUEBLO INDIAN RESERVATIONS

Geology

A majority of the Pueblo Indian Reservations are located within the Rio Grande Rift, which trends north-northeast from south-central New Mexico to central Colorado (Chapin, 1971). In addition, small segments of the Pueblo Reservation overlie the Acoma Basin, located to the west of the Rio Grande Rift, and the Raton Basin which lies east of the San Luis Basin in northeast New Mexico (Fig. P-1). The rift lies along boundaries of several major physiographic provinces, the most fundamental of which are the Great Plains and Southern Rocky Mountains to the east, and the Colorado Plateau and Basin and Range to the west (Fig. P-2). The sedimentary layers that fill these basins gently dip towards the center of the basin, which has dropped in relation to the surrounding strata due to normal or extensional faulting associated with the Rio Grande Rift.

The following sections describe the geology of the (1) Albuquerque-Santa Fe Rift Province, (2) Raton Basin-Sierra Grande Uplift Province with focus on the southern Raton Basin, and (3) South-Central New Mexico Province, in particular the Acoma Basin. Oil and gas production within each province is summarized in the "Production Overview" section.

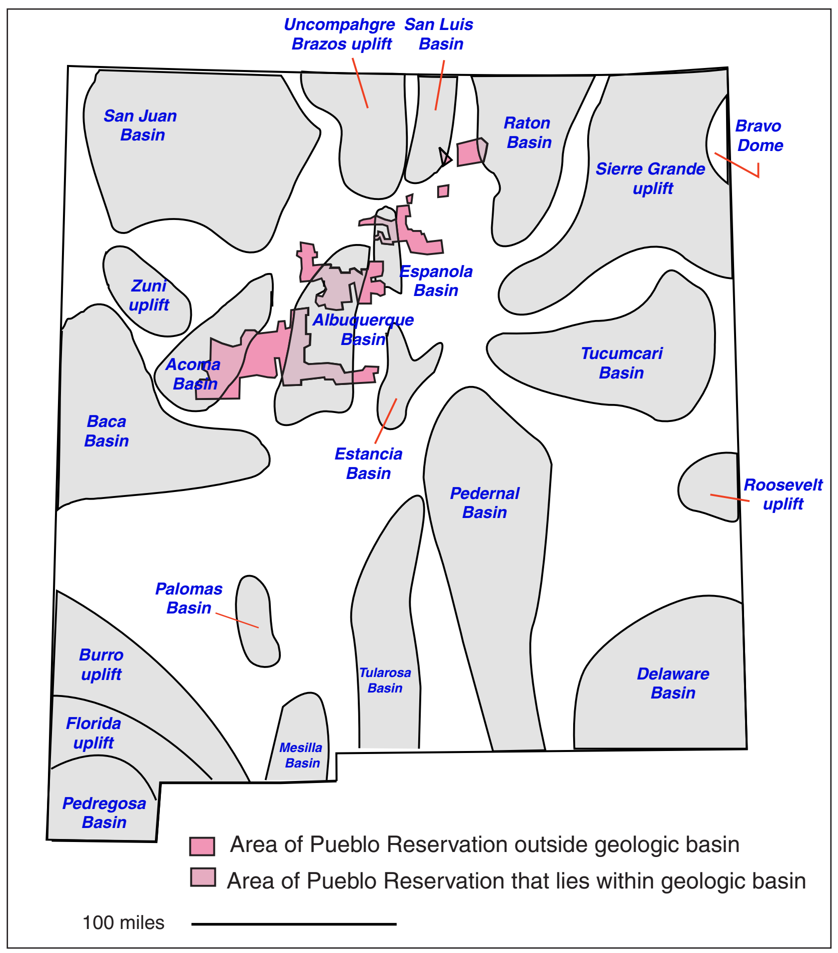


Figure P-1. Outline of major geologic basins in New Mexico with respect to the Pueblo Indian Reservations (modified after Broadhead, 1996).

ALBUQUERQUE, ESPANOLA, AND SAN LUIS BASIN

Geologic Structure

In mid-Oligocene time, regional extension occurred along a major north-trending zone of weakness called the Rio Grande Rift. As the rift opened, it broke en echelon along pre-rift lineaments developed during earlier orogenies (Fig. P-3). High heat flow and volcanism accompanied rifting. The resulting offset of the graben along old structural lineaments and the uneven distribution of the volcanic centers have divided the rift basin into sub-basins which include, from south to north, the Albuquerque, Espanola (or Santa Fe), and San Luis basins. The southern extension of the Espanola Basin is known as the Hagan and Santa Fe Embayments, which are separated by the Cerrillos Uplift, a late Tertiary east-tilted fault block (Fig. P-4). The Hagan embayment is west of the Cerrillos Uplift and the Santa Fe Embayment is to the east. For discussion purposes, these two embayments are combined and are called the Hagan-Santa Fe Embayment. In addition, the San Luis Basin has been further divided into, from east to west, the Baca Graben, the Alamosa Horst, the Monte Vista Graben, and the San Juan Sag (Gries, 1985).

Structure within the rift basins is largely masked by late Tertiary and Quaternary basin fill. Geophysical (mainly gravity) data indicate varying amounts of Tertiary fill (Cordell-Lindrith et al., 1982). The west sides of the basins are generally downdropped in a stepwise fashion by many down-to-the-east normal faults. The deepest parts of the basins are generally on the east side (Fig. P-4).

Wells penetrating the Mesozoic and Paleozoic section in the Albuquerque Basin also indicate that the basin is down-dropped by many normal faults. Wells in the middle of the basin indicate more than 10,000 feet of fault displacement between wells just a few miles apart (Black, 1982). The deepest well drilled in the Albuquerque Basin, the Shell Oil Co. Isleta No. 2 was in Tertiary rocks at a total depth of 21,266 feet. The vertical relief between the projected Precambrian surface in that well and the Precambrian rocks exposed in the Manzano Mountains 16 miles to the east is at least 32,000 feet.

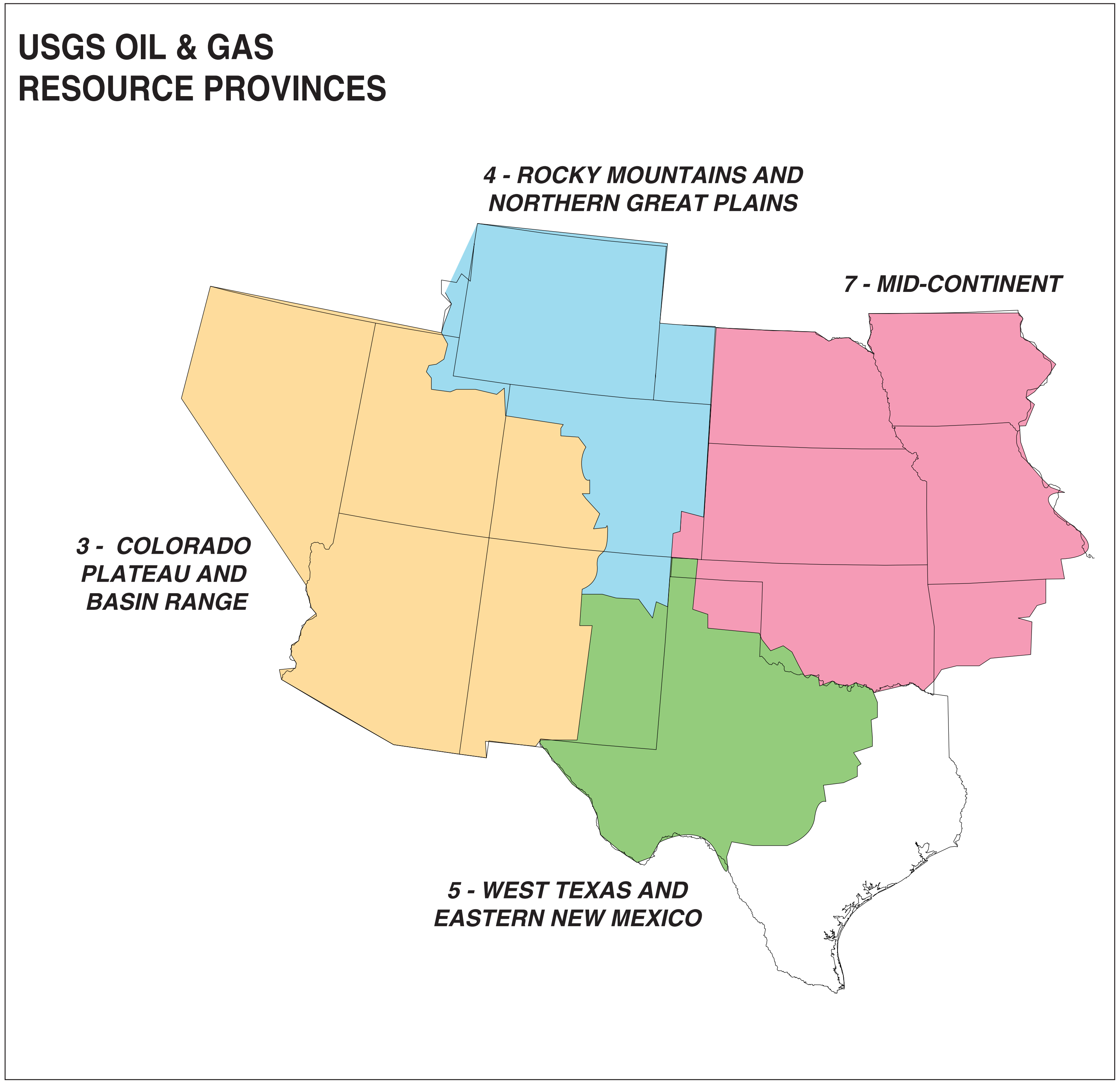


Figure P-2. Location of Pueblo Indian Reservations with respect to USGS defined geologic provinces of the United States (modified after Charpentier et al., 1996).

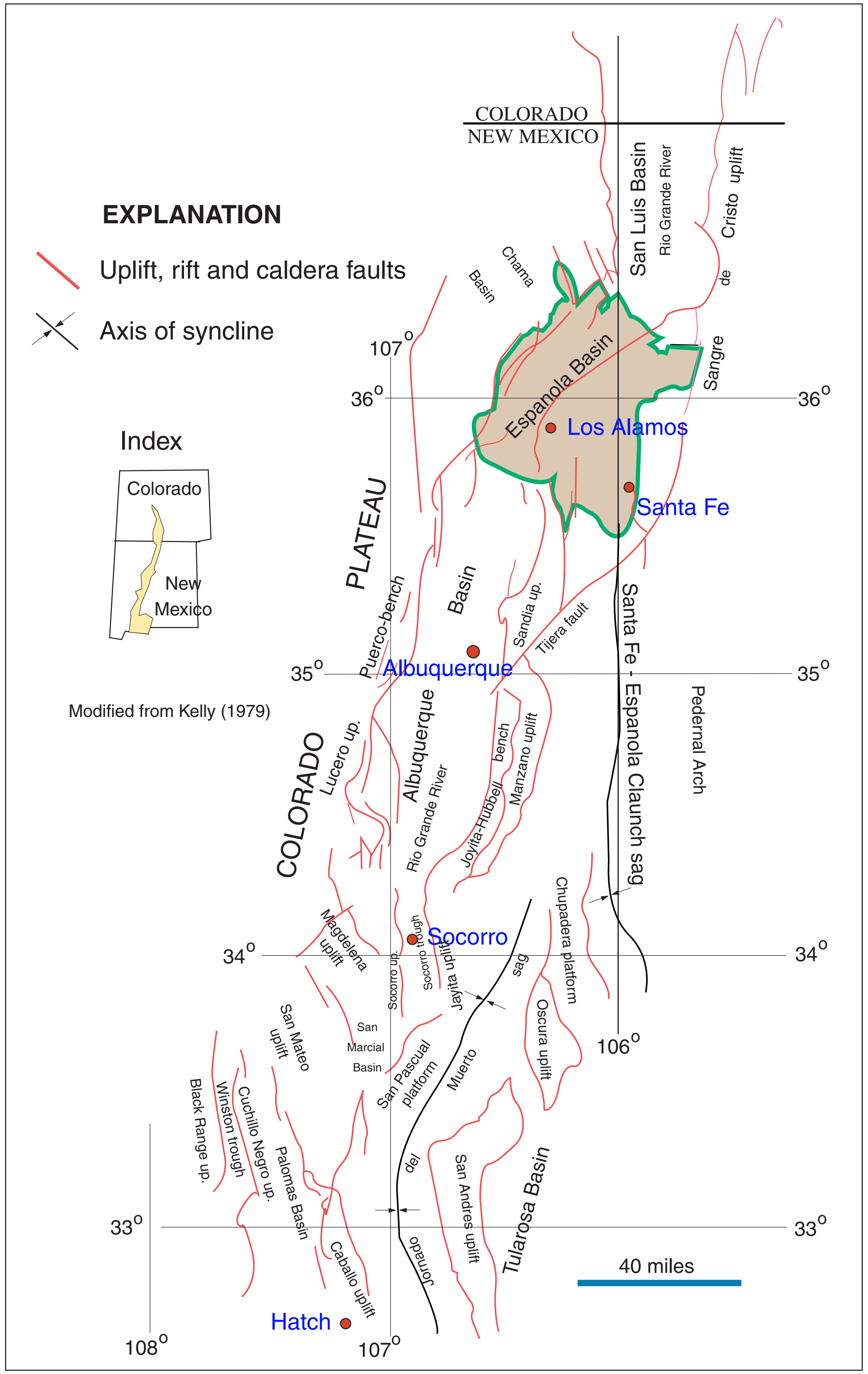


Figure P-3. Tectonic map of the Rio Grande Valley in North-Central New Mexico (modified after Kelley, 1979).

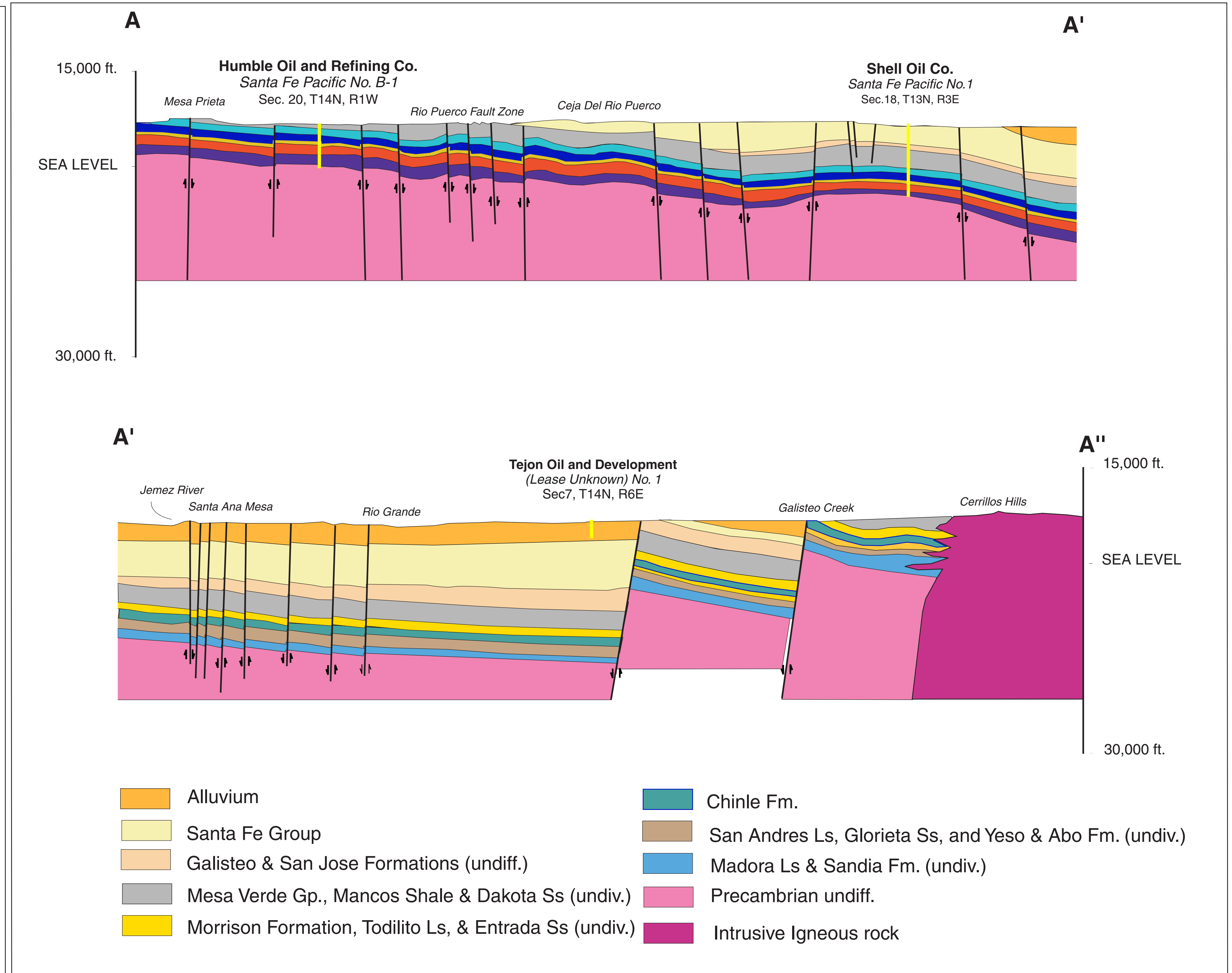


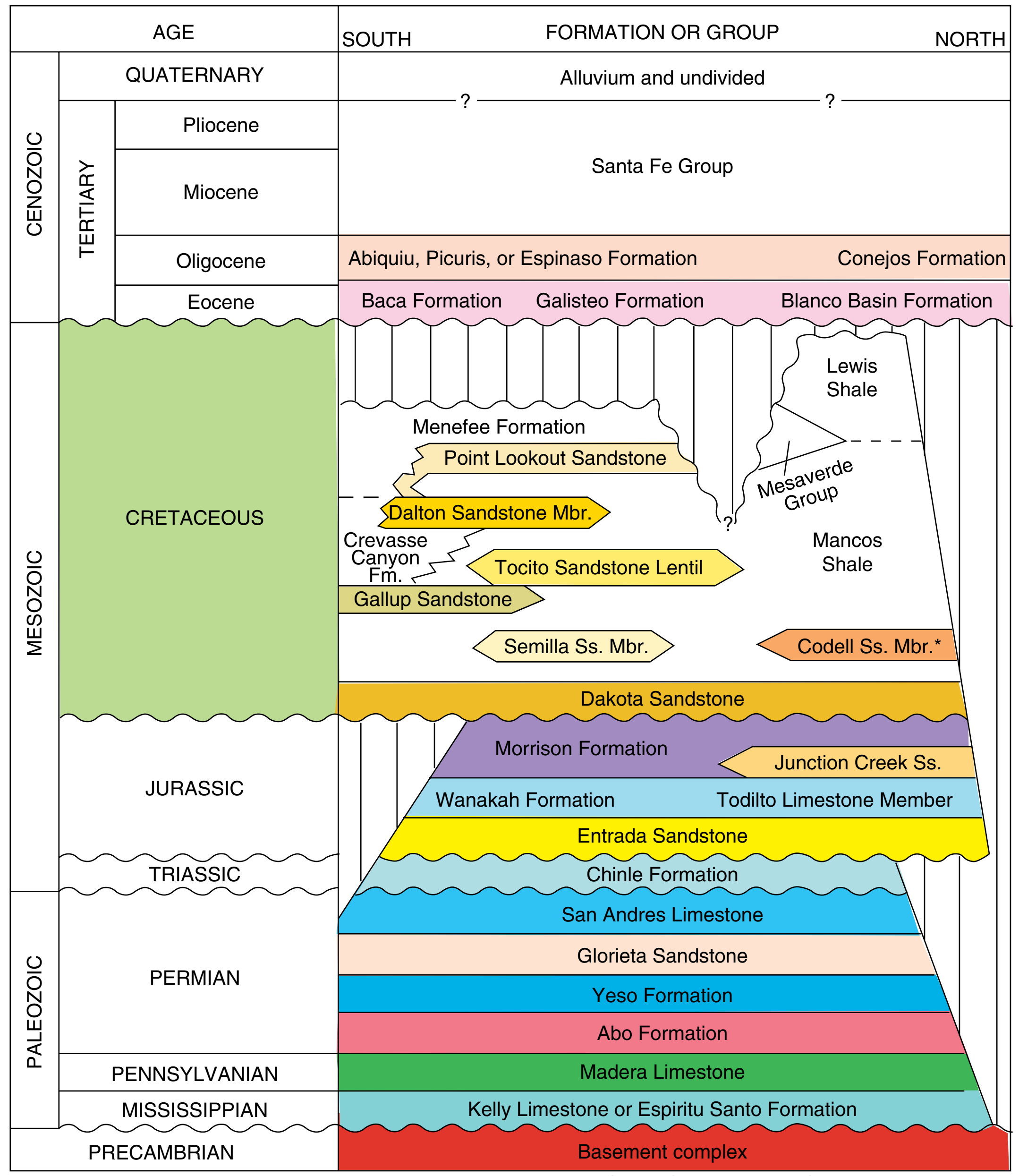
Figure P-4. Geologic cross-section across the northern part of the Albuquerque Basin and the southern part of the Espanola Basin (Fig. P-7; cross-section 1) (modified after Black and Hiss, 1974).

Stratigraphy

The Albuquerque-San Luis Rift Basin contains rocks ranging in age from Precambrian to Recent (Fig. P-5). Most of the basin fill consists of thick deposits of nonmarine synrift sedimentary rocks and intercalated volcanic rocks, especially in the lower part. Pre-rift (pre-Oligocene) sedimentary rocks are exposed on the flanks of the basin or have been penetrated by drill holes, primarily in the southern part of the rift basin. Much or all Mesozoic and Paleozoic strata, the petroleum prospective part of the section, are missing in the northern half of the basin because of Pennsylvanian-Permian and Laramide uplift and erosion that affected much of that area.

A nearly complete section of Cretaceous and older rocks is present in much of the Albuquerque Basin. Well control in the basin and outcrop control along the flanks indicate that pre-middle Eocene erosion has removed a variable amount of the Cretaceous section, which is the primary petroleum prospect within the section. To the north, in the Espanola Basin, the Eocene unconformity cuts down section, completely removing the Cretaceous section. Figure P-6 is a generalized stratigraphic column for the Albuquerque Basin with sections of interest to petroleum geology highlighted. Mesozoic and Paleozoic strata of the Albuquerque Basin are similar to these of the well-explored and productive San Juan Basin to the northwest, hence some analogues can be made. Figures P-7 and P-8 show the Cretaceous stratigraphic relations as determined from discontinuous outcrops along the east side of the Albuquerque Basin.

The Jurassic and Cretaceous section is partially preserved on the west side of the San Luis Basin. In that area, the Entrada Sandstone rests unconformably on Precambrian basement rocks. The Cretaceous section consists of the basal Dakota Sandstone (100 to 200-feet thick); the Mancos Shale (~1500-feet thick); and about 600 feet of Lewis Shale below the Eocene unconformity. The Gallup, Dalton, and Point Lookout marine shoreface sandstone units that are present to the southwest have pinched out and the Mancos and Lewis Shales have merged. The contact between the two shale units is identified by a silty or discontinuous sandy zone. Well and seismic data indicate that the Jurassic and Cretaceous section is progressively truncated from west to east under the Eocene unconformity in the western part of the San Luis Basin (Gries, 1985).



*of Carlile Shale (eastern Colorado terminology)

Figure P-5. Stratigraphic section depicting bedding relationships within the Albuquerque-Santa Fe Rift Geologic Province (modified after Gautier et al., 1996).

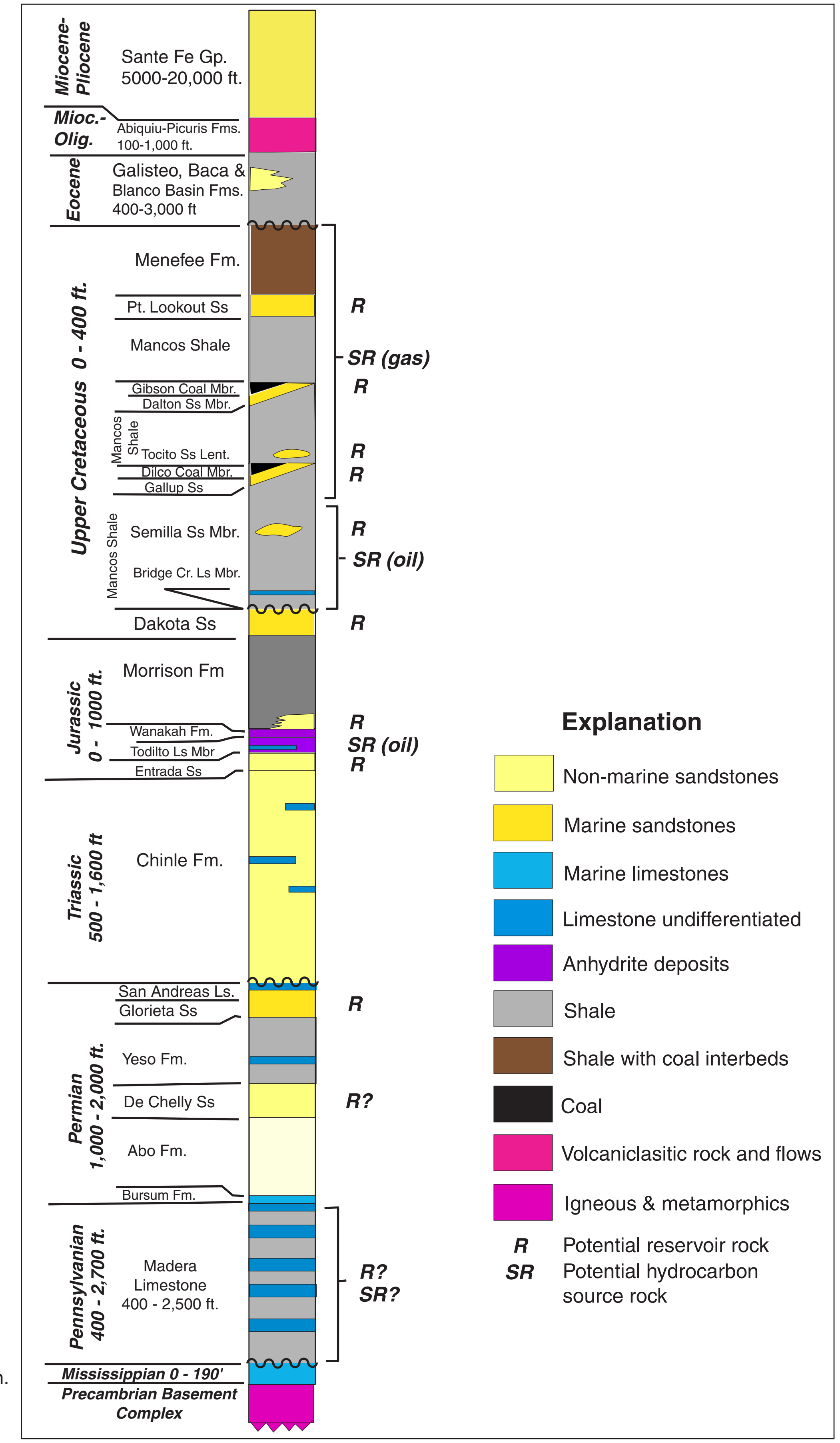


Figure P-6. Generalized stratigraphic columnar section for Albuquerque Basin. (modified after Molenaar, 1987).

