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 Reservations 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-1.1). 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-1.2). 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.