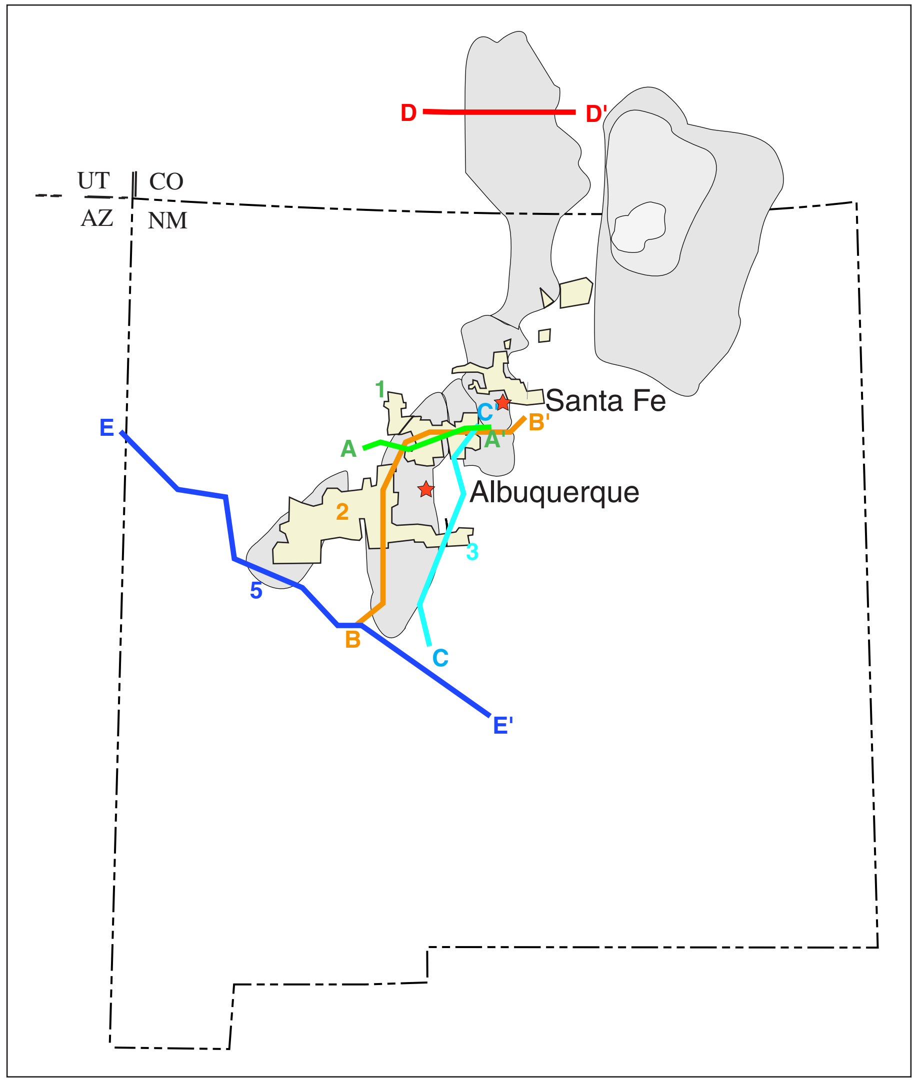


Figure P-7. Location of cross-sections through study area (modified after Molenaar, 1987; Black, 1982; and Woodward, 1984)

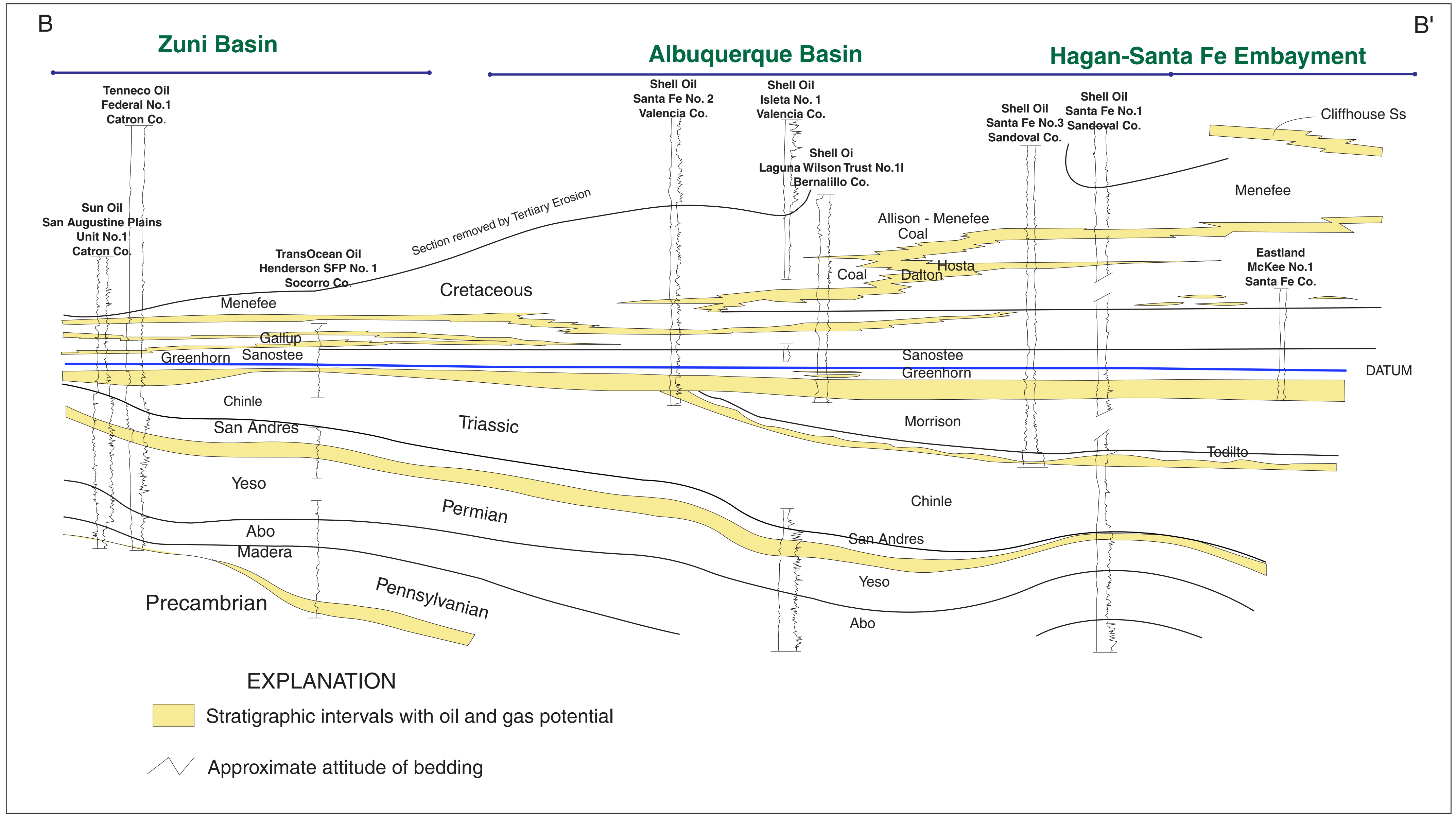


Figure P-8. Stratigraphic cross-section from outcrop along the Zuni and Acoma basins (Fig. P-7; cross-section 2). (modified after Molenaar, 1974)

RATON BASIN

Geologic Structure

The Raton Basin is asymmetrical with a steep western limb and a gently dipping eastern limb (Fig. P-9). The synclinal axis occurs near the western part of the basin. The part of the basin in New Mexico is about 100 miles long and is divided into 2 parts by the Cimarron Basement Arch that extends westward from Maxwell.

T ectonic evolution of the Raton Basin during Laramide time was described by Johnson and Wood (1956). Uplift of the Sangre de Cristo area west of the Raton Basin provided a source of detritus that was deposited as sand as the upper part of the Pierre Shale, Trinidad Sandstone, and Vermejo Formation during Late Cretaceous time. Strong uplift in the Sangre de Cristo area near the end of the Cretaceous time provided a source of sediment for the Raton Formation and the lower part of the Poison Canyon Formation. The uplift was rejuvenated in the Paleocene and Eocene times with tilting and folding as uplift continued to the west. Some of the Poison Canyon Formation was eroded at that time. Thrusting and folding occurred twice during the Eocene and the present structure outlines of the Raton Basin and the Sangre de Cristo Uplift were attained. Epeirogenic upwarping of the region in late Tertiary time was accompanied by normal faulting (Woodward, 1984).

The western mar gin of the basin is marked by steeply dipping thrust and reverse faults that have pushed Precambrian and Paleozoic rocks eastward for short distances over Paleozoic and, locally, over Mesozoic rocks. To the east, the basin merges gradually with the western limb of the Sierra Grande Arch through low dips. South of Las Vegas, the axis of the Raton Basin dies out in gently dipping Permian and Triassic rocks (Woodward, 1984).

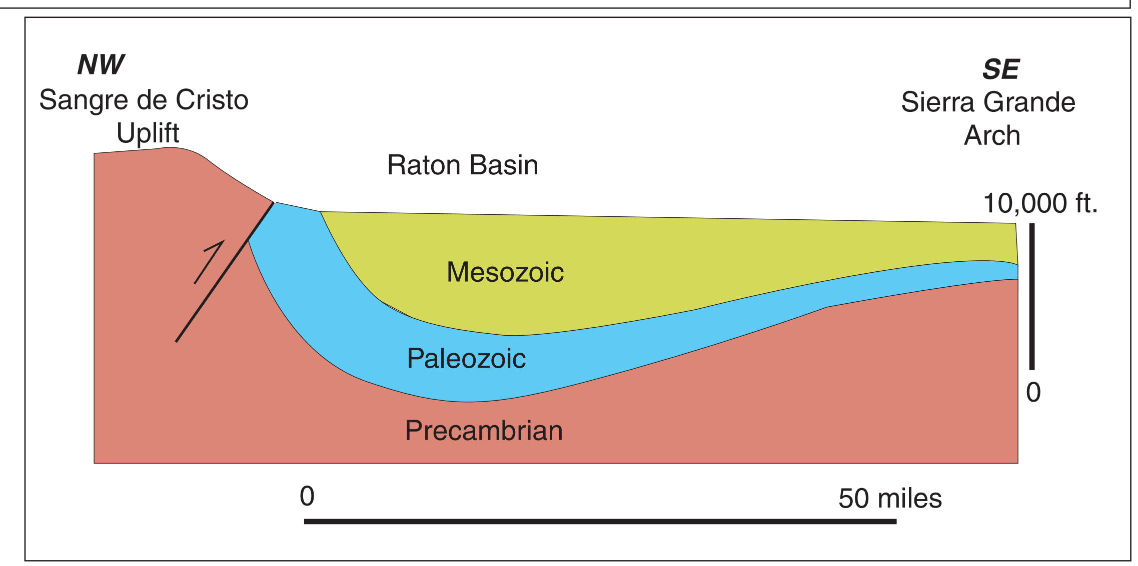


Figure P-9. Geologic cross-section across the Raton Basin illustrating the asymmetrical syncline associated with the Sangre de Cristo Uplift (modified after Woodward, 1984).

Stratigraphy

Strata of Cretaceous age are the most significant for hydrocarbon exploration and production in the Raton Basin and have a maximum thickness of about 4,700 feet near the New Mexico-Colorado border. The following units, in ascending order, are present: Purgatoire Formation, Dakota Sandstone, Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, Pierre Shale, Trinity Sandstone, Vermejo Formation, and the basal part of the Raton Formation. Figure P-10 shows the gamma ray log of the Cretaceous strata in the Raton Basin. Figure P-11 represents a complete stratigraphic section within the Raton Basin.

Baltz (1965) reported that the Purgatoire Formation is present in most of the Raton Basin, but Jacka and Brand (1972) suggested that no Purgatoire is present in the southern part of the basin near Las Vegas, New Mexico. The Purgatoire consists of a lower conglomerate sandstone and an upper unit of interbedded sandstone and carbonaceous shale. Woodward (1984) stated that the Purgatoire is often included as part of the Dakota Sandstone because differentiation is difficult.

The Dakota Sandstone in the Raton Basin consists of three intervals (Jacka and Brand, 1972). Gilbert and Asquith (1976) reported that the lower interval is sandstone with conglomerate lenses, the middle interval contains interbedded sandstone, carbonaceous shale, and coal, and the upper interval is composed of transgressive sandstone. Total thickness of the Dakota Sandstone plus the Purgatoire Formation, where present, ranges from 110-220 feet.

Lying conformably on the Dakota is the Graneros Shale, which consists of dark-gray marine shale with minor interbeds of bentonite, limestone, and fine-grained sandstone. This unit is about 115-270 feet thick, but most sections are about 170 feet thick.

The Greenhorn Limestone, lying conformably on the Graneros, consists of thin-bedded marine limestone with intercalated gray calcareous shale. In the Raton Basin, the Greenhorn is 20-90 feet thick, but most sections are 30-60 feet thick.

In conformable contact on the Greenhorn is the Carlile Shale, which is composed of dark-gray marine shale with minor thin limestone interbeds, calcareous concretions, and calcareous sandstone and sandy shale, particularly in the upper part. Where the sandstone is prominent, it is referred to as the Codell Sandstone Member and attains thicknesses up to 20 feet. The Carlile ranges in thickness from about 110 to 320 feet, with most localities having thicknesses of approximately 175 feet.

The marine Niobrara Formation above the Carlile has a lower member, the Fort Hays Limestone, composed of thin-bedded limestone and subordinate intercalated gray calcareous shale, and an upper member, the Smokey Hill Marl, made up of calcareous shale with subordinate thin interbeds of gray limestone and sandy shale. The Fort Hays Limestone Member is about 20-45 feet thick, and the Niobrara as a whole is about 250-285 feet thick.

Conformably above the Niobrara is the marine Pierre Shale,

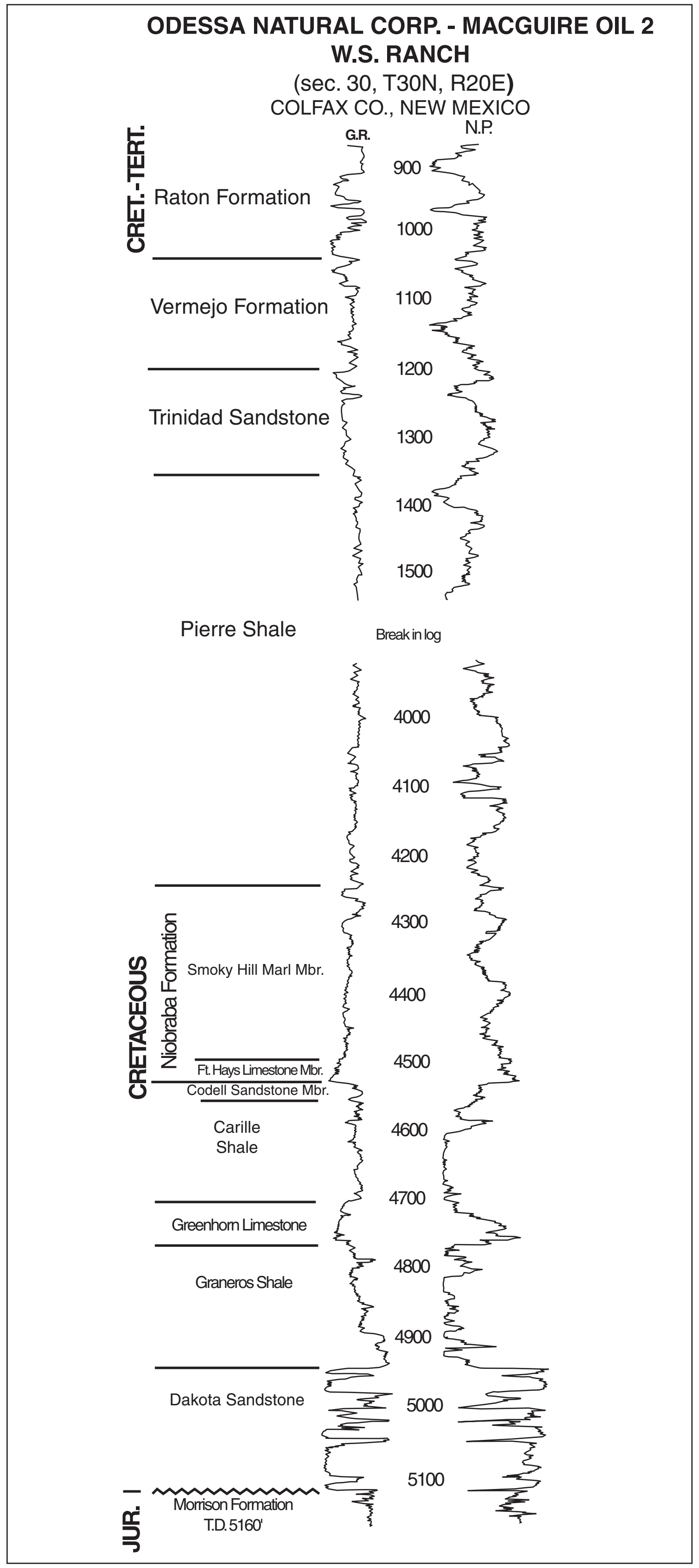


Figure P-10. Gamma ray-neutron porosity log showing Cretaceous strata of Raton Basin, New Mexico. Log from Odessa Natural Corporation-Maguire Oil No.2, W.S. Ranch; sec 30, T30N, R20E (modified after Woodward 1984).

which consists mainly of dark-gray to blackish shale with minor thin interbeds of sandy shale, sandstone, and limestone. The upper 100 feet is transitional with overlying Trinidad Sandstone and consists of interbedded shale and thin beds of sandstone. The Pierre Shale is generally 2,400-2,900 feet thick, although the reported thickness in one well was only 1,700 feet.

The Trindad Sandstone is an argillaceous sandstone with a maximum thickness of about 200 feet in the New Mexico part of the Raton Basin and a minimum subsurface thickness of 100 feet. Matuszczak (1969) interpretated the Trinidad Sandstone as beach, nearshore, and offshore deposits formed by a regressive sea retreating toward the northeast. Occasional pauses in regressions or transgressions toward the southwest resulted in thickening and winnowing of the sands, leading to northwest-elongated, thick lenses with high porosities. Reports of maximum porosity of 21% and permeability of 200 md were made for areas where the sandstone is thickest.

The Vermejo Formation ranges from a maximum thickness of about 400 feet in the subsurface to a wedge edge on the east side of the basin near Raton. It is composed of fine to medium-grained sandstone, gray carbonaceous shale, and coal interpreted as a flood-plain and swamp deposit.

The Raton Formation is Cretaceous and Paleocene in age and consists of very fine to coarse-grained sandstone, arkose, and gray wacke with interbedded gray siltstone, shale, and coal. A thin conglomerate or conglomeratic sandstone is present at the base of the formation. This unit was deposited in back-barrier swamps and alluvial-plain back swamps (Pillmore, 1991) and ranges from a wedge to about 1,700 feet thick in the Colorado part of the basin. Toward the southwest, beds in the upper part of the Raton Formation intertongue with and grade into the lower beds of the overlying Paleocene Poison Canyon Formation. The Poison Canyon is the youngest formation preserved in the New Mexico part of the Raton Basin.

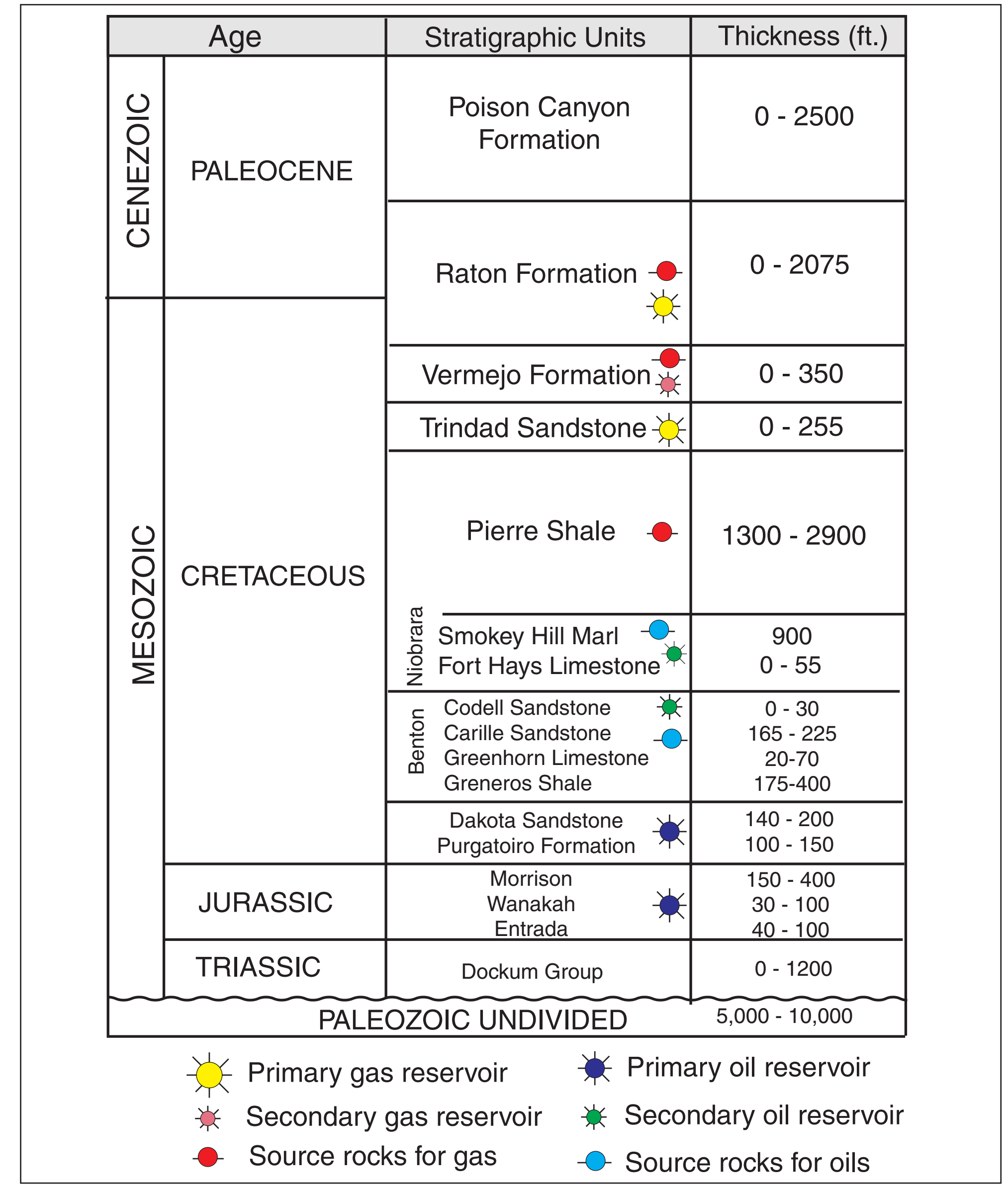


Figure P-11. Stratigraphic section depicting bedding relationships within the Raton Basin-Sierra Grande Uplift Geologic Province (modified after Gautier et al., 1996).

ACOMA BASIN

The Acoma Basin has a complex structural history, having been deformed by three major periods of tectonism during Phanerozoic time: (1) Late Paleozoic formation of the ancestral Rockies during the Sevier orogeny, (2) Laramide thick and thin-skinned compressional tectonics, and (3) Cenozoic relaxation, extension, and volcanism.

The Sevier orogenic belt and Mogallan Highlands (Fig. P-12) constrained a subsiding foreland basin from Early Cretaceous through Late Paleocene time (Armstrong, 1968; Villien and Kligfield, 1986). The constrained basin, in combination with long-term eustatic sea level changes along the margin of the Cretaceous seaway, resulted in complex depositional patterns reflecting the interaction of tectonics and eustacy (Molenaar, 1983; Nummedal and Riley, 1991). The western shoreline of the epicontinental seaway advanced and retreated across New Mexico many times, leaving a record of intertonguing marine and non-marine sediments (Mellere, 1994). Higher-frequency cyclicity during transgressions in Middle Cenomanian through mid-Turonian time resulted in various tongues with interfingered members of the Dakota and Mancos shale (Fig. P-13; Landis et al., 1973; Molenaar, 1983; Hook, 1983). One of the most widespread of tongues in the Acoma Basin is the Late Cenomanian Twowells Tongue (Dane et al., 1971; Hook et al., 1980). The Twowells Tongue is underlain by the dark-gray Whitewater Arroyo Shale Tongue of the Mancos Shale and is overlain by the Graneros Shale Member of the Mancos Shale (Fig. P-12).

The Twowell Tongue of the Dakota Sandstone encompasses two depositional sequences, albeit incomplete in terms of systems tracts (Van Wagoner et al., 1988, 1990). The first is associated with the Whitewater Arroyo Shale and shoreface sediments, and the second includes estuarine cross-bedded sandstone lithosome, oyster beds, and black shale that caps the Twowells Tongue (Mellere, 1994). Figure P-14 illustrates a hypothetical paleogeographic reconstruction of the Twowells Tongue during highstand, lowstand, and transgressive phases.

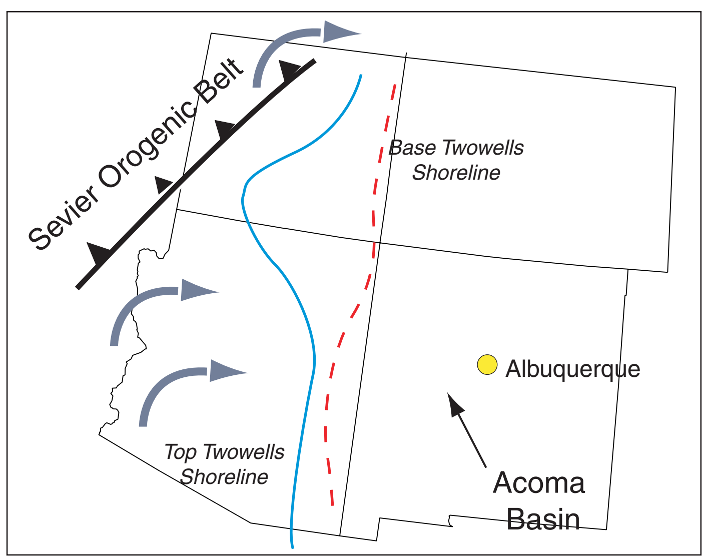


Figure P-12. Location of Pueblo Indian Reservations (esp. Acoma Pueblos) with indication of transport direction (arrows) of sediment that filled the Sevier foreland basins during the Cretaceous and, in particular, the Dakota Sandstone. The map also indicates the position of the shoreline at the base of the Twowells Tongue and the maximum transgression (modified after Mellere, 1994; Molenaar, 1983; and Eaton and Nations, 1991).

PRODUCTION OVERVIEW

Oil and gas production in north central New Mexico was described in the *1995 National Assessment of United States Oil and Gas Resources* (Gautier et al., 1996). All plays discussed in the "Play Summary Overview" combines the research from that publication along with other recent publications of interest to oil and gas in the Pueblo Indian Reservations. The following is a summary of the oil and gas plays within the (1) Albuquerque-Santa Fe Rift Province, (2) South-Central New Mexico Province, and (3) Raton Basin-Sierra Grande Uplift (Fig. P-15).

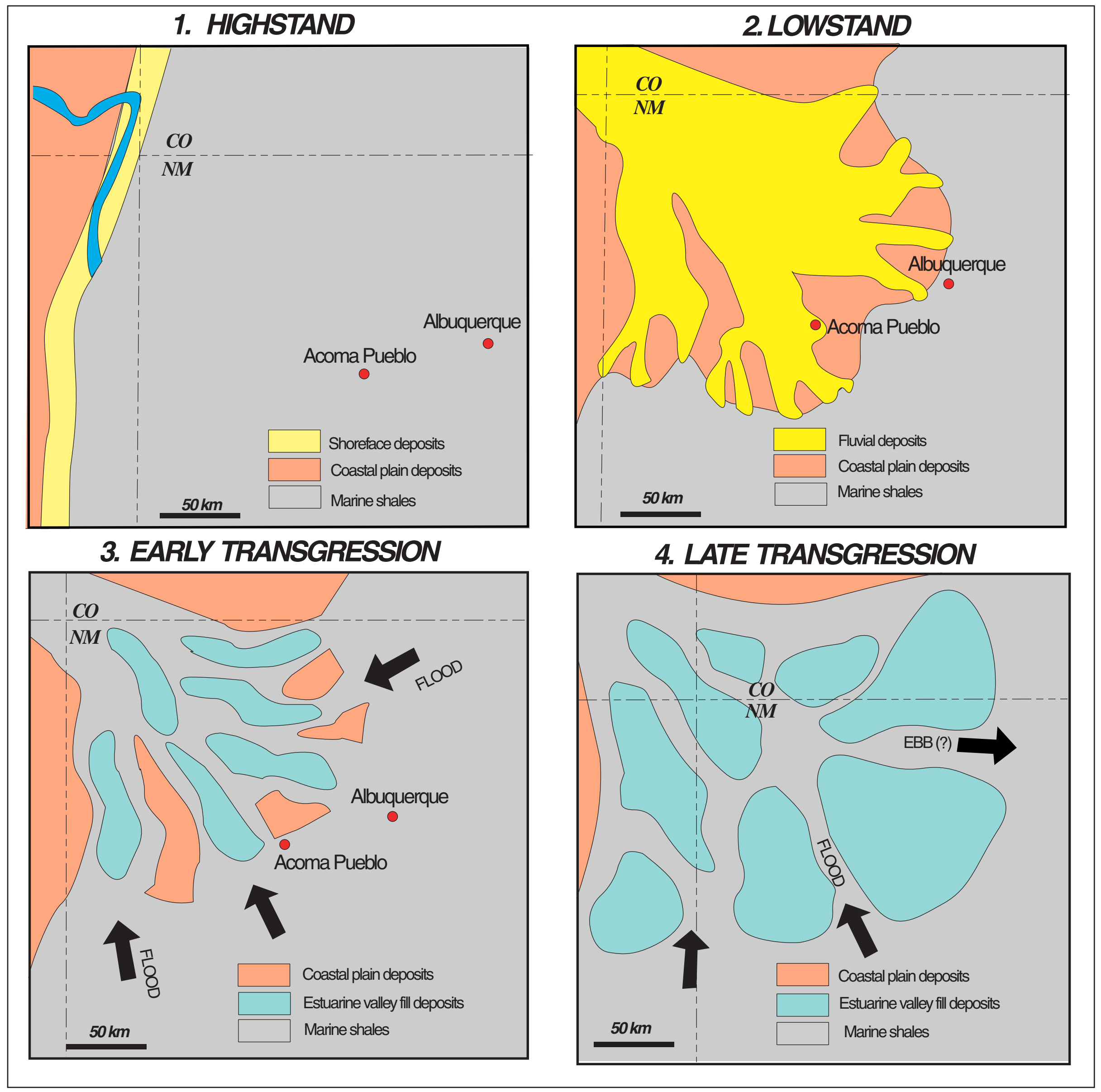
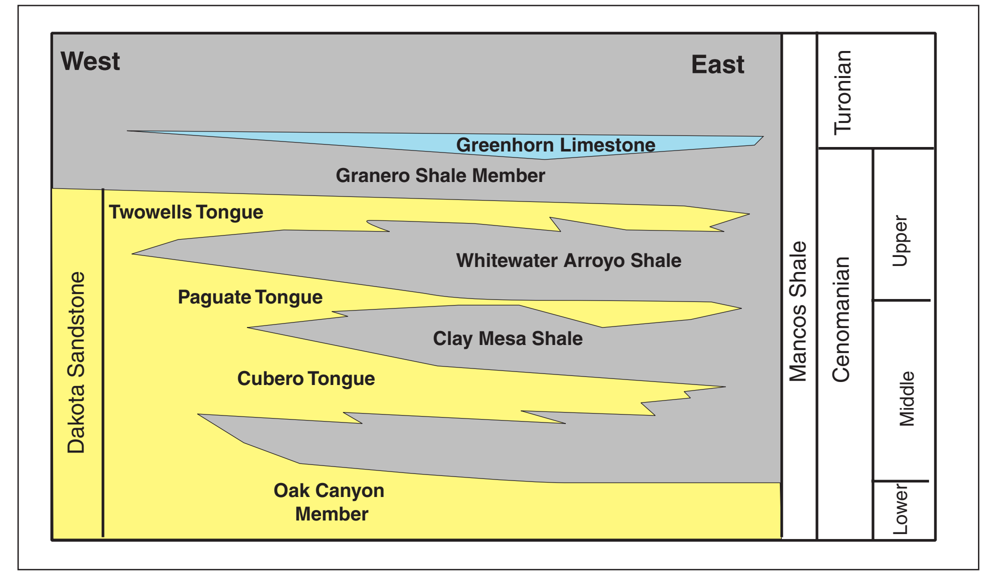


Figure P-14. Hypothetical paleographic reconstruction of the Twowells Tongue during (1) highstand, (2) lowstand, (3) early transgression and (4) late transgression (modified after Mellere, 1994).

Figure P-13. Schematic cross-section of the intertonguing relationships of the Dakota Sandstone and the Mancos Shale in the Acoma Basin (modified after Cobban and Hook, 1989).



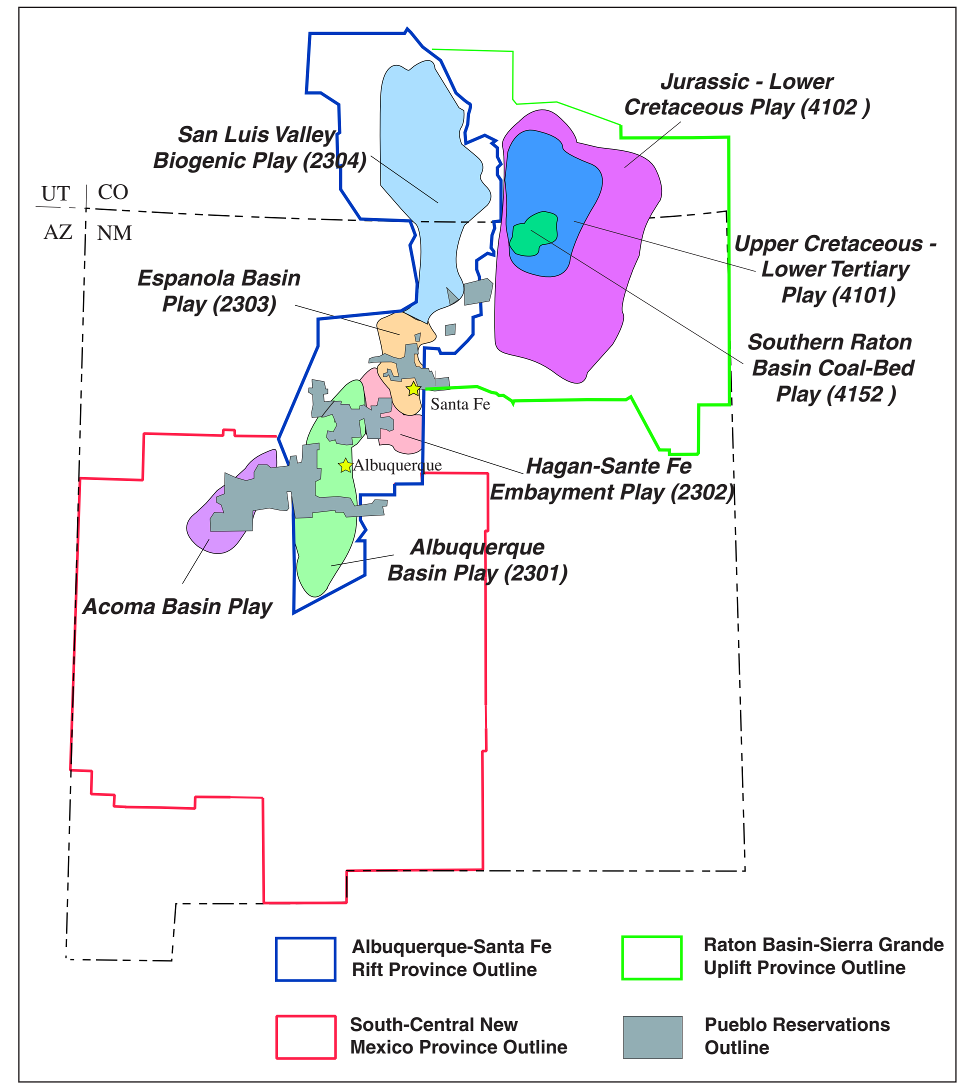


Figure P-15. Location of Pueblo Reservations with respect to the major geologic provinces and the respective hydrocarbon plays of northern New Mexico (modified after Gautier et al., 1996).

Play Summary

The United States Geology Survey (USGS) identifies several petroleum plays in the Albuquerque-Santa Fe Rift, Raton Basin-Sierra Grande Uplift, and South-Central New Mexico Provinces. Table 1 summarizes the petroleum plays relevant to the Pueblo Indian Reservations and describes the key characteristics of each field. The discussions that follow are limited to those plays with direct significance for future petroleum development in the Pueblo Indian Reservations.

Play Types

Conventional Plays - Discrete deposits, usually bounded by a downdip water contact, from which oil, gas, or NGL can be extracted using traditional development practices, including production at the surface from a well as a consequence of natural pressure within the subsurface reservoir, artificial lifting of oil from the reservoir to the surface, where applicable, and the maintenance of reservoir pressure by means of water or gas injection.

Unconventional Plays - A broad class of hydrocarbon deposits of a type (such as gas in "tight" sandstones, gas shales, and coal-bed gas) that historically has not been produced using traditional development practices. Such accumulations include most continuous-type deposits.

Reservation: Pueblo Indian Reservations
Geologic Province: Albuquerque-Santa Fe Rift Province, South-Central New Mexico Province, and the Raton Basin-Sierra Grande Uplift Province
Province Area: Appproximately 7,000, 39,900, and 18,800 square miles, respectively
Reservation Area: ?

Total Production (by Province-1996)
Oil:
Gas:
NGL:

There has been no significant production in the three provinces.

Undiscovered resources and numbers of fields are for Province-wide plays. No attempt has been made to estimate number of undiscovered fields within the Pueblo Indian Reservations.

Play Type	USGS Designation	Description of Play	Oil or Gas	Known Accumulations	Undiscovered Accumulations > 1 MMBOE (med., mean)	Number of Undiscovered Accumulations (min., med., max., mean)	Play Probability (chance of success)	Drilling depths (min., max., med.)
Albuquerque Basin Play 1	2301	Structural and Stratigraphic	Gas and Minor Oil	Gas (448,740 MMCFG) Oil (521,090 MBO)	20, 35.5 BCFG 3, 4.1 MMBO	Gas 2, 8, 30, 5.6 Oil 1, 2, 10, 1.7	0.49	6,000, 10,000, 8,000
Hagan-Santa Fe Embayment Play 2	2302	Structural and Stratigraphic	Oil	Gas (199,800 MMCFG) Oil (174,135 MBO)	2, 2.5 MMBO	Oil 1, 2, 4, 0.9	0.42	1,500, 7,500, 2,500
Espanola Basin Play 3	2303	Structural and Stratigraphic	Minor Oil	Gas (94.42 BCFG, est. mean) Oil (188.85 MMBO, est. mean)	Not Quantitatively Assessed	Not Quantitatively Assessed	0.06	Not Reported
San Luis Valley Biogenic Gas Play 4	2304	Stratigraphic; biogenic gas from lacustrine deposits	Minor Gas	Gas (7,000 BCFG)	Not Quantitatively Assessed	Not Quantitatively Assessed	0.03	Not Reported
Upper Cretaceous-Lower Tertiary Play 5	4101	Stratigraphic	Gas (methane)	Gas (7.8 BCFG, est. mean) Oil (7.8 MMBO, est. mean)	8, 12 BCFG	Gas 2, 4, 8, 2.8	0.64	4,000, 6,000, 5,000
Jurassic-Lower Cretaceous Play 6	4102	Stratigraphic	Minor Gas and Oil	Gas (62,100 MMCFG) Oil (22,8559 MBO)	Not Quantitatively Assessed	Not Quantitatively Assessed	0.09	Not Reported
Southern Raton Basin Play 7	4152	Coal-bed gas within fractured coal	Gas	Gas (8211.28 BCFG, est. mean)	571 BCFG (mean)	Not Reported	Not Reported	500, 1,400, 1,200
Acoma Basin Play 8	Not Designated	Stratigraphic	Gas and Minor Oil	Gas (59,518 MMCFG) Oil (53,700 MBO)	Not Reported	Not Reported	Not Reported	Not Reported

Table 1. Summary table of oil and gas plays that are located in or near the Pueblo Reservations.

Conventional play type (plays 1, 2, 3, 5, 6, 8)   Unconventional/Hypothetical play type (plays 4, 7)

Albuquerque-Santa Fe Province

This province is part of the Rio Grande Rift system and consists of segmented or offset basins that formed as a result of middle Tertiary to Quaternary rifting. The province extends from Socorro, New Mexico, northward 280 miles through the San Luis Valley in Colora do (Fig. P-16). The east-west width of the province ranges from 15 to 65 miles and the eastern and western boundaries are mostly uplift ed mountain blocks exposing Precambrian and Mesozoic rocks gen erally dipping away from the rifted basins. The primary hydrocarbon objectives in the province are pre-rift Cretaceous and older strata, which in most of the province are covered by continental Tertiary-Quaternary fill. More than 20,000 feet of fill has masked the Lara mide and older structures, thereby necessitating seismic data to delin eate structure.

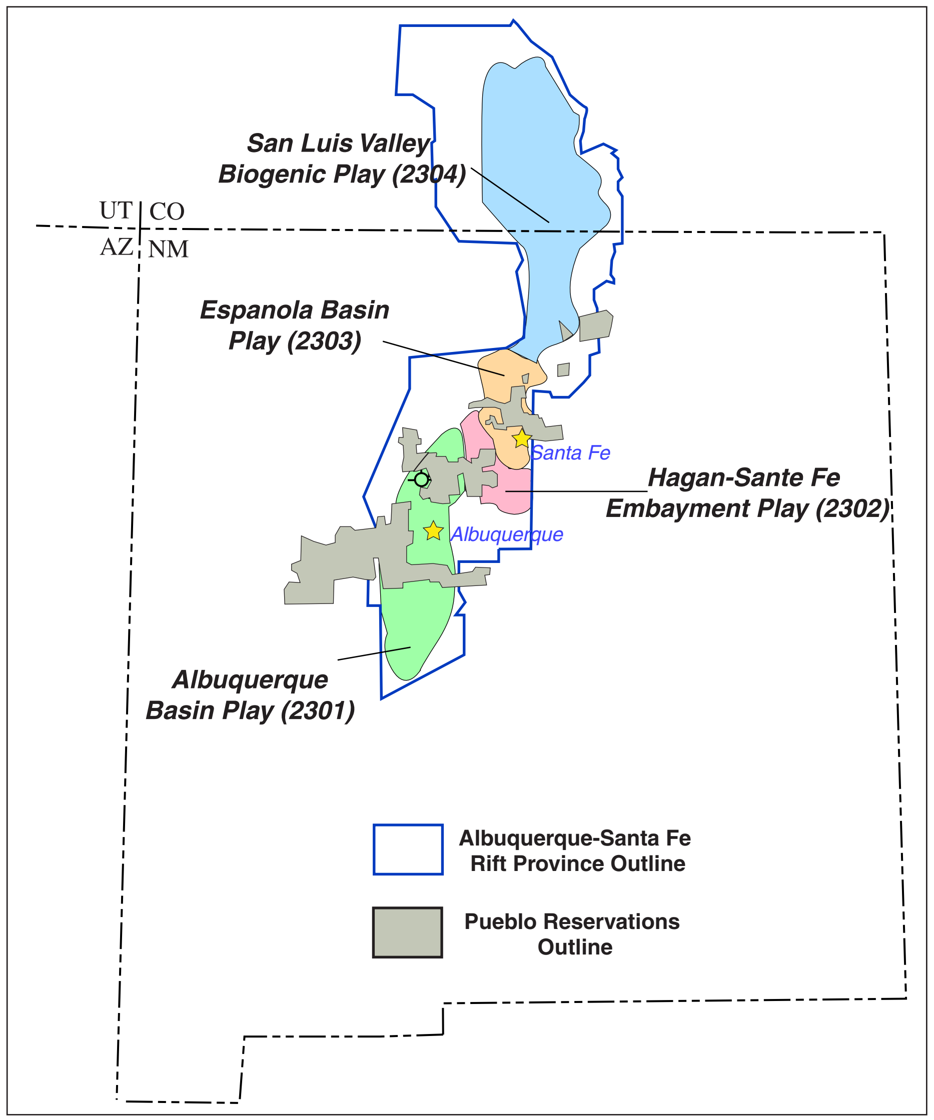


Figure P-16. Outline of Pueblo Reservations with respect to the Albuquerque-Santa Fe Rift Province. The Albuquerque Basin Play (2301), Hagan-Santa Fe Embayment Play (2302), Espanola Basin (2303), and the San Luis Valley Biogenic Play (2304) are depicted (modified after Gautier et al., 1996).

About 120 wells have been drilled in the province (Fig. P-17), but only about 50 wells penetrated Cretaceous or older rocks. Most of these latter wells were drilled in the 1970's and early 1980's. There is no production in the province, although there was marginal oil production for a short time from two wells in different areas of the province. Recent exploration has been minimal in the basin, with the exception of dry holes in the northwestern part of the province (Molenaar, 1993).

Based on expected reservoirs, reservoir depth, type of hydrocar bon expected, drilling history, and geography, four relevant and hy pothetical plays were identified by the USGS. These are the Albu querque Basin Play (2301), Hagan-Santa Fe Embayment Play (2302), Espanola Basin Play (2303), and the San Luis Valley Bio genic Gas Play (2304). The plays of interest to the Pueblo Reserva tions are discussed in the Play Summary Overview.

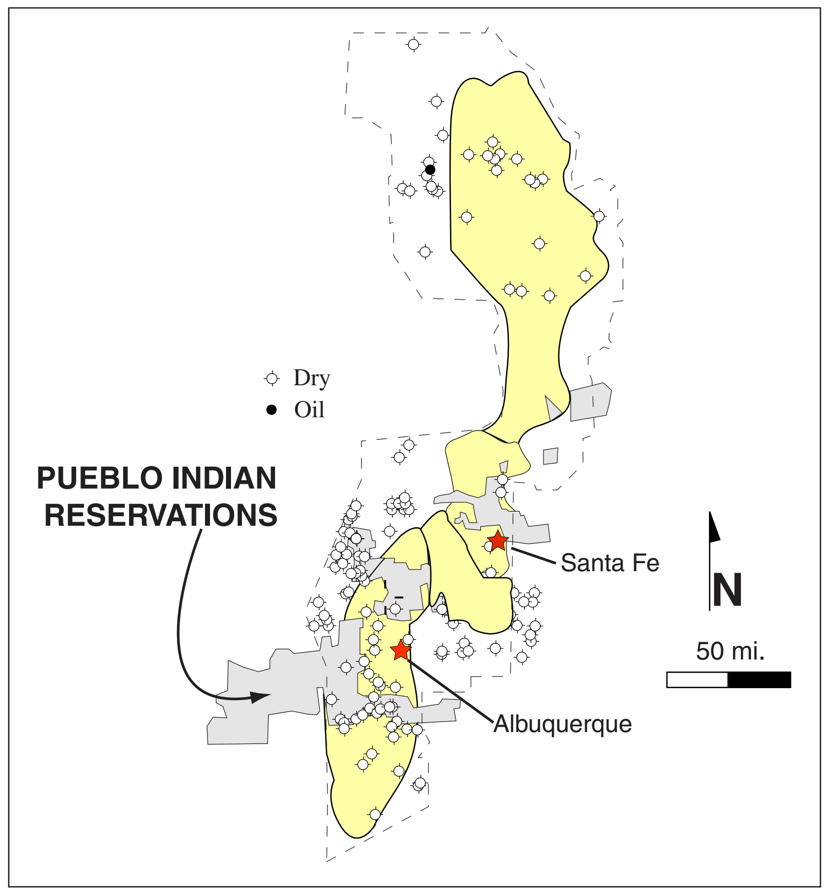


Figure P-17. Outline of Albuquerque-Santa Fe Rift Geologic Province with exploration wells from 1900-1993 depicted. The Albuquerque, Espanola and San Luis Basins are highlighted in addition to the Hagan-Santa Fe Embayment (modified after

Albuquerque Basin Play
(USGS 2301)
General Characteristics

This is a hypothetical structural play related to down-dropped blocks of Mesozoic and Paleozoic rocks that have been buried to a sufficient depth for the generation of hydrocarbons, or in areas where struc tures are along migration paths of downdip-generated hydrocarbons (Black, 1982). The Albuquerque Basin Play is in the large, generally flat or low-relief area of the Albuquerque Trough (Fig. P-18) and is bounded on the east by the Sandia, Manzano, and Los Pios Moun tains, which are composed of Paleozoic and older rocks. The west side is bounded by the Puerco Platform, composed of Cretaceous rocks, and the Lucero Uplift and Ladrone Mountains, both of which consist of Paleozoic and older rocks. The northern boundary is a volcanic-covered area where the rift is offset to the east and the southern boundary is marked by the converging of the flanking up lifts in the vicinity of Socorro.

Reservoirs: The primary objec tives of this play are coastal and marine Cretaceous sandstones that are along depositional strike with the San Juan Basin where these rocks are major producers of oil and gas. Secondary objectives are the Jurassic Entrada Sandstone and Paleozoic shelf sandstones and car bonates. All these potential reser voirs range in thickness, but are generally less than 100 feet thick. Recoveries on drill-stem and pro duction tests of Cretaceous sand stones in wells in the play area in dicate low permeabilities for these potential reservoirs (Molenaar, 1993).

Source rocks: Oil-prone source rocks are in the basal marine part of the Cretaceous section (Green horn interval). In the northern part of the play area, the middle part of the Mancos Shale is the major source rock. Good gas-prone, Type III source rocks are in Cretaceous carbonaceous shales and coals. The ma turation ranges from immature to marginally mature along the shallow er basin margins to overmature or gas-prone in the deeper parts. Most of the play is considered a gas play because of the predominance of gas shows in the drilled wells, the gas-prone nature of most of the source rocks, and the generally high maturations.

Timing and migration: Data are lacking on the timing and migration of hydrocarbons, but it seems likely that the amount of burial by Terti ary sediments and the degree of tilting of individual fault blocks was a controlling factor, thereby indicating recent hydrocarbon migration.

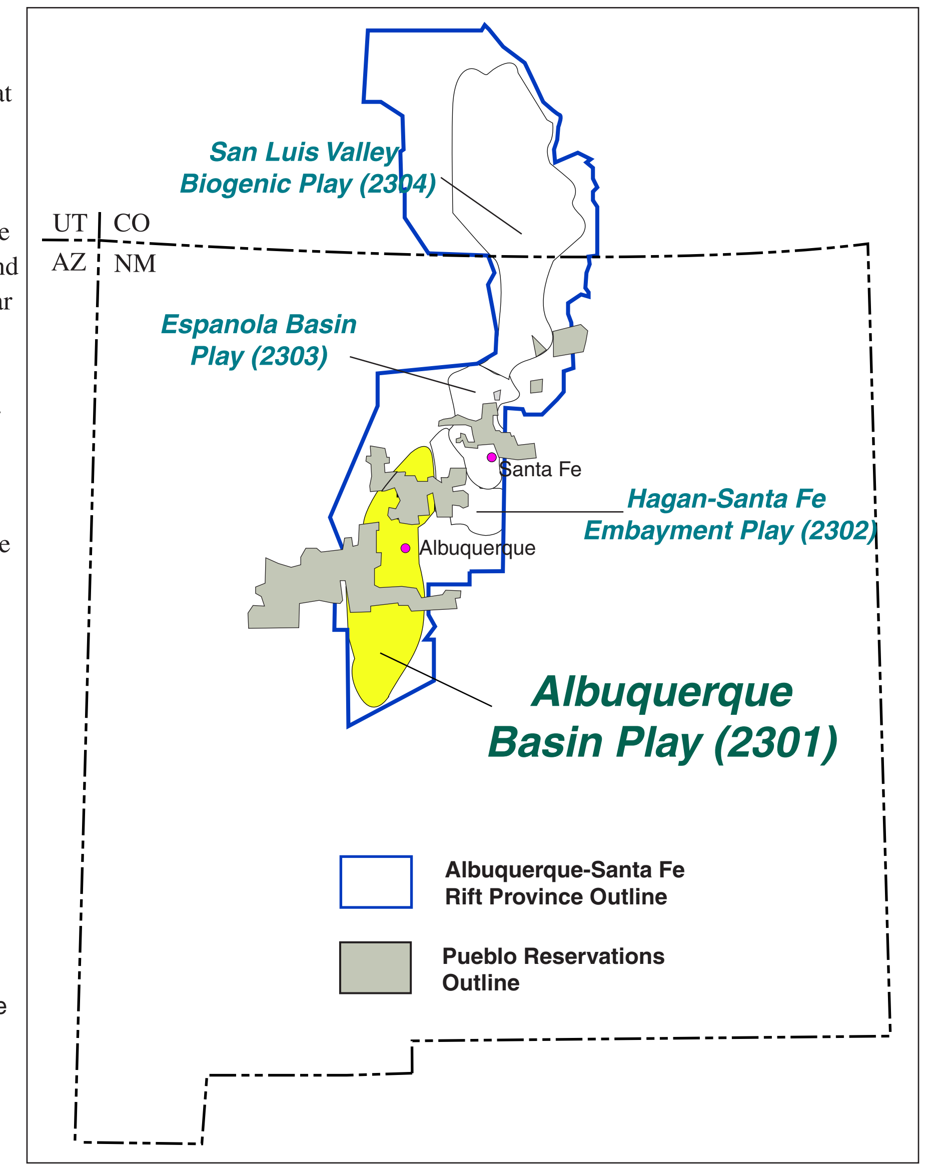


Figure P-18. Location of Albuquerque Basin Play (2301), with respect to the Pueblo Reservations (modified after Gautier et al., 1996).

Traps: Although the structure of underlying rocks is obscured by the late Tertiary fill, normal faulting seems to be a predominant structural feature of the Albuquerque Basin (Figs. P-4 and P-19). At least three of the nine Cretaceous test wells encountered normal faults that cut out significant parts of the section (Fig. P-20). Traps are anticipated closures within different fault blocks, and many probably would be fault traps. Drilling depths to the Dakota Sandstone are 6,000 to 20,000 feet, and the size of the possible traps are unknown. Seals are dependent on fault seals and overlying impermeable shales, either within the Cretaceous section or overlying Tertiary fill. The abundance of gas shows in the Tertiary continental section, which probably was sourced from Cretaceous rocks, suggests that sealing of Cretaceous or older reservoirs may be a problem.

Exploration status: Of 46 tests in the play area, only nine penetrated the Cretaceous section (Table 2) and four penetrated all or parts of the Paleozoic section. The Tertiary and Quaternary fill, which is greater than 20,000 feet in some places, has masked Laramide and older structures, thereby necessitating seismic data to delineate structure. Published data on pre-Tertiary structure are not available, but Shell Oil Company conducted seismic surveys throughout the basin in the 1970's and drilled, or caused to be drilled, nine deep test wells (Fig. P-20). The seismic data must have been difficult to interpret in places, judging by the differences between the prognosticated formational depths and the actual drilled depths. Gas and some oil shows were reported in Cretaceous rocks (Fig. P-21). Unsuccessful attempts were made in one well to complete for gas production in the Shell farmout (Molenaar, 1987).

Resource potential: In summary, the Albuquerque Basin Play covers a large area and has the potential for large amounts of hydrocarbons, probably gas. Little is known about the subsurface structure. Seismic data collected in the recent past seem to have been of only moderate quality, necessitating additional seismic surveys because the few deep tests indicate that large normal faults are present and may control hydrocarbon occurrence.

Well No. and Name	Location	Completion Date	Total Depth (ft)
Shell SFP No. 1	18-13N-3E	6-19-72	11,045
Shell Laguna-Wilson Trust No. 1	8-9N-1W	9-21-72	11,115
Shell SFP No. 2	29-6N-1W	3-29-74	14,305
Shell Isleta No. 1	7-7N-2E	10-25-74	16,346
Shell SFP No. 3	28-13N-1E	4-19-76	10,276
TransOcean Isleta No. 1	8-8N-3E	10-4-78	10,378
Shell Isleta No. 2	16-8N-2E	11-23-79	21,266
Shell West Mesa Fed. No. 1	24-11N-1E	12-30-80	19,375

Table 2. Summary table of eight deep test wells in Albuquerque Basin (modified after Molenaar, 1987).

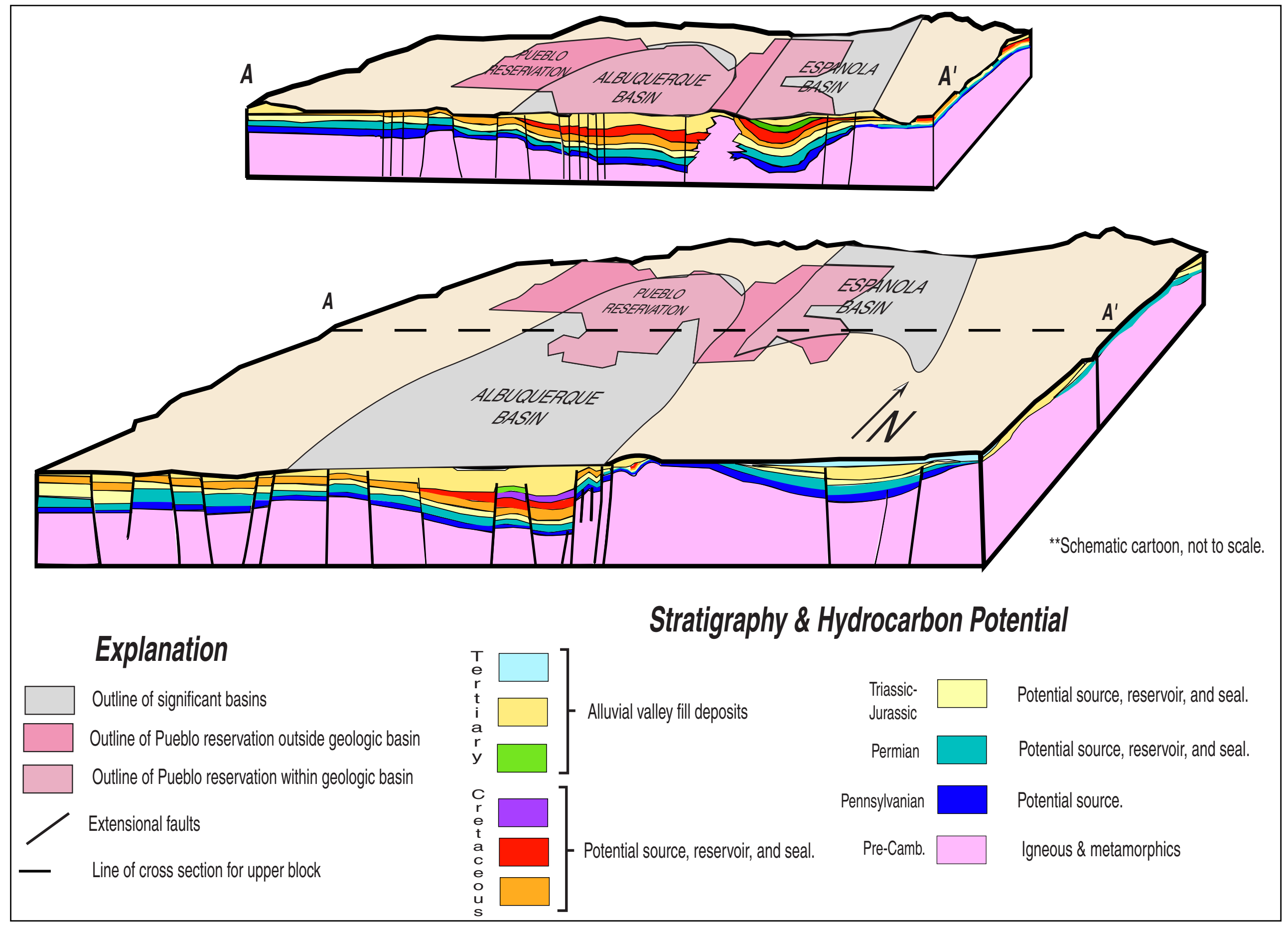


Figure P-19. Block diagram depicting schematic structure across the Albuquerque and Espanola Basins (modified after Black, 1982).

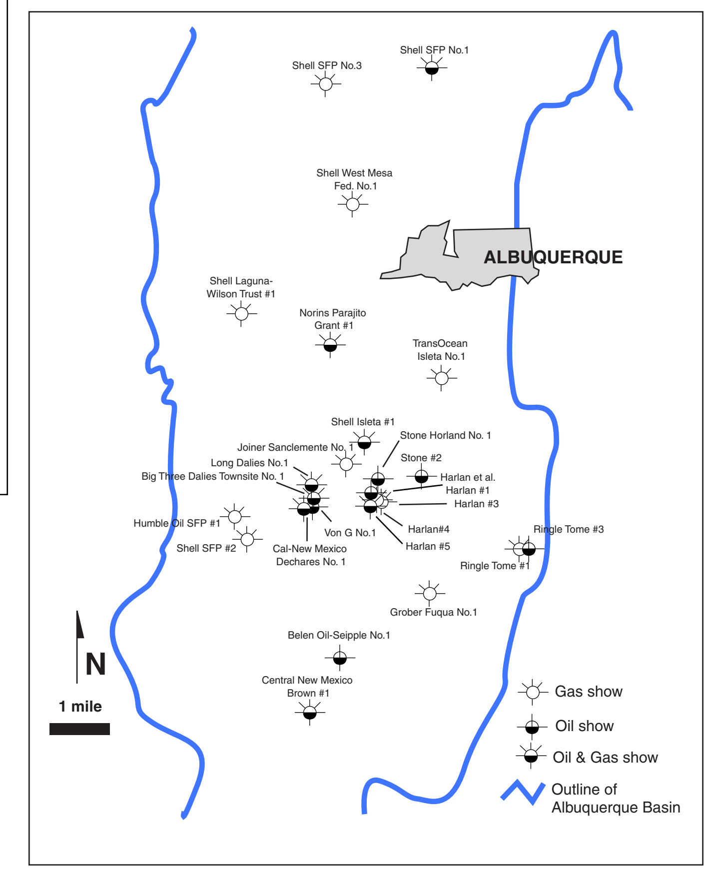


Figure P-21. Test wells that had shows of oil and gas in Albuquerque Basin (modified after Black, 1982).

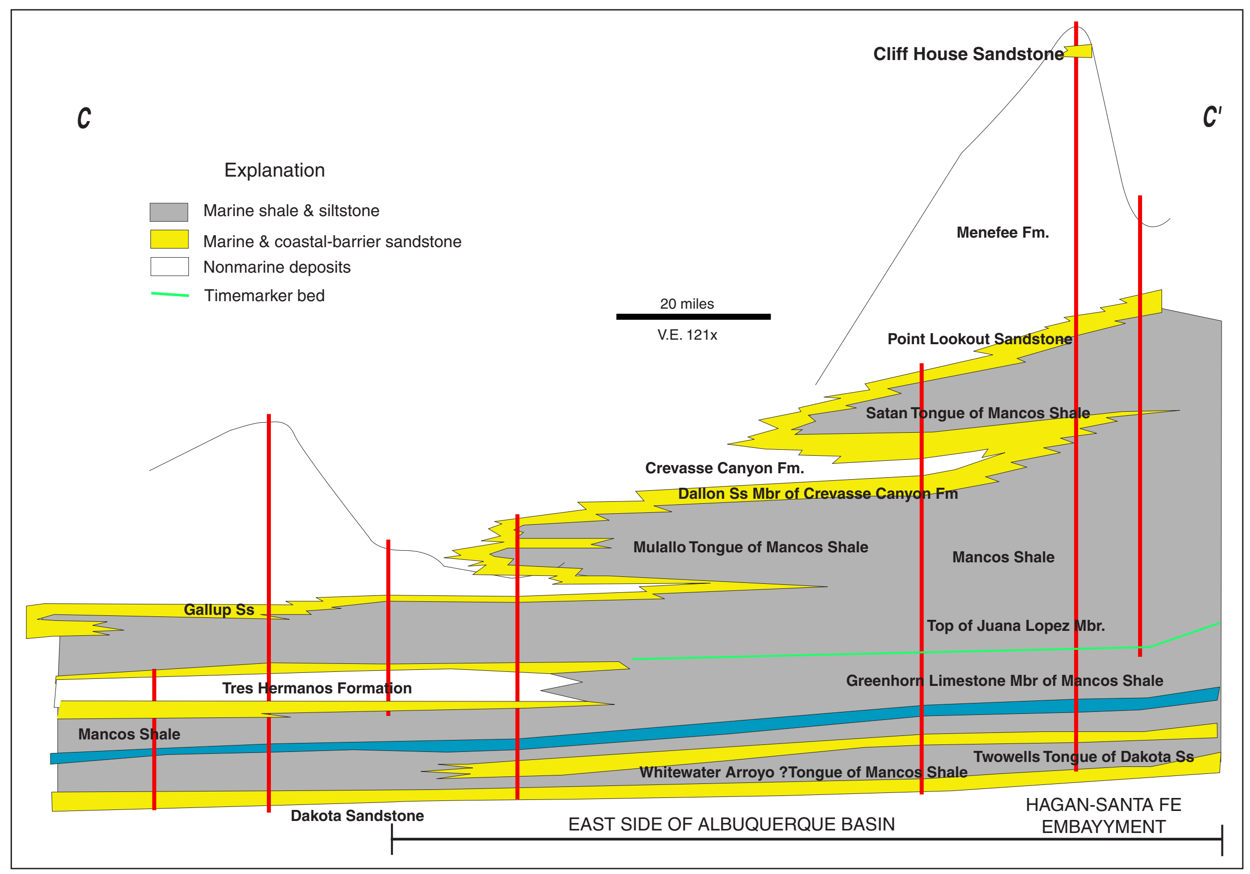


Figure P-20. Stratigraphic cross-section C-C' of Cretaceous rocks along the east side of the Albuquerque Basin into the Santa Fe Embayment (Fig. 7; cross-section 3) (modified after Molenaar, 1983).

Hagan-Santa Fe Embayment Play

(USGS 2302)

General Characteristics

The Hagan-Santa Fe Embayment is in the southern part of the Espanola Basin, but because of the different play attributes, this hypothetical play is split off from the Espanola Basin Play and is considered separately (Fig. P-22). The play area is tear-drop shaped and about 25 miles in diameter. It is bound on the west by the northern volcanic-covered end of the Albuquerque Basin, on the east by the southern plunge of the Sangre de Cristo Mountains, and on the south by the Sandia Mountains and their broad eastern flank. To the north, the play is separated from the Espanola Basin along the line of truncation of Cretaceous rocks, which is controlled by wells in one area.

Reservoirs: The play is a structural-stratigraphic play for oil and gas in relatively shallow (<4,000 feet) Cretaceous objectives (Black, 1979 and 1984). The primary reservoir objectives are the Dakota Sandstone, 25-100 ft thick, and the Tocito and Semilla Sandstone Members of the Mancos Shale, 10-25 ft thick (Figs. P-23 and P-24). The Jurassic Entrada Sandstone, about 50 feet thick, and possibly Pennsylvanian carbonates, are secondary objectives.

Source rocks: The primary oil-source rocks are of moderate quality and are in the lower part of the Mancos Shale and, where preserved, the Niobrara-equivalent within the Mancos. Shales at the base of the Todilto Limestone are also potential source rocks. In addition, carbonaceous shales in the Dakota and above the Mancos Shale are potential gas source rocks. All of these rocks are mostly in the oil-generating range, although maturation levels range widely because of Oligocene intrusion of volcanics in the area (Molenaar, 1987).

Timing and migration: Unlike the other plays in this province, the Hagan-Santa Fe Embayment Play area is only partially covered by late Tertiary synrift fill. The structural history of the Hagan-Santa Fe Embayment is poorly understood, but is complex (Black, 1979). At least 6,000 ft of Eocene Galisteo Formation and Oligocene Espinaso Formation were tilted eastward 20° to 30° in middle or late Tertiary time. It seems likely that the time of maximum maturation was prior to this deformation or in the Oligocene, when the intrusive rocks were emplaced and there was sufficient overburden of the Eocene Galisteo Formation and Oligocene Espinaso Formation.

Traps: Traps of probable small to moderate size are both structural and stratigraphic, the latter in the case of lenticular Semilla and Tocito Sandstone Members (Fig. P-23). Seals would be overlying Mancos Shale for Cretaceous reservoirs, Todilto Anhydrite for the Entrada Sandstone, and interbedded shales for the Pennsylvanian carbonate reservoirs.

Exploration status: About 34 wells have been drilled in the play area, most since 1974, and all but two of three wells were drilled into or through the Cretaceous section. Several wells were drilled to the Entrada Sandstone. Oil or gas shows were reported in most or all the wells. A small amount of oil has been produced in one well from the Tocito Sandstone Lentil of the Mancos Shale at a depth of 2,740 ft (Molenaar, 1987).

Resource potential: In summary, the Hagan-Santa Fe Embayment Play covers a relatively small area, and the individual trap sizes are probably small. Although gas has been encountered, the main potential is oil. Shallow drilling depths along with outcrop and well control allow for a better understanding of the geologic structure when compared to the Albuquerque Basin.

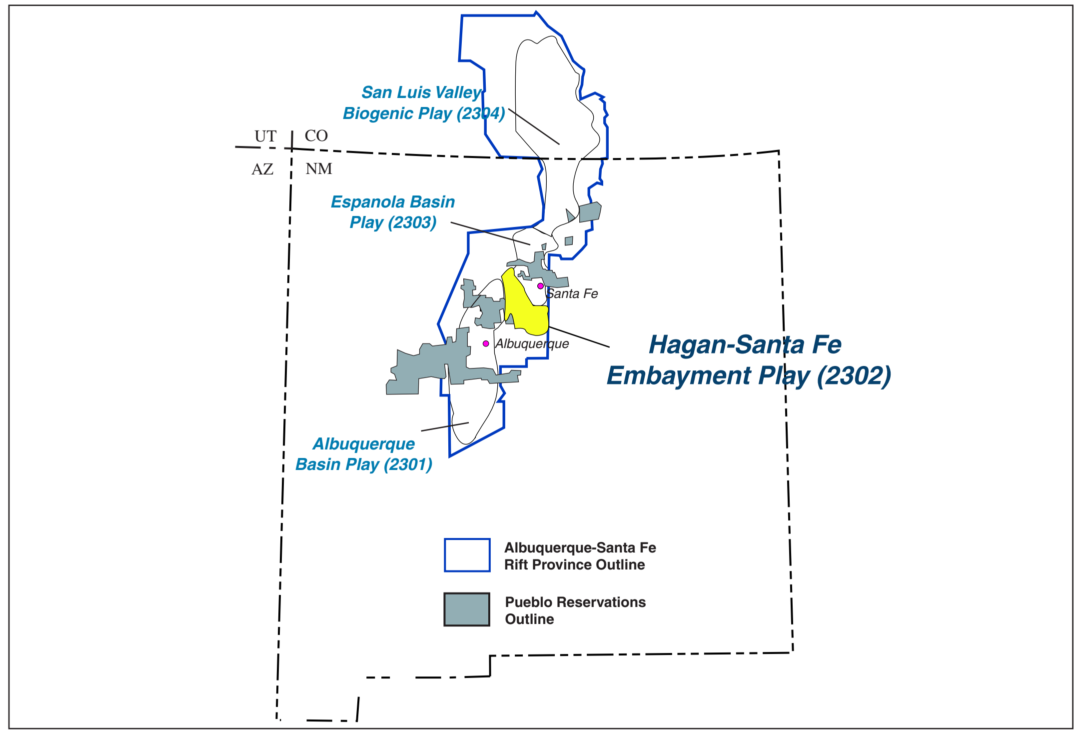


Figure P-22. Location of Hagan-Santa Fe Embayment Play (2302) with respect to the Pueblo Reservations (modified after Gautier et al., 1996).

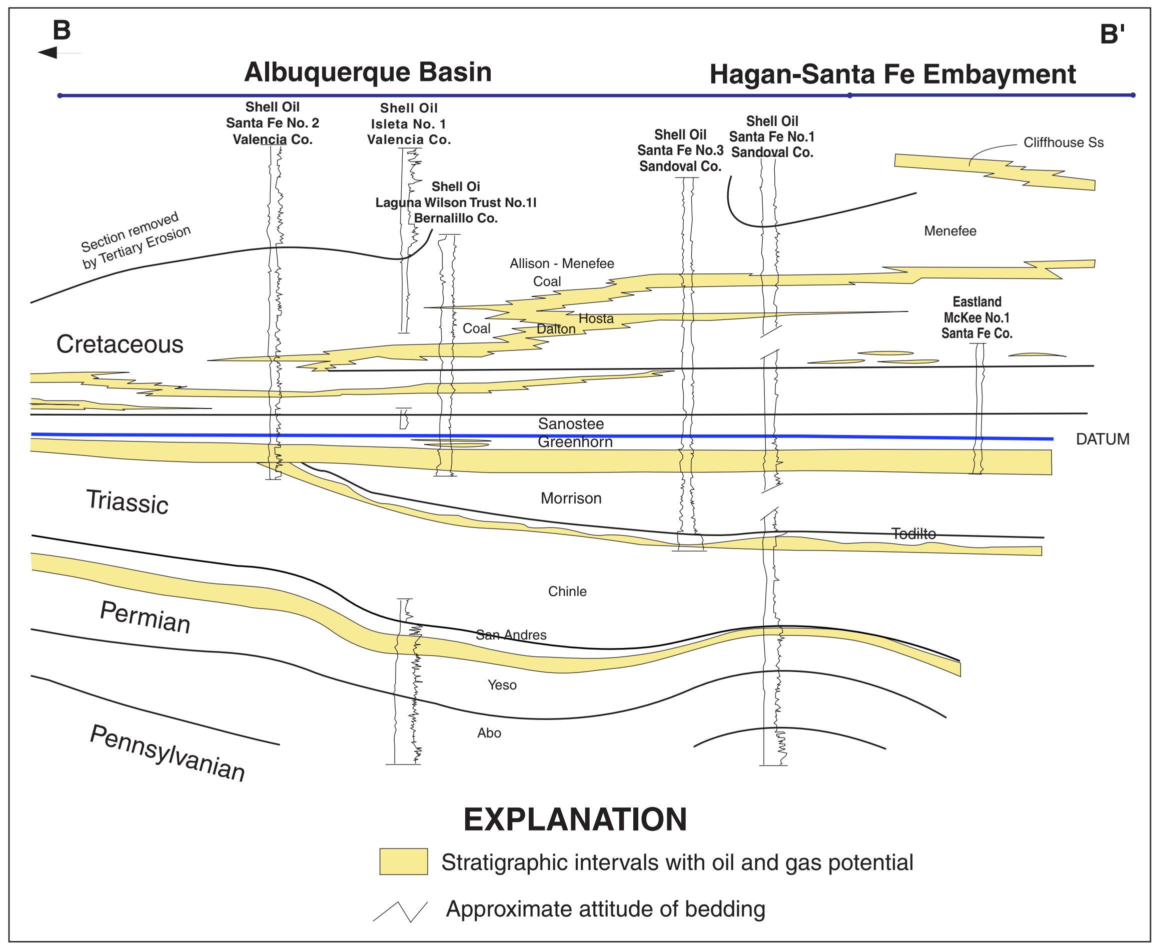


Figure P-23. Stratigraphic section showing facies relationships from Albuquerque Basin north to the Santa Fe Embayment of the Espanola Basin (Fig. P-7; cross-section 2) (modified after Black, 1982).

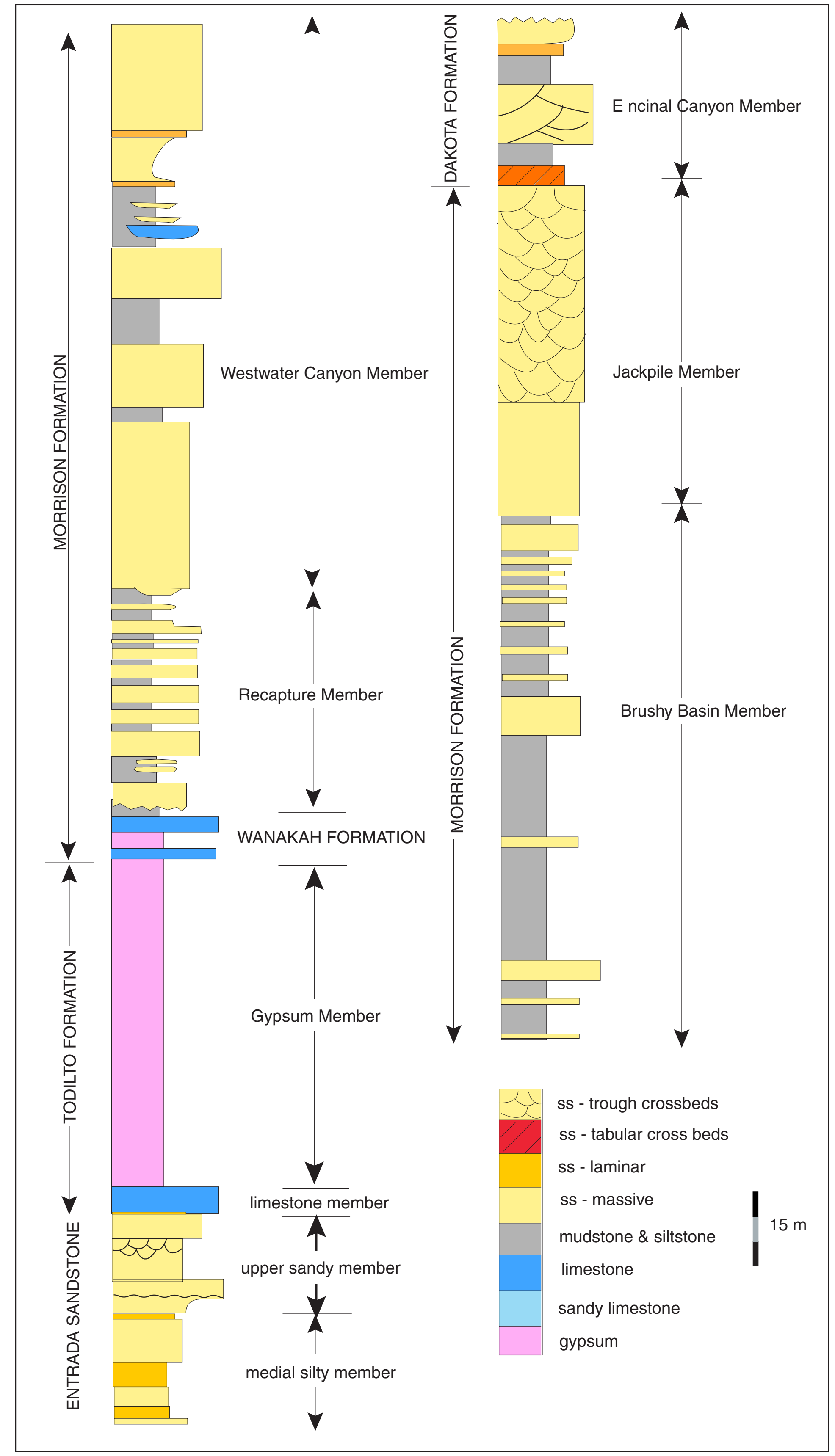


Figure P-24. Measured stratigraphic section of Jurassic strata in the Western Hagan Basin (modified after Black, 1982).

Española Basin Play

(USGS 2303)

General Characteristics

This hypothetical play covers a major part of the Española Basin north of the Hagan-Santa Fe Embayment (Fig. P-25). The southern boundary, which separates this play from the Hagan-Santa Fe Embayment Play, is the projected northern truncation edge of Cretaceous rocks. The eastern boundary is the uplifted Sangre de Cristo Mountains, the northern boundary is the narrowing and eastward offset of the rift system, and the western boundary is the volcanic Jemez Mountains. The entire play area is covered by late Tertiary synrift deposits, and little is known about the subsurface structure and stratigraphy (Fig. P-26).

Reservoirs: Potential reservoirs are Pennsylvanian carbonate rocks and possibly the Jurassic Entrada Sandstone along the southern margin, where it has not been removed by pre-Galisteo erosion. Reservoir thickness is estimated to be less than 100 feet.

Source rocks, timing and migration: Postulated source rocks would be marine shales within the cyclic Pennsylvanian system and, where preserved, the basal shale of the Todilto Limestone Member. Sparse data indicate the maturation levels in Pennsylvanian rocks and Tertiary rocks to be in the oil-generating window. The data on Tertiary rocks are from depths of 6,000-7,000 feet (Gautier et al., 1996).

Traps: The play is an oil play for structural traps.

Exploration status: Only about four exploration tests have been drilled in the Española Basin Play area. Two wells east of the city of Española, drilled in 1931 and 1961, bottomed in Pennsylvanian rocks at depths of about 1,700 and 2,730 feet, respectively. Minor oil shows were reported in both wells. These wells were probably drilled on an intermediate fault block adjacent to the Sangre de Cristo Mountains (Molenaar, 1987). No specific data has been provided on these wells.

Resource potential: In summary, the Española Basin Play is speculative and risky. Although oil shows have been reported, good source rocks and reservoirs have not been documented. Seismic data and additional well control are necessary to further evaluate the play.

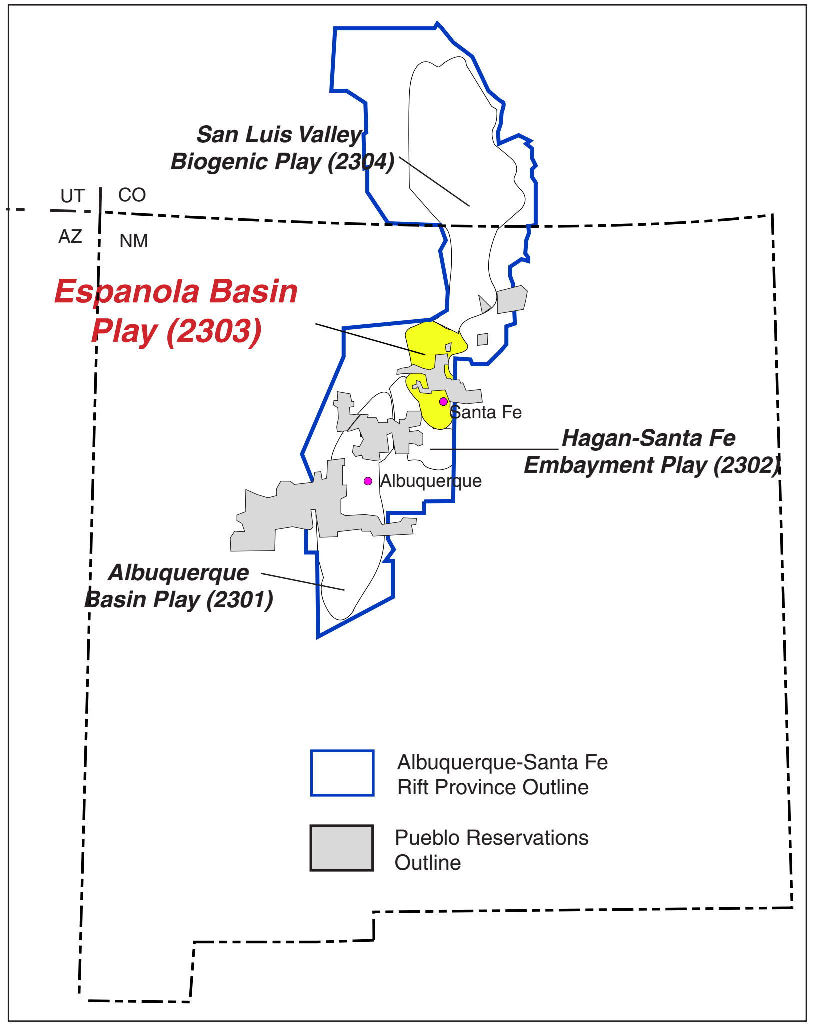


Figure P-25. Location of Espanola Basin Play (2303) with respect to the Pueblo Reservations (modified after Gautier et al., 1996).

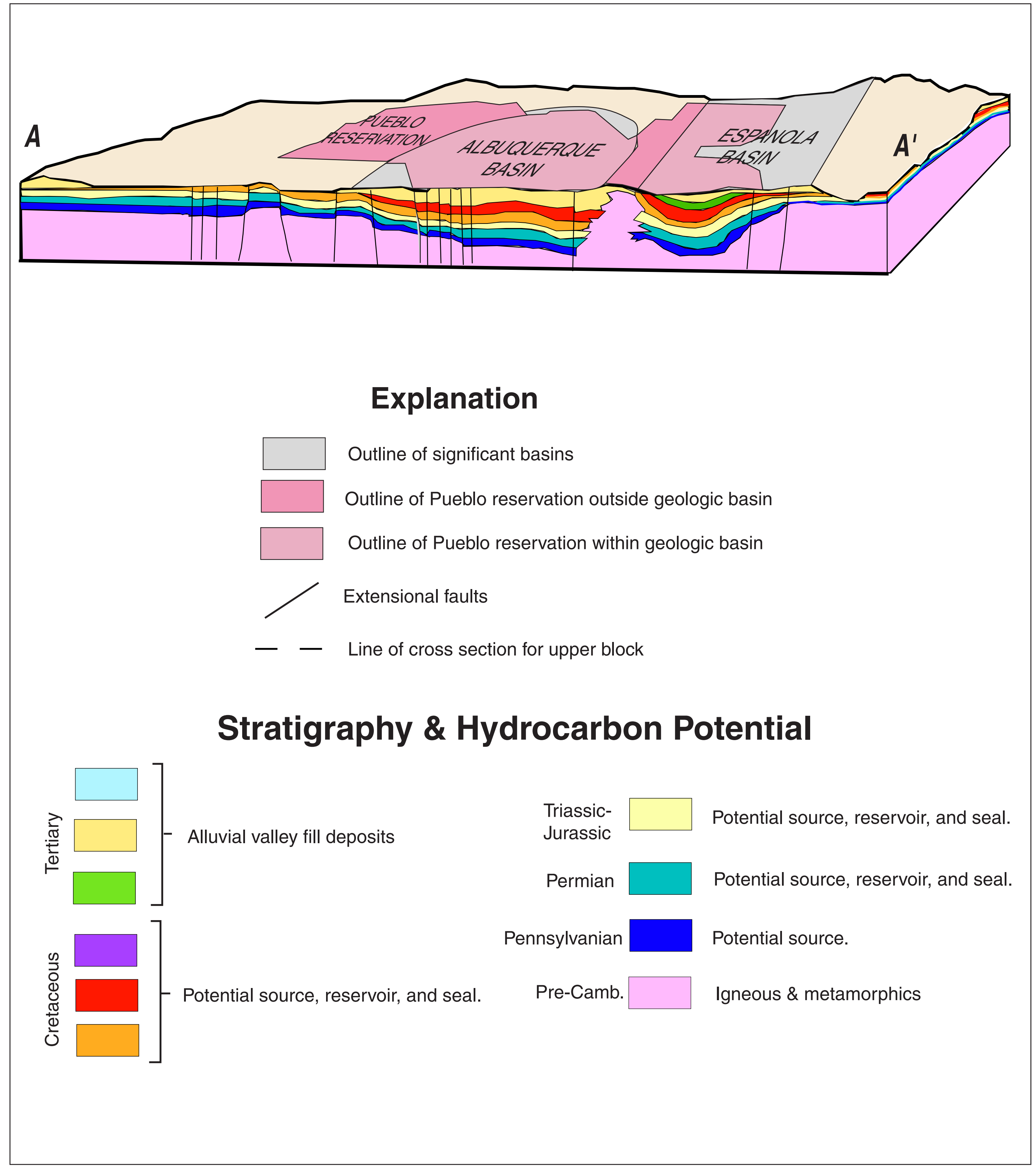


Figure P-26. Block diagram of the Espanola Basin (modified after Black, 1982).

San Luis Valley Biogenic Gas Play

(USGS 2304)

General Characteristics

This hypothetical play covers an elongate area about 70 miles long and 20 miles wide in the east-central part of the San Luis Valley (Fig. P-27), which is a rifted valley filled with continental Tertiary deposits (Fig. P-28). The boundaries are arbitrary, and the play is based on the many gas shows in shallow water wells in the area north and east of Alamosa, Colorado (Fig. P-29). Gas has been produced from about 35 of these wells and used by farmers for heating purposes for many years. Analytical data indicate that the gas is of biogenic origin. The reservoirs for gas in this play are sands or sandstones in lacustrine, clay-rich beds of Pliocene age. Whether or not a commercial accumulation of gas exists in this play is speculative. Certainly at such shallow depths, the reservoir pressure would be low.

Limited geophysical and well data indicate that a basement high or horst block underlies the play area (Fig. P-28). Depth to Precambrian Basement is as shallow as 6,000 feet. The deepest part of the greater San Luis Basin, which is bounded by the foothills of the San Juan Mountains on the west, and by the Sangre de Cristo Mountains on the east, is near the east margin. According to gravity calculations, the top of the Precambrian surface is at a depth of about 22,500 feet in the structurally low area northeast of Alamosa. A slightly greater depth was calculated for the area a few miles west of Taos, New Mexico.

In addition to the shallow wells that were drilled for gas, or water wells that were converted to gas wells, about 23 wells were drilled in the greater San Luis Valley area (Fig. P-29). Three wells in the northern third of the San Luis Valley that penetrated the entire section found Tertiary on Precambrian. The other wells were still in Tertiary rocks at total depth. The hydrocarbon potential of this large area is very low.

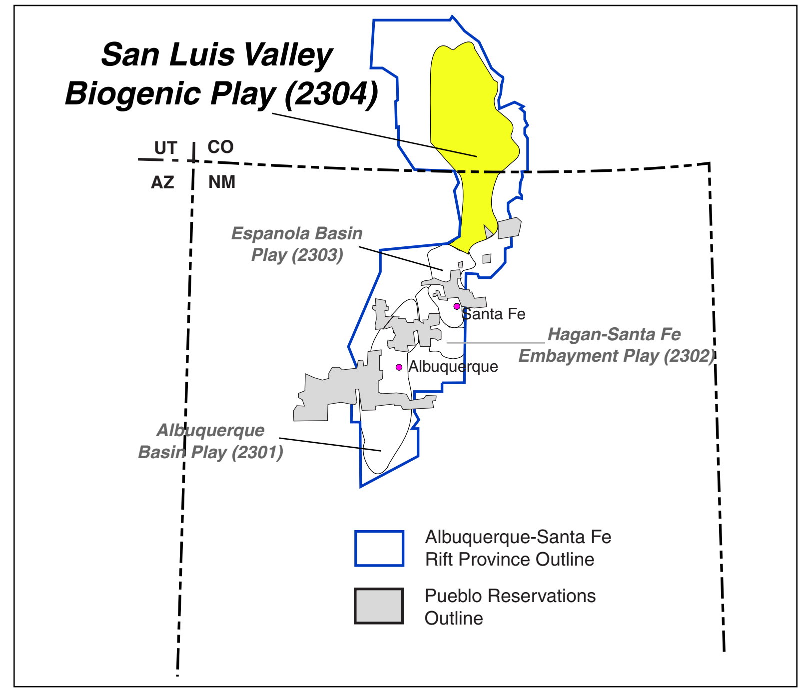


Figure P-27. Location of the San Luis Biogenic Play (2304) with respect to the Pueblo Indian Reservations (modified after Gautier et al., 1996).

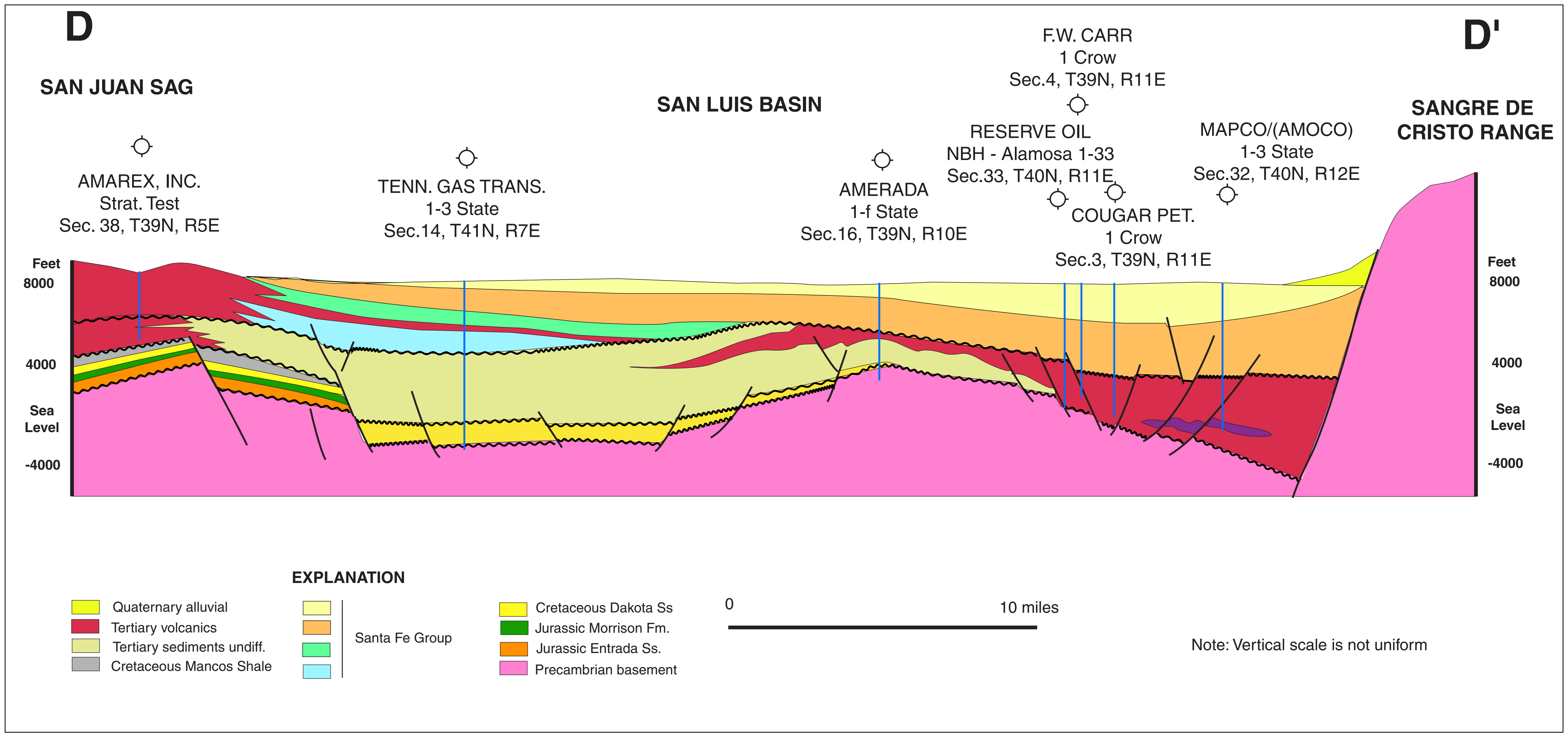


Figure P-28. Geologic cross-section across San Luis Basin. Vertical scale is a conversion of a time-depth scale from a seismic section. Therefore, the vertical scale is not uniform (Fig. P-7; cross-section 4) (modified after Gries, 1985).

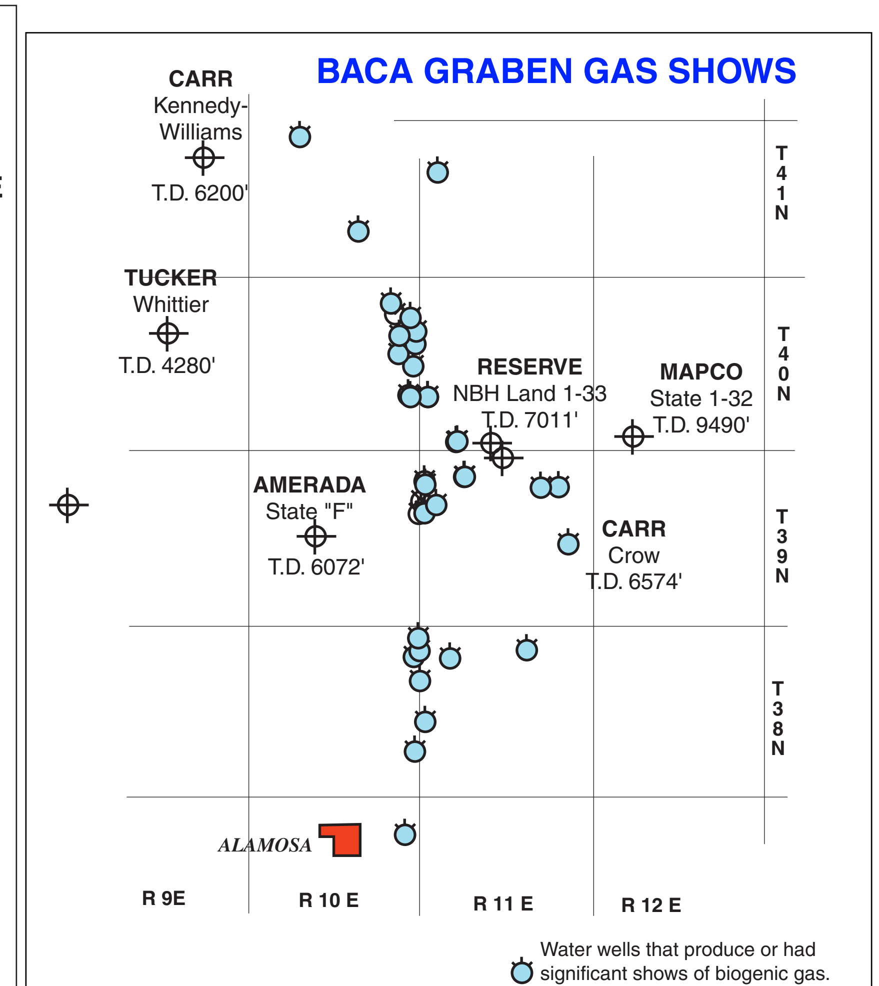


Figure P-29. Location of water wells that produce or had significant shows of biogenic gas within the Baca Graben of the San Luis Valley (modified after Black, 1982)

Raton Basin-Sierra Grande Uplift Province

The Raton Basin is an elongate, asymmetric basin in southeastern Colorado and northeastern New Mexico, analogous to other Rocky Mountain structural-stratigraphic basins associated with the Rocky Mountain Laramide Orogenic Belt. It is bounded on the west by the Sangre de Cristo Uplift, on the north by the Wet Mountains and the Apishipa Arch, and on the southeast by the Sierra Grande Uplift. The basin is approximately 175 miles long and up to 65 miles wide. It encompasses approximately 18,800 square miles (Fig. P-30) and sedimentary rocks within the basin may be 15,000-20,000 feet thick in the deepest part (Fig. P-31). The western flank of the basin dips steeply to the east and has been affected by substantial transcurrent and thrust faulting. In the Miocene, the basin was intruded by the Spanish Peaks igneous complex, which was accompanied by extensive fracturing and intrusion of numerous dikes and sills. Intrusion of the Spanish Peaks Complex does not appear to have significantly elevated the general geothermal level of the entire basin.

Post-Precambrian stratigraphy in the Raton Basin is typical of the southern Rocky Mountains. A thin carbonate succession (Devonian/Mississippian) overlies the Precambrian Basement (Fig. P-32). Overlying this sequence are 5,000-10,000 feet of terrigenous Permian-Pennsylvanian strata, largely sandstones and redbeds. Triassic redbeds (approximately 1,000 feet thick) overlie about 500 feet of terrigenous Jurassic sediments. The Cretaceous section includes 200 feet of the basal sequence of clastic Purgatoire/Dakota, followed by 1,000-2,000 feet of marine chalks, marls, and organic-rich shales of the Benton and Niobrara Groups. This sequence is overlain by approximately 2,500 feet of Pierre Shale. The marginal marine, partly deltaic Trinidad Sandstone overlies the Pierre, and is in turn overlain by the coal-bearing Vermejo Formation. The Upper Cretaceous/Paleocene coal-bearing Raton Formation overlies the Vermejo. Tertiary sediments of the Poison Canyon Formation overlying these strata are highly variable, and represent continental terrigenous sedimentation during the end of the Laramide Orogeny. Perhaps 10,000 feet of Tertiary sediments were originally deposited, but erosion has removed much of the sediment, especially around the basin margins. A generalized stratigraphic section showing the hydrocarbon-bearing strata is shown in Figure P-31.

In the Colorado portion of the Raton Basin, gas wells have produced measurable quantities from Permian, Upper Triassic, and Cretaceous strata in Las Animas County, and from Cretaceous age rocks in Huerfano County (Fig. P-33). Approximately 4,000 bbl oil were produced from the Codell Formation (Cretaceous) at the Gardner Field (now plugged and abandoned) in Huerfano County. The Garcia Field (Fig. P-34), now abandoned, in Las Animas County, Colorado, produced 1.5 BCFG from the Cretaceous Pierre Formation and Apishipa Member of the Niobrara Formation between 1896 and 1943. Natural gas was produced from the Dakota and Morrison Formations in the now-abandoned Wagon Mound Field in Mora County, New Mexico (Fig. P-35).

Carbon dioxide is produced from the Sheep Mountain Field and Dike Mountain Fields, Huerfano County, Colorado. Drilling began in the early 1970's, when the target was oil and (or) gas. Production of CO_2 is from the Cretaceous Dakota and Jurassic Entrada Formations at depths between 3,500 and 6,000 feet. The field has produced approximately 481 BCF of CO_2. The Bravo Dome [Bueyeros Field] (Fig. P-36), located in parts of Harding, Union, and Quay Counties, New Mexico, also produces CO_2, in part from the Permian Glorieta and Yeso Formations, and has produced [through 1990] 118 BCF of CO_2. This field is estimated to contain more than 16 TCF of CO_2 reserves; approximately one-half is estimated to be recoverable with existing technology (Keighin, 1995).

No commercial oil or gas fields are now active in the basin area, although the coal-bearing Raton and Vermejo Formations yield significant quantities of methane. Two hypothetical conventional gas plays are defined. These are the Upper Cretaceous-Lower Tertiary Play (4101), and Jurassic-Lower Cretaceous Play (4102). An unconventional coalbed gas play, the Southern Raton Basin Play (4152) is also relevant for gas production in or near the Pueblo Indian Reservations (Fig. P-30).

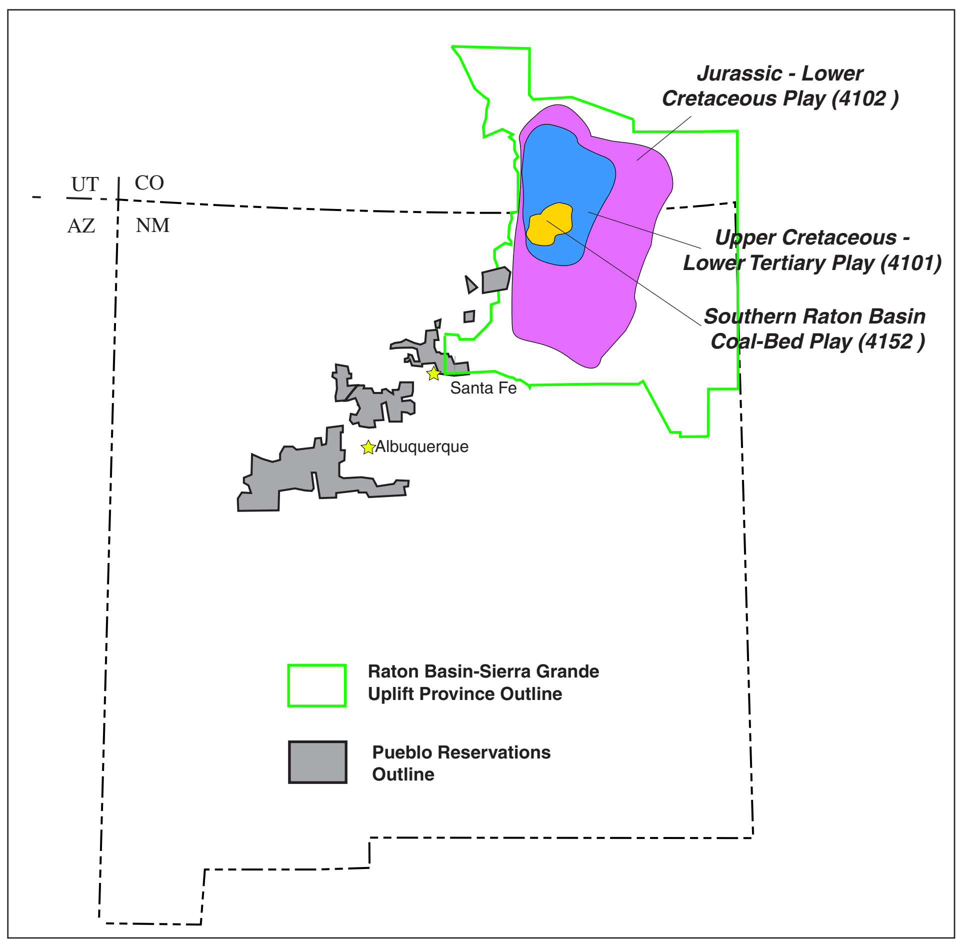


Figure P-30. Outline of Pueblo Reservations with respect to the Raton Basin-Sierra Grande Uplift Province. The Upper Cretaceous-Lower Tertiary Play (4101), Jurassic-Upper Cretaceous Play (4102) and Southern Raton Basin Coal-Bed Play (4152) are depicted (modified after Gautier et al., 1996).

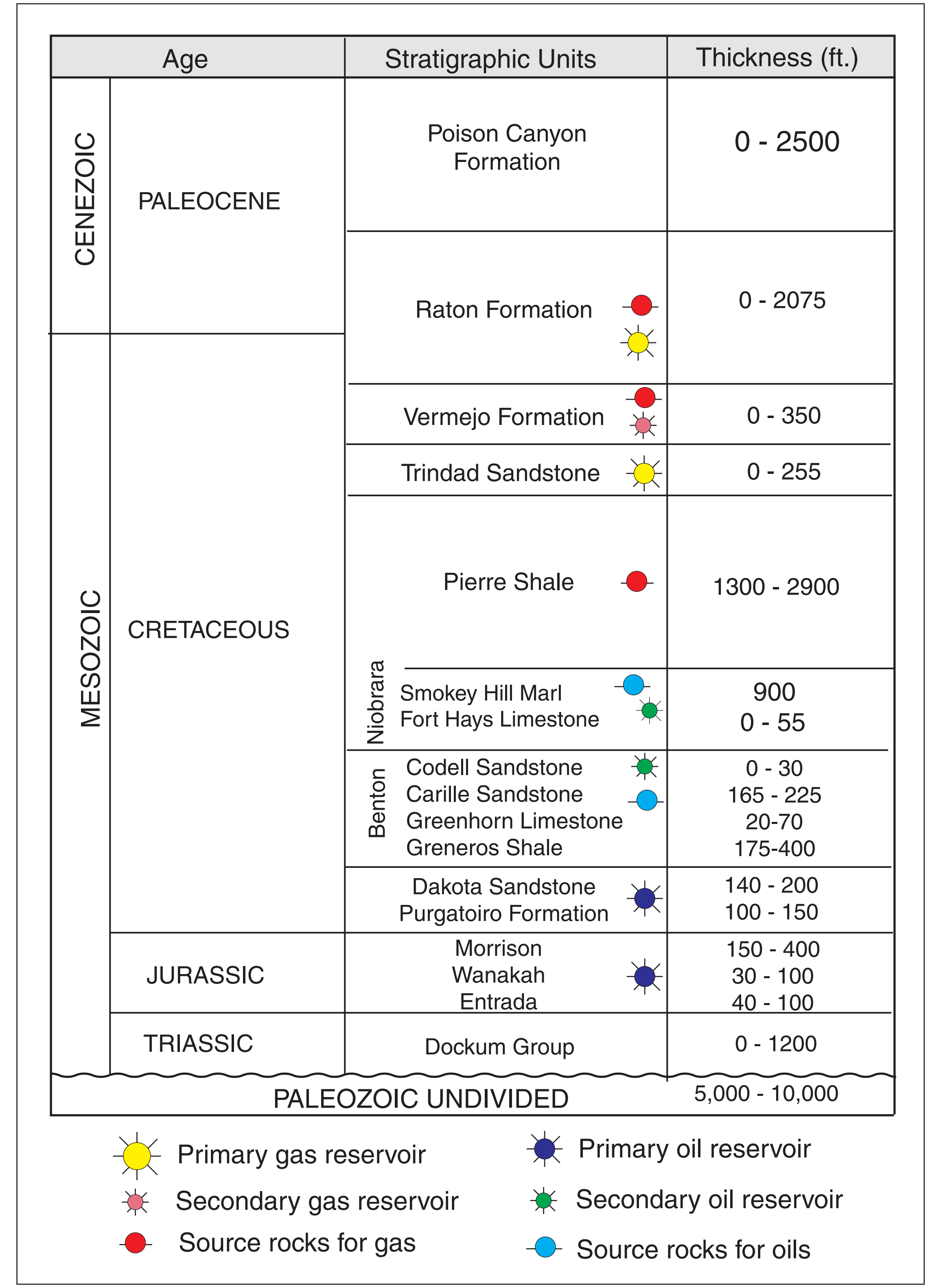


Figure P-31. Stratigraphic section depicting bedding relationships within the Raton Basin-Sierra Grande Uplift Geologic Province (modified after Gautier et al., 1996).

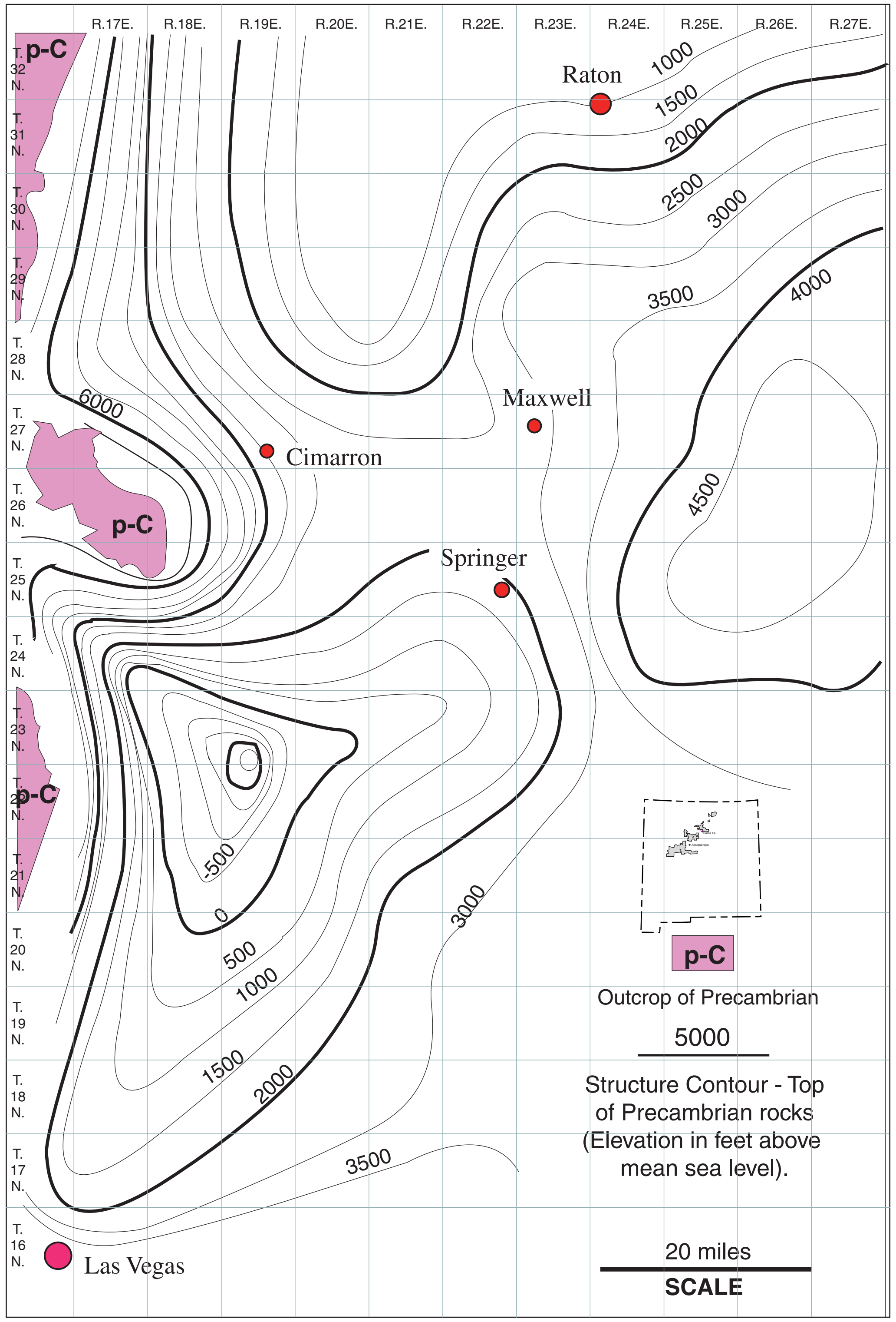


Figure P-32. Structure-contour map of top of Precambrian basement rocks in Raton Basin, New Mexico (modified after Woodward and Snyder, 1976).

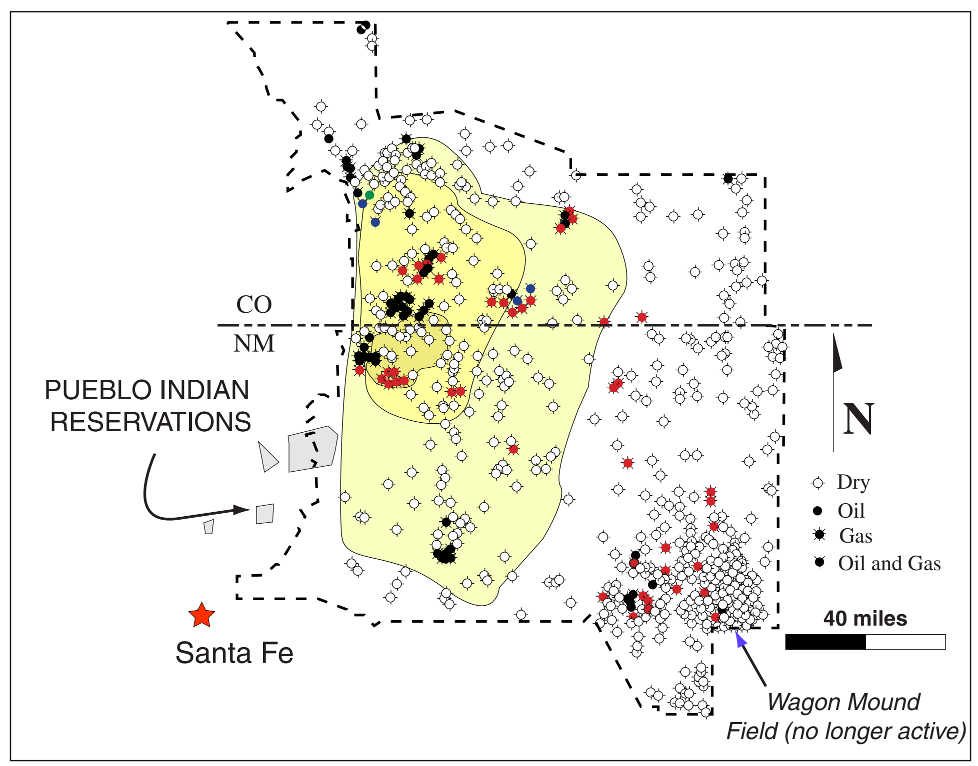


Figure P-33. Outline of Raton Basin-Sierra Grande Uplift Geologic Province with exploration wells from 1900-1993 illustrated. Also highlighted is the outline of the hydrocarbon plays within the region (modified after Gautier et al., 1996).

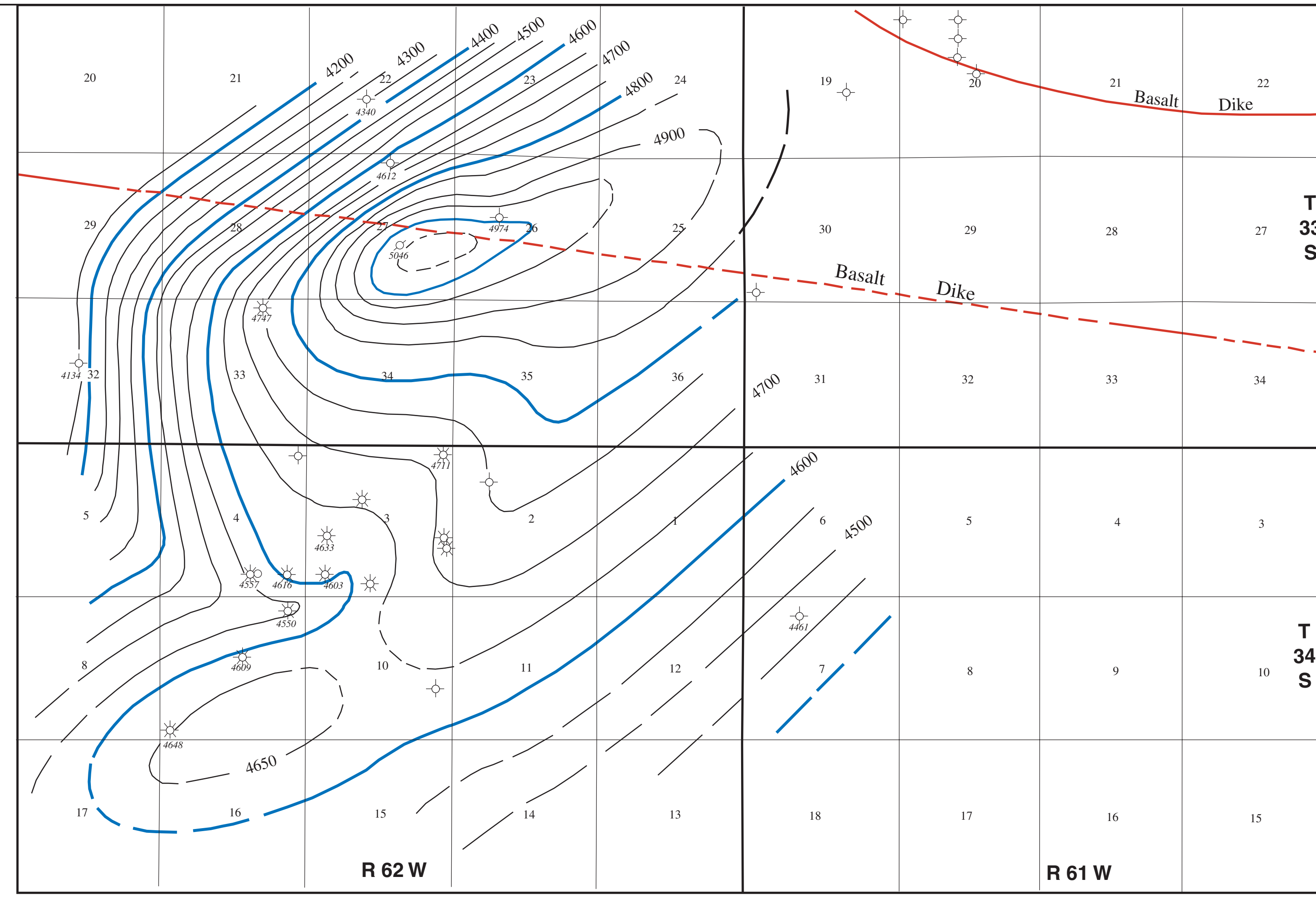


Figure P-34. Structure map of Garcia Field. Datum is the base of the Timpas limestone; contours are in feet (modified after Clair and Bradish, 1956).

Analog Field Within Raton Basin near Pueblo Reservations

Garcia Field

(Figure P-34)

- Location of Discovery Well: T34S , R62W
- Producing Formation: Codell Fm; Greenhorn Lms; Dakota Ss
- Type of Trap: Str atigraphic; anticline
- Initial Production: 1.5 MCFD
- Cumulative Production: NA
- Gas Characteristics: 26.6 g ravity API
- Type of Drive: Lo w pressure
- Average Net Pay: v ariable
- Porosity: NR
- Permeability: NR

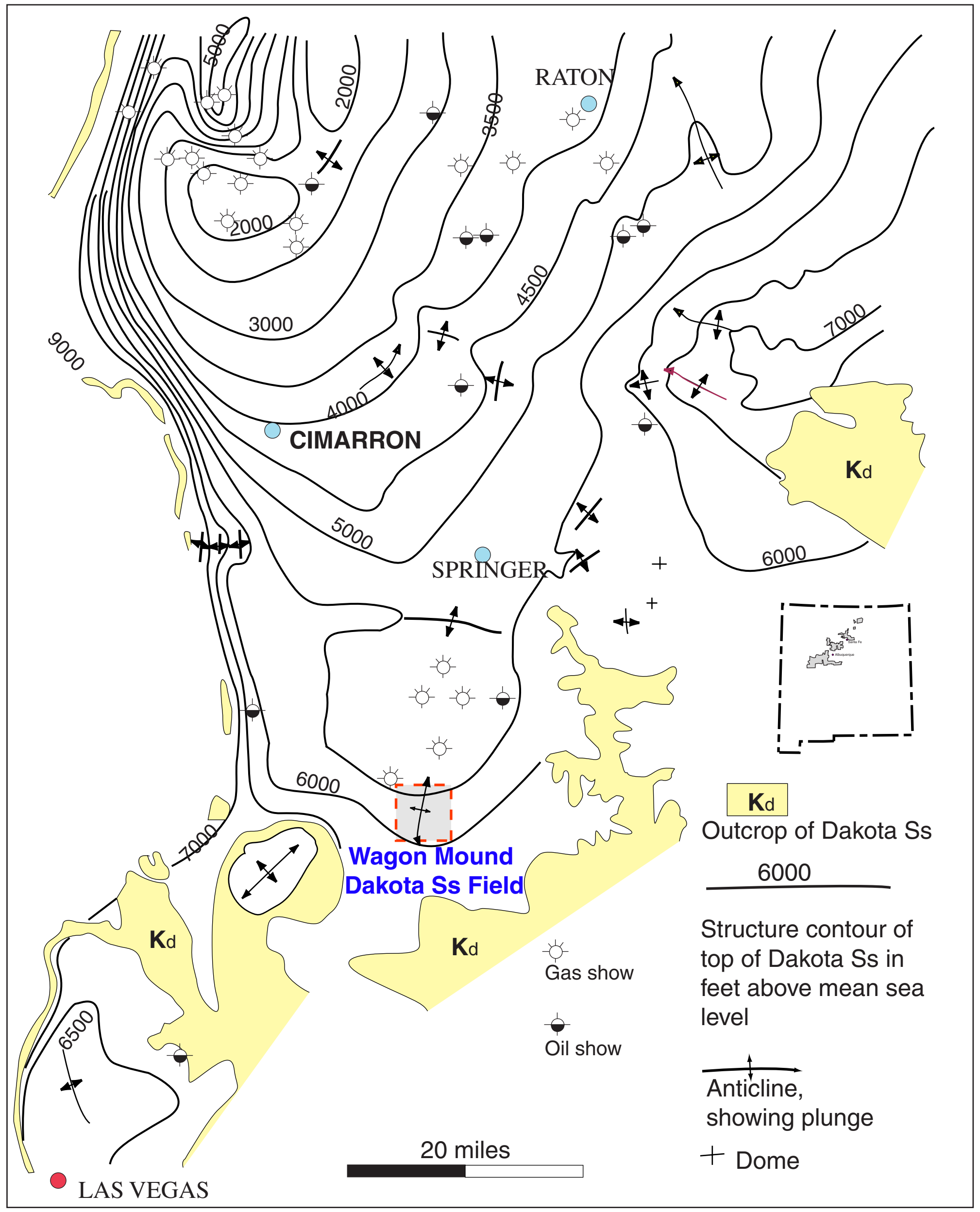


Figure P-35. Structure-contour map of top of Dakota Formation (Cretaceous) in Raton Basin, New Mexico (modified after Northrop et al., 1946; Bachman, 1953; Simms, 1965; Pilmore, 1969; Speer, 1976; and , 1974).

Wagon Mound Field

(Fig. P-35)

Location of Discovery Well:	T21N, R21E, sec14, Mor a County, NM
Producing Formation:	Cretaceous Dak ota Ss & Jurassic Morr ison Fm
Type of Trap:	Shale (Gr aneros Shale); Stratigraphic
Initial Production:	300-500 thousand cubic f eet per day
Cumulative Production:	NR
Gas Characteristics:	NR
Type of Drive:	Gas pressure (lo w)
Average Net Pay:	110 f eet
Porosity:	15%
Permeability:	~2 darcies

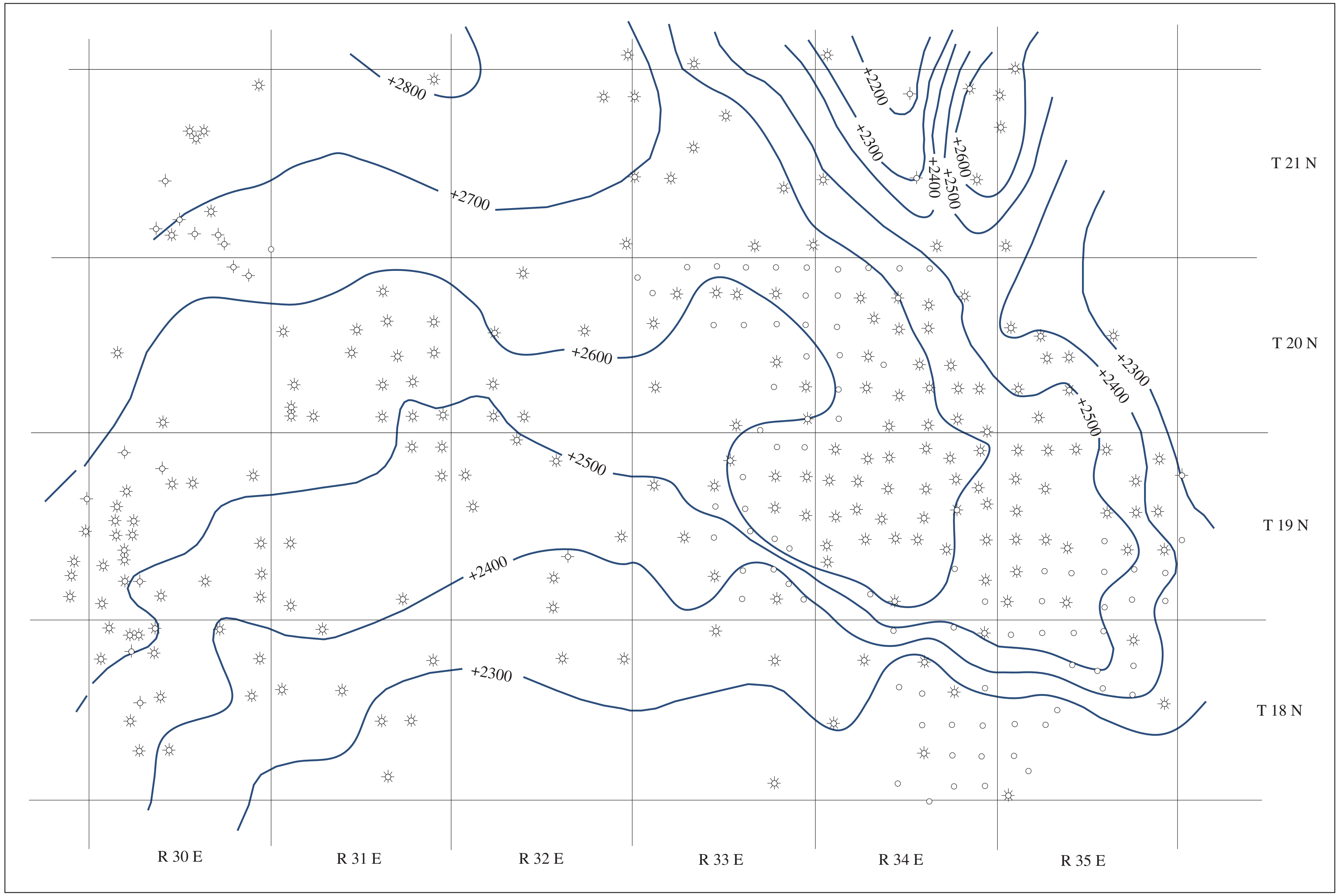


Figure P-36. Structure map of the Bravo Dome Carbon Dioxide Area Field showing the base of the Cimarron Anhydrite. Contour lines are in feet (modified after Johnson, 1983).

Bravo Dome Field

(Figure P-36)

Location of Discovery Well:	s w nw sec 32, T20N, R31E (No.1 Bueyeros)
Producing Formation:	Santa Rosa ss (T riassic); Sangre De Cristo Fm
Type of Trap:	Str atigraphic
Initial Production:	1,500 MCFD
Cumulative Production:	5.3 to 9.8 TCF (estimated)
Gas Characteristics:	98.6 to 99.8% CO_2
Type of Drive:	Gas Expansion
Average Net Pay:	100 f eet
Porosity:	20%
Permeability:	42 millidar cies

Conventional Plays

Upper Cretaceous-Lower Tertiary Play

(USGS 4101)

General Characteristics

This hypothetical, continuous-type "tight-gas" play is largely restricted to the marginal marine, partly deltaic Trinidad Sandstone. Although, stratigraphic traps could occur in the Vermejo and Raton Formations (Fig. P-37). Dolly and Meissner (1977) estimated the uppermost Cretaceous/lowermost Tertiary section may have generated approximately 23 TCFG, of which approximately 6 TCFG may be recoverable. Additionally, as much as 750 BCF of recoverable gas reserves exists in basin-centered gas in the northern portion of the Raton Basin.

Reservoirs: The Cretaceous Trinidad Sandstone, characterized as marginal marine and partly deltaic, is the potential reservoir rock. General thickness probably varies between 100 and 250 feet. Reservoir sandstones may be as much as 50 feet thick and reservoir porosity is probably 10-14 percent, but porosity usually varies between 2 and 18 percent. Other potential clastic reservoirs include the Cretaceous Vermejo and Cretaceous/Paleocene Raton Formations.

Source rocks, timing, and migration: Pierre Shale and coal/carbonaceous beds are potential sources in the Vermejo, Raton, and Poison Canyon Formations. Generation and migration probably began no earlier than Eocene.

Traps: Trinidad Sandstones, in a basin-center environment, may lack a conventional seal. Depth to production is rather shallow, ranging between approximately 4,000 and 6,000 feet.

Exploration status and resource potential: The play is poorly explored. It is possible that a few new discoveries will exceed 6 BCFG. A number of small gas fields possibly could be found.

Jurassic-Lower Cretaceous Play

(USGS 4102)

General Characteristics

This is a high-risk play, and potential reservoirs are restricted to Jurassic Morrison and Cretaceous Dakota Sandstones deposited as highly lenticular marine bars and fluvial channels (Fig. P-38). Sandstones may be fine to coarse grained, 10-40 feet thick and log-derived porosity may reach 15-25 percent. Field pressure, determined from the now-abandoned Wagon Mound Field (Mora County, New Mexico) is low.

Reservoirs: Jurassic Morrison and Cretaceous Dakota Sandstones, deposited as highly lenticular marine bars and fluvial channels, are the potential reservoirs. Sandstones are fine to coarse grained, 10-40 feet thick. Porosity, determined from logs (Figs. 39 and 40), varies between 15 and 25 percent and permeability appears high. Field pressure is low (5.5 psi). Most of the gas has been found in the upper Dakota Sands.

Source rocks, timing, and migration: Shale and coal are possible sources within the Purgatoire-Dakota sequence, and overlying shales include potential source beds for oil and gas. Generation probably began in early Tertiary (Eocene-time) when overlying strata were at least 10,000 feet thick. Migration probably began in the Eocene.

Traps: Gas was structurally trapped in the Dakota Sands in a low-relief, northeast-trending Laramide Anticline. Some gas was trapped in lenticular, fluvial Jurassic Morrison Sandstones. Interbedded shales probably act as traps. Depth to known occurrences is 500-5,000 feet.

Exploration status: The play is poorly explored. It is unlikely that new discoveries will exceed 6 BCFG or 1 MMBO. A number of small gas fields could probably be found.

Resource potential: This is a high risk play; undiscovered resources are estimated to be of small size.

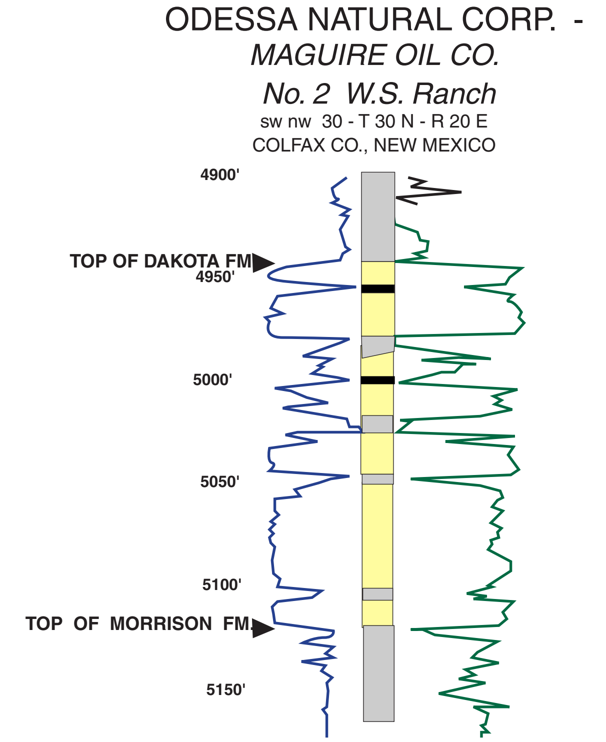


Figure P-39. Typical gamma-ray log of Dakota Formation in south-central Raton Basin (modified after Gilbert and Asquith, 1976).

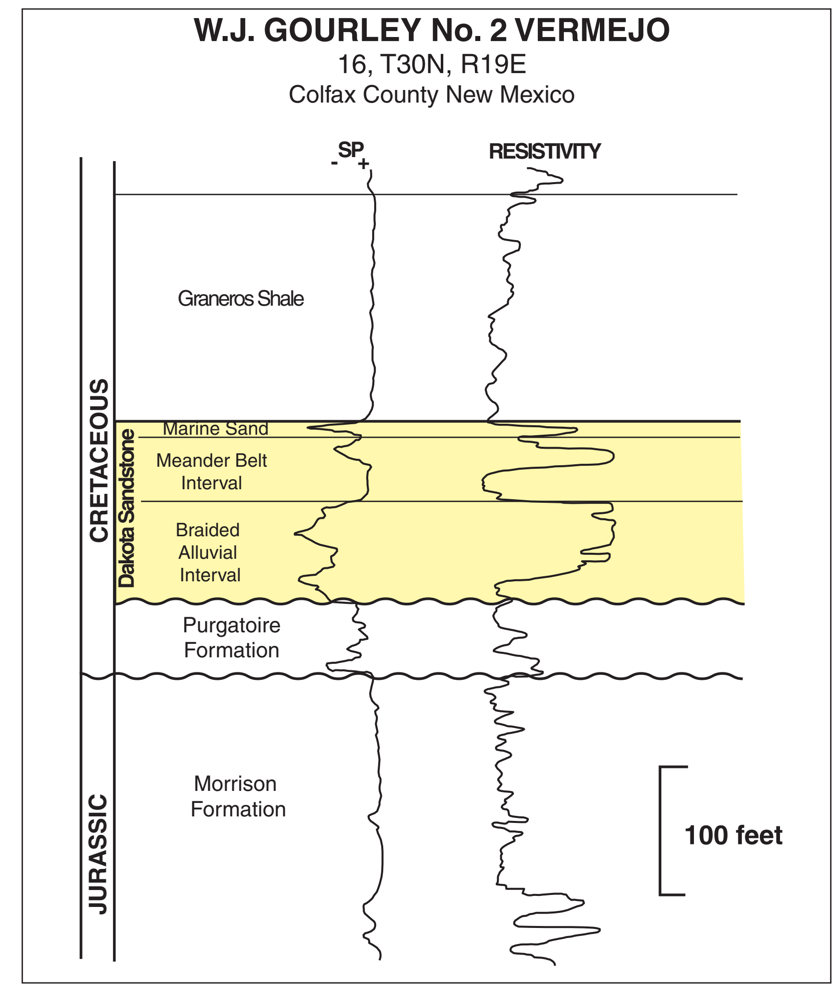


Figure P-40. Typical electric log characteristics of the Dakota Sandstone in the Raton Basin, Colfax County, New Mexico (modified after Gilbert and Asquith, 1976).

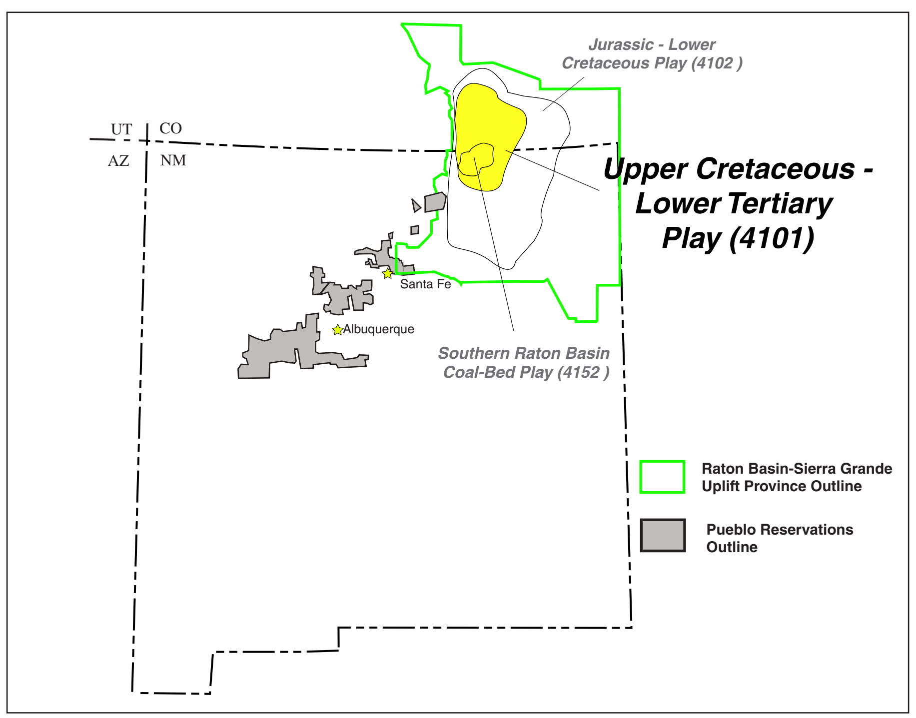


Figure P-37. Upper Cretaceous-Lower Tertiary Play (4101) with respect to the Pueblo Indian Reservations (modified after Gautier et al., 1996).

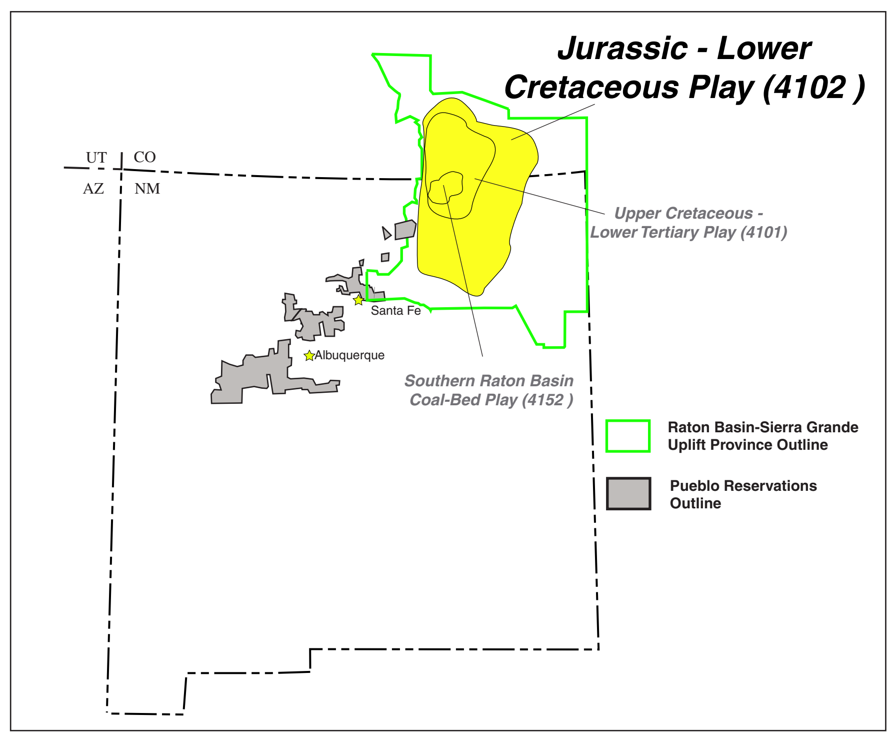


Figure P-38. Jurassic-Lower Cretaceous Play (4102) with respect to the Pueblo Indian Reservations (modified after Gautier et al., 1996).

UNCONVENTIONAL PLAYS

Coal-Bed Gas Plays

Three coal-bed gas plays are identified in the Raton Basin Province. The Southern Raton Basin Play (4152) is relevant to the Pueblo Indian Reservations (Fig. P-41). Tyler et al., 1991; Stevens et al., 1992; and Close and Dutcher, 1993, have described the geologic controls and potential of coal-bed gas in the Raton Basin, southeastern Colorado and northeastern New Mexico.

In the Raton Basin, coal beds with potential for coal-bed gas are contained within the Upper Cretaceous Vermejo and Upper Cretaceous-Paleocene Raton Formations (Fig. P-42). The Vermejo Formation is as much as 350 feet thick and individual coal seams are as much as 14 feet thick. The cumulative coal thickness for the formation ranges from 5 to 35 feet. The overlying Raton Formation is as much as 1,600 feet thick and has a net coal thickness in the range of 10 to 120 feet. Although the Raton Formation contains more coal, individual coal seams are thinner, more discontinuous, and distributed over 1,200 feet of section. The nature of the coal seams in the two formations is controlled by depositional environment; the Vermejo was deposited in a lagoonal environment; whereas, the Raton was deposited in a fluvial setting. Although coal beds are as much as 4,100 feet deep in the northern part of the basin along the LaVeta Syncline, they are generally less than 1,200 feet over a large part of the basin.

The rank of coals in the Vermejo Formation ranges from high-volatile C bituminous along the margins of the basin to low-volatile bituminous in the central part of the basin. The rank generally coincides with present-day depth of burial and structural configuration, and probably resulted from maximum depth of burial that occurred in early Tertiary time. However, the highest ranks (low-volatile bituminous) occur along the eastward-flowing Purgatoire River where the present-day depths of burial are less than about 1,200 feet. These high ranks are interpreted to be the result of high heat flow from the crust, upper mantle, and (or) deep igneous intrusions which was transferred laterally by groundwater flow in middle Tertiary time. During this time, Vermejo and Raton coal beds commonly served as planes of weakness for igneous intrusions. However, the thermal maturity of the coal beds is only locally affected (one-dike width) by the intrusions.

Coal-bed gases from production tests in the Raton Basin are composed mostly of methane with minor amounts of ethane, carbon dioxide, and nitrogen (each less than 1 percent). Isotopic analyses indicate that the gases are predominantly of thermogenic origin and were probably generated during time of maximum burial and (or) heat flow. Some mixing of relatively recent biogenic gas may occur in areas of groundwater flow.

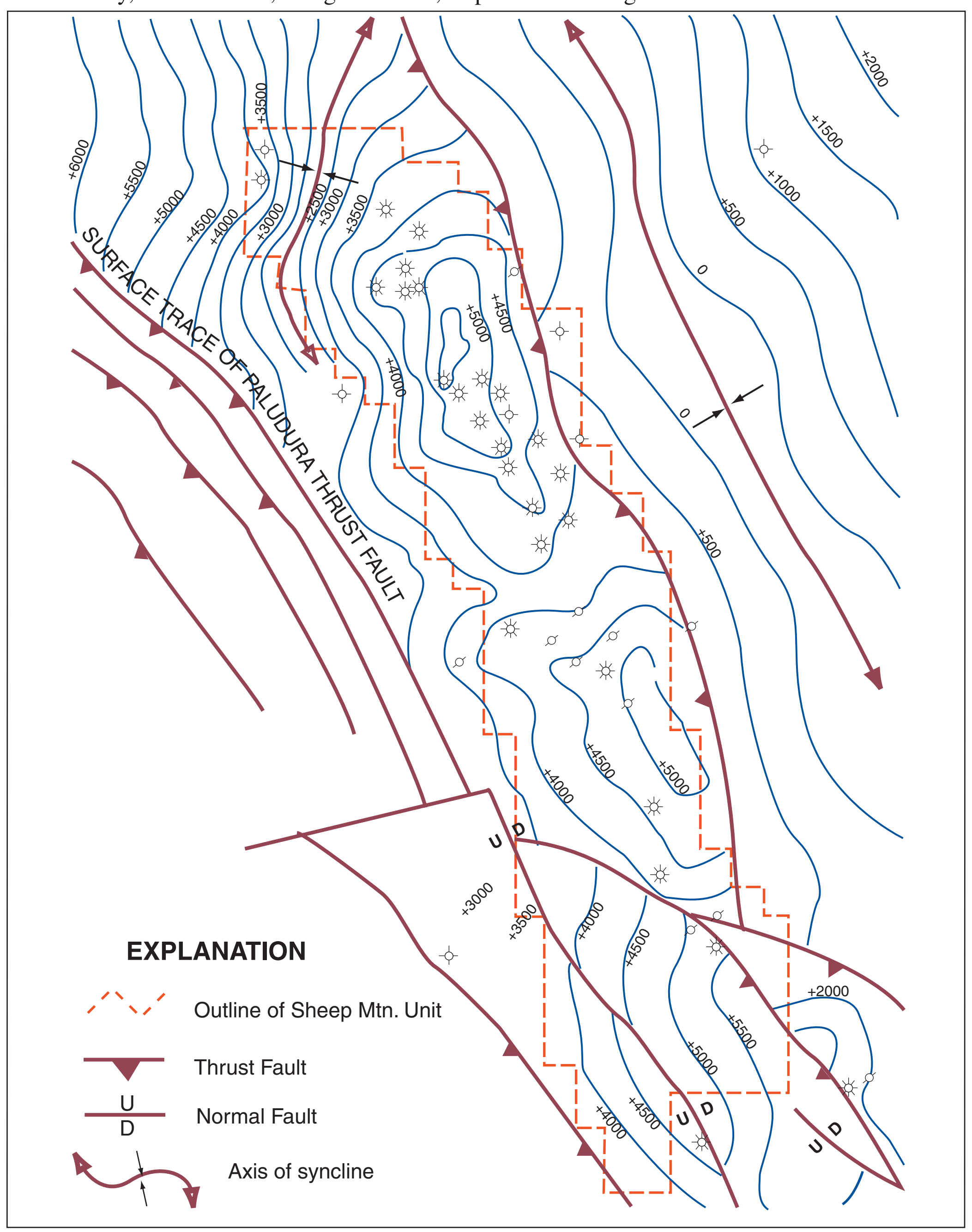
The Raton Basin is a strongly asymmetric basin with a gently dipping eastern flank and a steeply dipping western flank that is thrust-faulted (Fig. P-9). Several major folds are located along the western margin of the basin. Minor normal faulting occurs within the basin with displacements generally less than 50 feet. The primary fracture permeability system in both the coals and adjoining rocks is oriented east-west.

Groundwater recharges the topographically high Vermejo-Raton Aquifer along the western margin of the basin and flows eastward to discharge at the topographically lower eastern outcrops along major seeps and drainage areas (Geldon, 1989; Stevens et al., 1992). The primary fracture (face cleat) trend in the Raton Basin coals is perpendicular to the local trend of the Sangre de Cristo thrust front and thus enhances groundwater flow and the potential for artesian overpressuring (Tyler et al., 1991).

Gas contents of coal beds in the basin are highly variable and range from 4 to 810 Scf/t. These contents seem to correlate more closely with depth below the hydrologic potentiometric surface than with depth below the ground surface. On the basis of coal thickness, coal density, drillable area, and gas content, in-place coal-bed gas resources of the Raton Basin are estimated to be as much as 12 TCF (Fig. P-42).

Some coal is produced by both underground and surface methods in the Colorado and New Mexico parts of the basin. Mine-related emissions are minor. An explosion in an underground mine near Trinidad, Colorado, indicates that the coal beds are gassy.

Since the late 1970's, more than 110 exploration wells have been drilled for coal-bed gas in the Raton Basin, both in Colorado and New Mexico. Production tests have been variable, but gas rates of more than 300 MCF/D have been reported. At present, all wells are shut-in because of the absence of gas pipelines in the basin. However, a pipeline is under construction and a pilot nitrogren injection project for coalbed gas wells has been approved (Rice and Finn, 1995).



<- Figure P-41. Structure map of the Sheep Mountain Field showing the outline of the Sheep Mountain unit. Datum is the top of the Dakota Sandstone Formation (modified after Roth, 1983).

Analog Field Within Raton Basin
(near Pueblo Indian Reservations)

Sheep Mountain Field
(Figure P-41)

Location of Discovery Well:	No .1 Faris, nw se 15, T25S, R70W
Producing Formation:	Cretaceous Dakota Ss; Jurassic Entrada Ss
Type of Trap:	Stratigraphic (shale)
Initial Production:	4900 MCFD
Cumulative Production:	NR
Gas Characteristics:	NR
Type of Drive:	Gas pressure
Average Net Pay:	350 feet, 110 feet
Porosity:	NR
Permeability:	NR

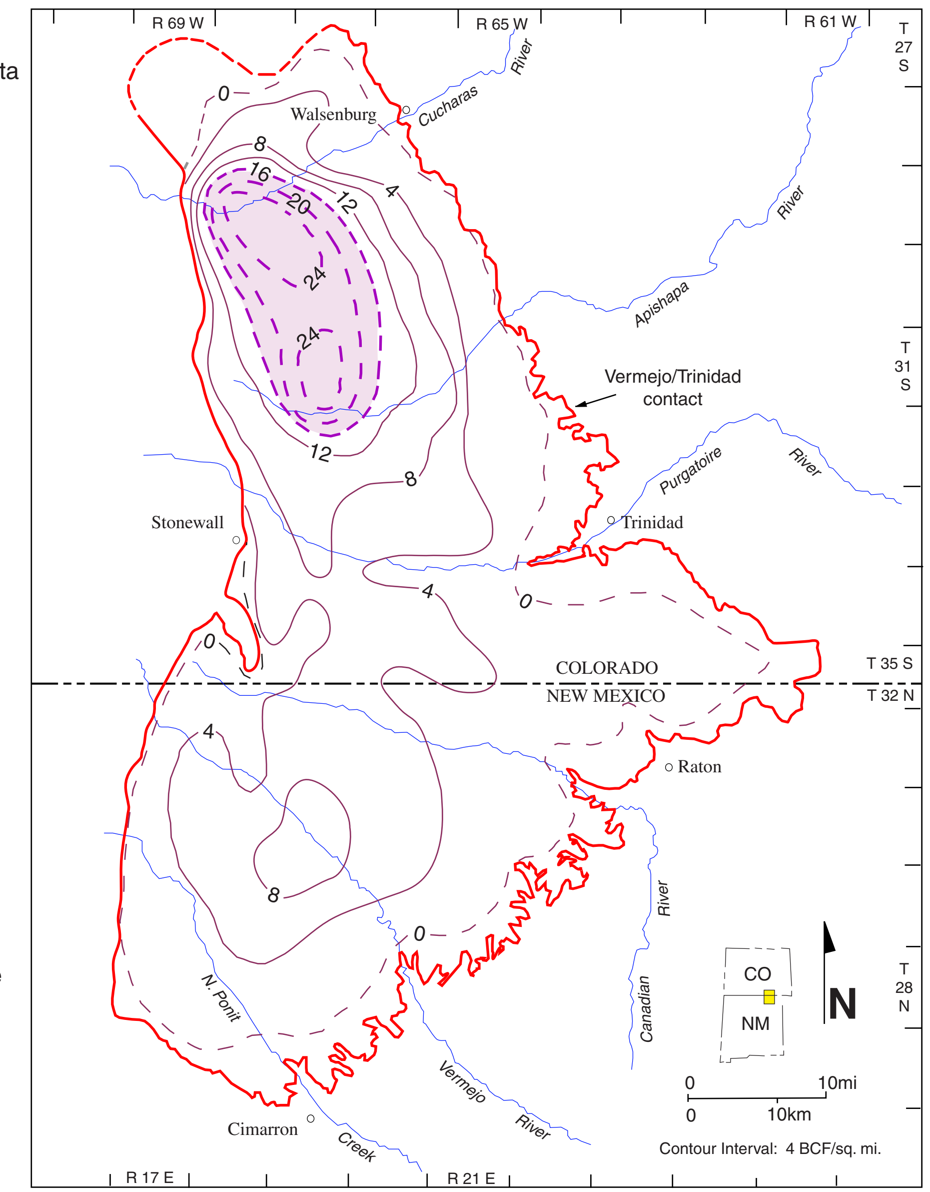


Figure P-42. -> Raton Basin coal-bed methane in place, contoured in 4 BCF/mi intervals; data inside the 16 BCF/mi contour have a high degree of uncertainty (modified after Stevens et al., 1992).

Southern Raton Basin Play

(USGS 4152)

General Characteristics

The target area for coal-bed gas is where coal beds of the Vermejo and Raton Formations are greater than 500 feet deep. The thicker, more continuous seams of the Vermejo Formation are probably better targets for coal-bed gas production. The Southern Raton Basin Play target area (Fig. P 43) is based on depth, coal rank, and concentration of gas in place. Exploration wells have been drilled for coal-bed gas in the play, but production has not been established (as of 1996). The reserve potential of coal-bed gas from all three plays is considered very good, but production will depend on infrastructure development, particularly pipeline construction.

In the Southern Raton Basin Play (4152), coal ranks are as much as medium-volatile bituminous, but depths of burial are less than 1,400 feet. Because of these relatively shallow depths, concentra tions of gas in-place are about 8 BCF/square mile or less. The re serve potential of this play is also regarded as good (Rice and Finn, 1995).

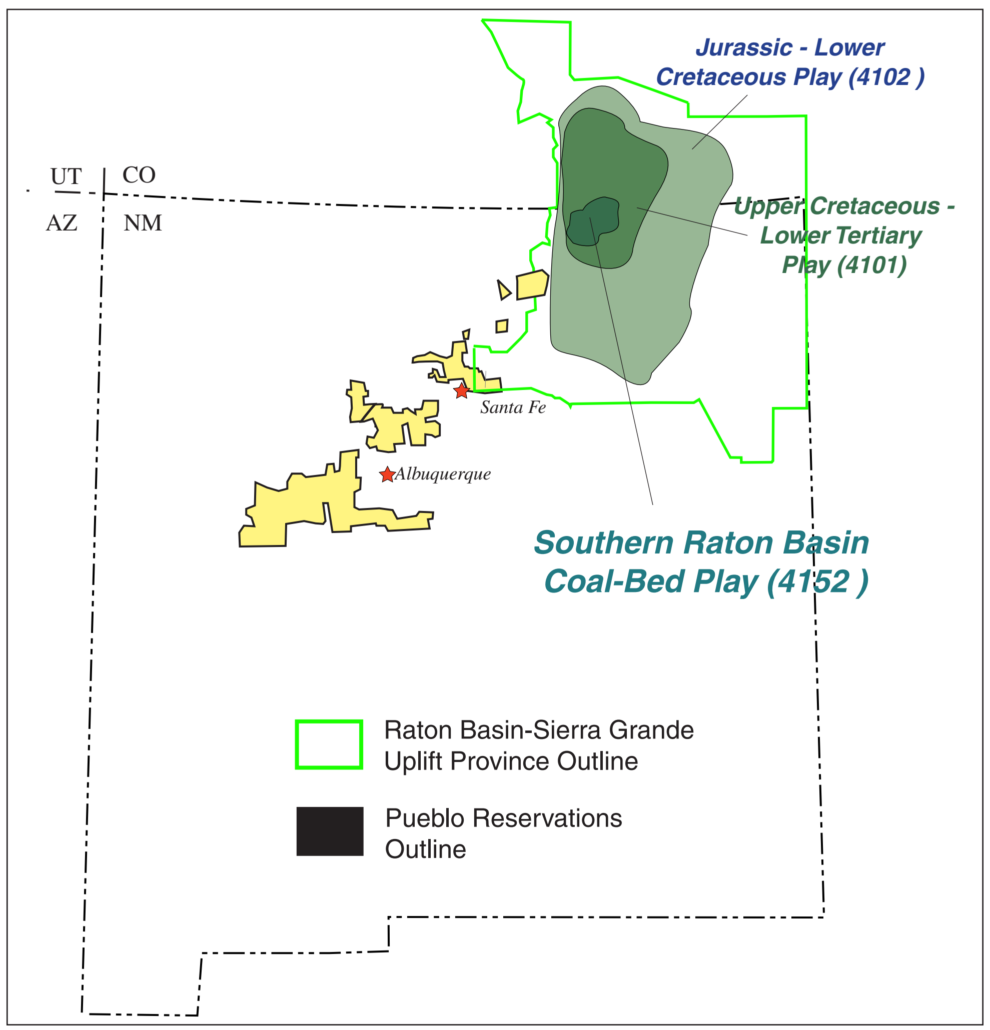


Figure P-43. Southern Raton Basin Coal-Bed Play (4152), with respect to the Pueblo Indian Reservations (modified after Gautier et al., 1996).

South-Central New Mexico Province

This frontier petroleum province covers about 39,900 square miles, primarily in the easternmost part of the Basin and Range Physio graphic Province; it has no production (Fig. P-44). For a more com plete description of this province, see Butler, 1988; and Grant and Foster, 1989.

Small, northeast-trending rift basins are the predominant ph ys iographic feature of the South-Central New Mexico Province. As much as 10,000 feet of alluvium and volcanic rocks fill these exten sional basins, obscuring a moderately thick section of Paleozoic stra ta.

This pro vince has a complex geologic history, having been de formed by three major periods of tectonism during Phanerozoic time: (1) Late Paleozoic formation of the Ancestral Rocky Mountains, (2) Laramide compression, and (3) Cenozoic relaxation and extension and volcanism. South-Central New Mexico was near the terminus of the northeast-trending transcontinental basement arch during the Late Proterozoic and Paleozoic. Within this time span, sediments were deposited in platform, shallow shelf, basinal, and alluvial plain envi ronments. Epeiric seas generally transgressed from the south, and thus a greater thickness of strata was deposited during this time in the southern part of the province. During the mid-Paleozoic, general quiescence of the craton in the equatorial paleo-latitudes resulted in widespread deposition of fossiliferous carbonates accompanied by basin-margin organic buildups. Convergence of the North and South American tectonic plates in the late Paleozoic resulted in intraplate defor mation.

T riassic and Jurassic strata are not well represented in the province, which depositio nally represents an erosional surface shifting from highlands to interior lowlands and coastal plains. Nascent opening of the Gulf of Mexico (Chihuahua Trough) deposited as much as 750 feet of marine Jurassic sediments in the south ernmost Mesilla Basin. Continued opening near the New Mexico-Mexico border resulted in an east-west Early Cretaceous rift, extending into southeastern Arizona. A thick Late Creta ceous section of marine sandstones and shales and continental fluvial clastics and paludal coals was deposited as seas transgressed and re gressed from the north-northeast and from the south-southwest; about 3,000 feet of this sec tion is preserved. Laramide compression from the southwest re juvenated older fault-bounded structures and other paleo-zones of weakness (for example thrust faults) and created basement-cored up lifts. Plutons, with attendant rich mineralization, intruded the prov ince. Early Tertiary uplift provided cyclic alluvial-fluvial fan grav els and deltaic clastics to continental interior-drained basins and small lakes.

T wo hypothetical conventional plays were assessed in this province. They are Orogrande Basin Play (2602) and Mesilla-Mimbres Basins Play (2603), neither of which occur in or near the Pueblo Indian Reservations. However, limited exploration has occurred within the Acoma Basin Play, which underlies a segment of the Pueblo Reserva tion. A brief description of the production within the Acoma Basin is presented in the following section.

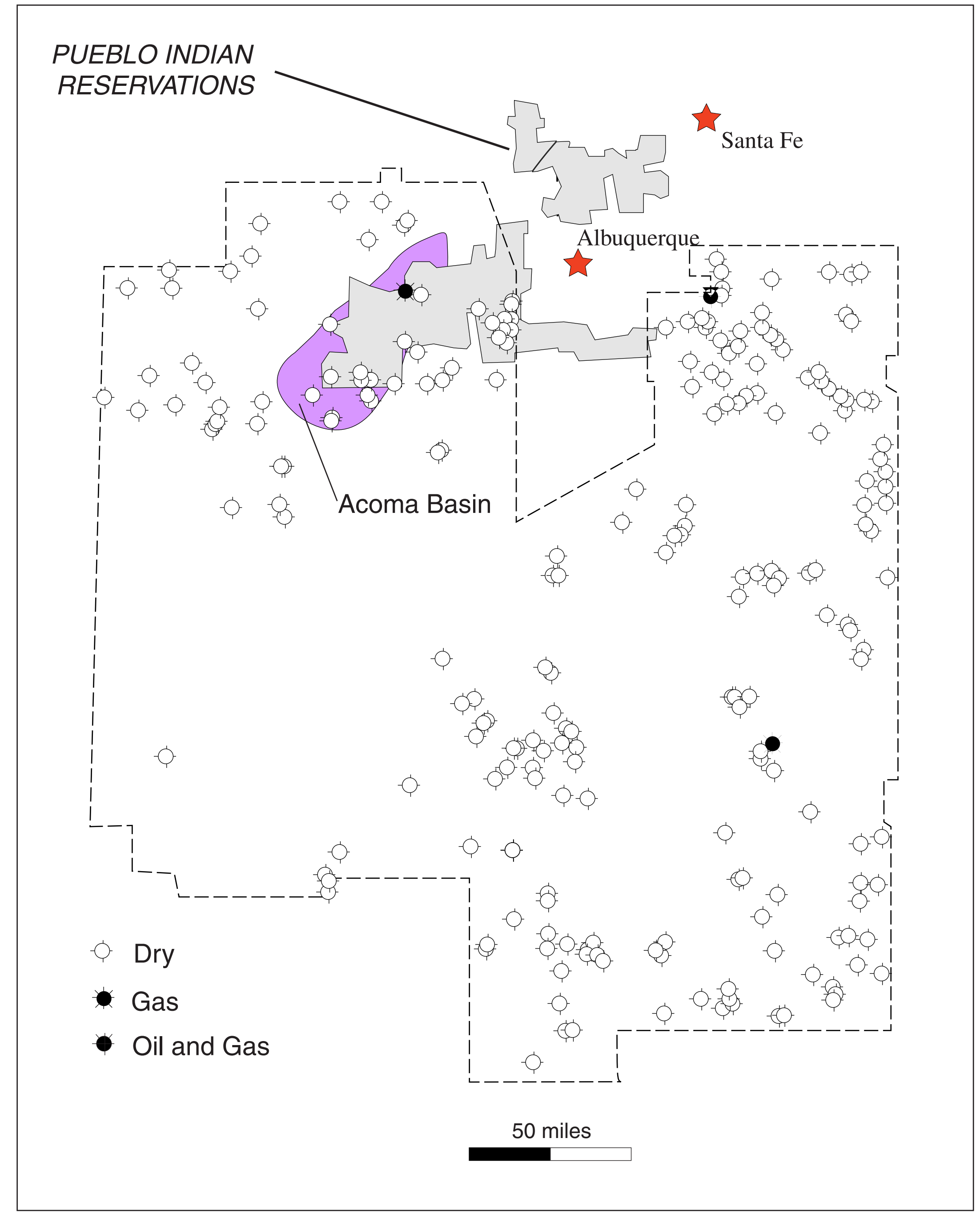


Figure P-44. Outline of South-Central New Mexico Geologic Province with exploration wells from 1900-1993 illustrated. The Acoma Basin is highlighted (modified after Gautier et al., 1996).

Acoma Basin Play

The Acoma Basin has seen limited exploration since the 1920's (Fig. P-45). The boundary between the Acoma Basin and the San Juan Basin to the northwest and the eastern Baca Basin is transitional.

Three signif icant exploratory wells have been drilled in the Acoma Basin since 1981. The Topaz Southwest Number 1 State tested Cretaceous sandstones and shales and Jurassic sandstones with no reported shows. The Austra-Tex Numbers 1 through 7 Rio Puerco Federal, were drilled to test the Pennsylvanian section (Fig. P-46).

Primary reserv oir targets in the Acoma Basin are Permian limestones and sandstones of the San Andres and Yeso Formations and Pennsylvanian sandstone and limestones (Fig. P-47). The Cretaceous Mesaverde and Dakota Sandstones are secondary reservoir targets that have been eroded from the eastern part of the basin and are present only at shallow depths (less than 1500 feet {Broadhead, 1989}) in the western part of the basin (Fig. P-48). Pennsylvanian and Cretaceous marine shales are potential source rocks, but the Cretaceous section may be thermally immature (Broadhead, 1989).

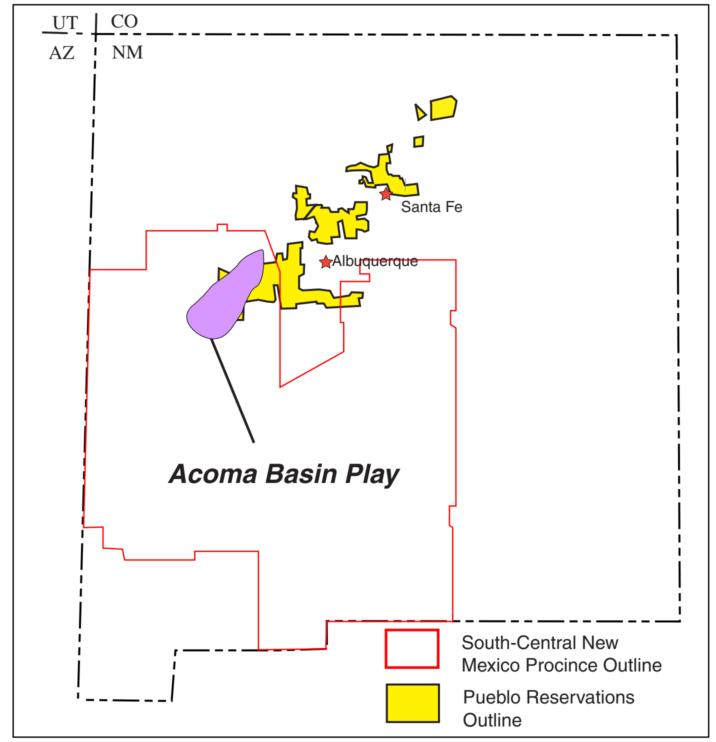


Figure P-45. Outline of the South-Central New Mexico Province with the Acoma Basin Play Highlighted (modified after Gautier et al., 1996).

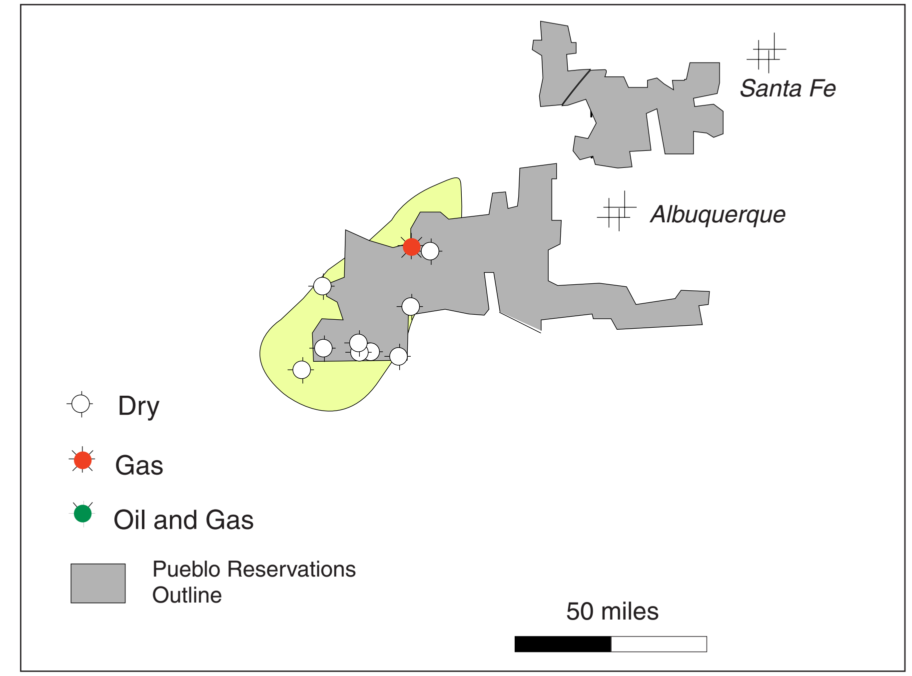
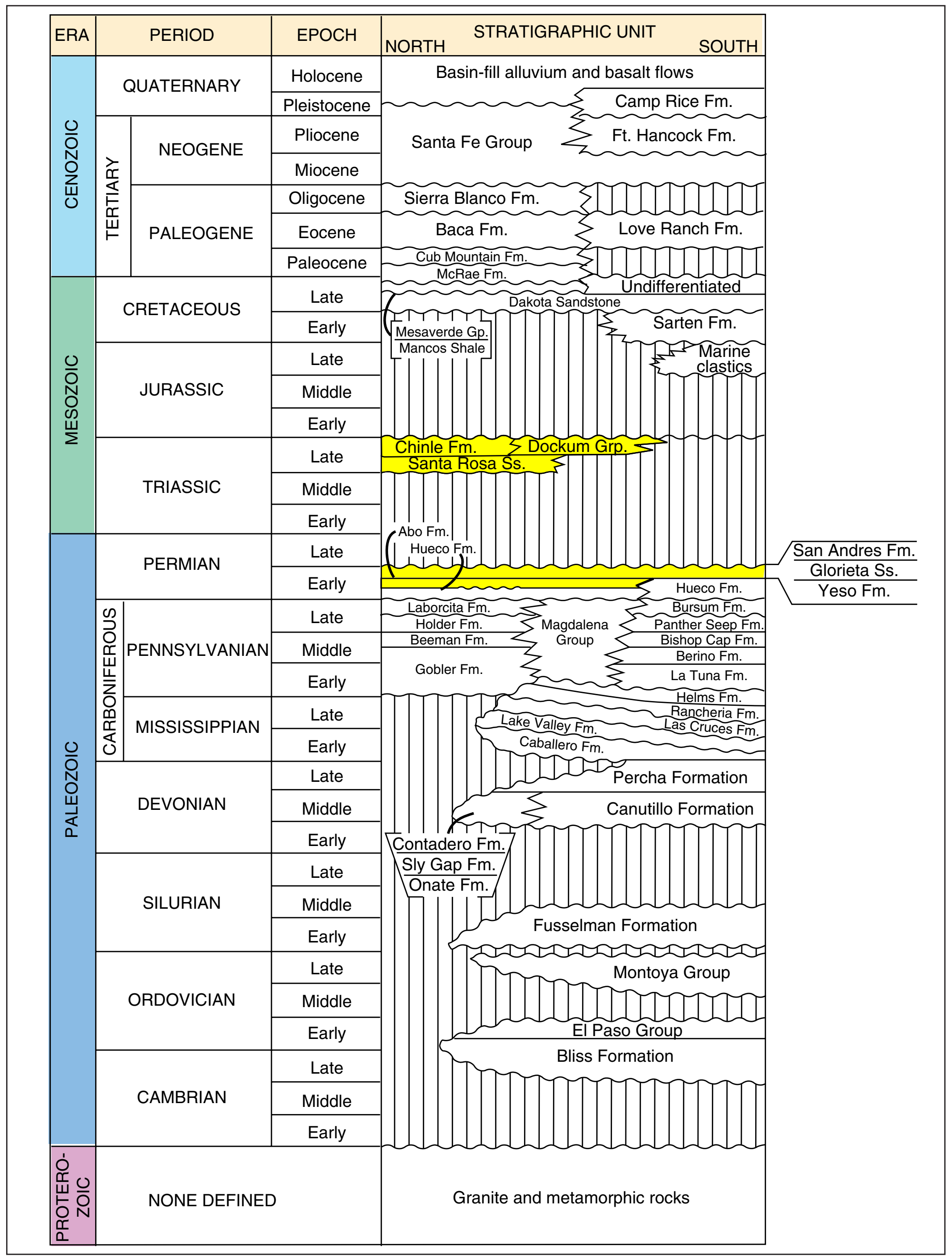


Figure P-48. Location of exploration wells in Acoma Basin (modified after Gautier et al., 1996.)



<-Figure P-46. Stratigraphic section depicting bedding relationships within the South-Central New Mexico Geologic Province (modified after Gautier et al., 1996).

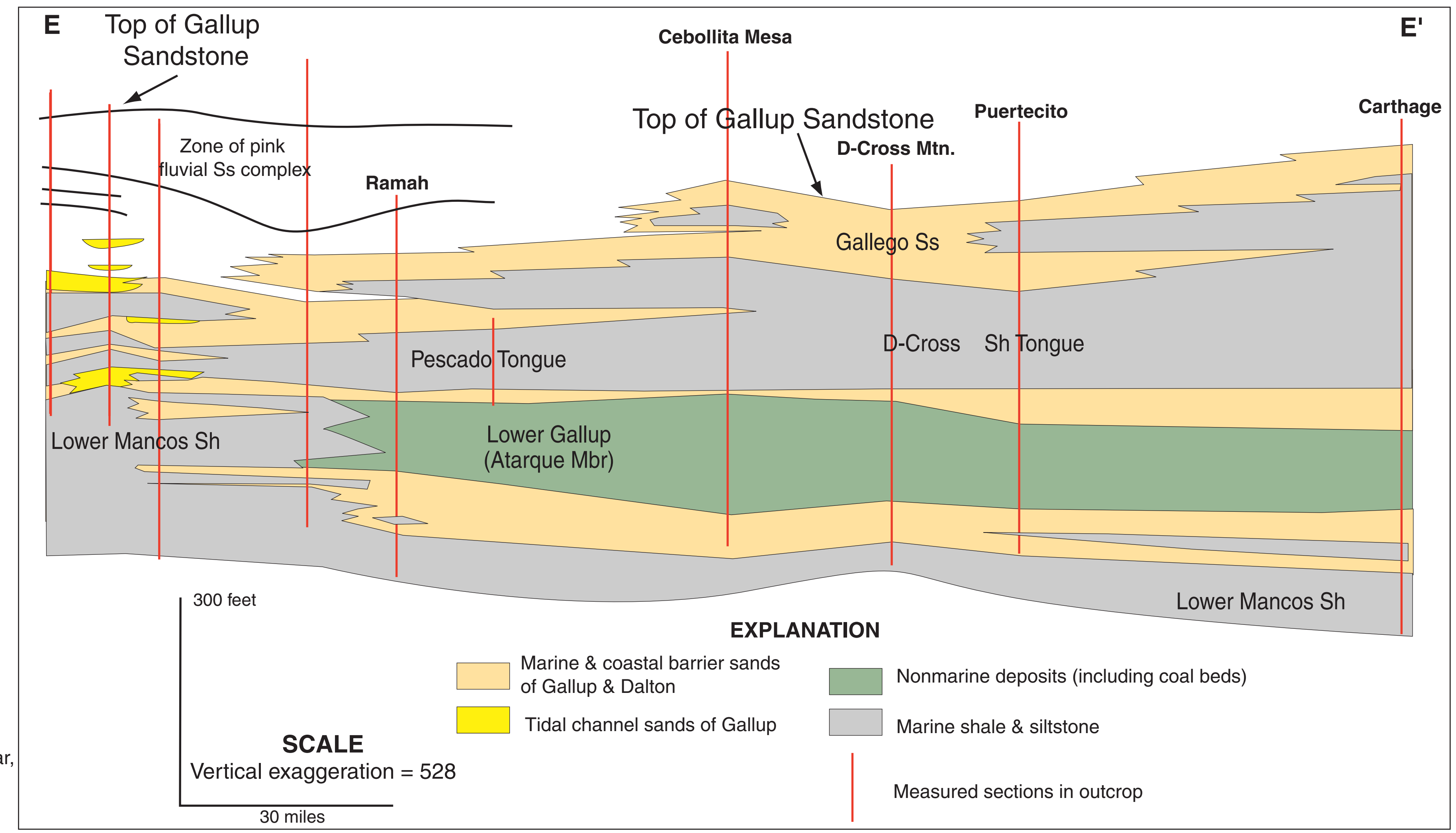


Figure P-47.-> Stratigraphic cross-section E-E' of the Acoma Basin (Fig. P-7; cross-section 5) (modified after Molenaar, 1974).

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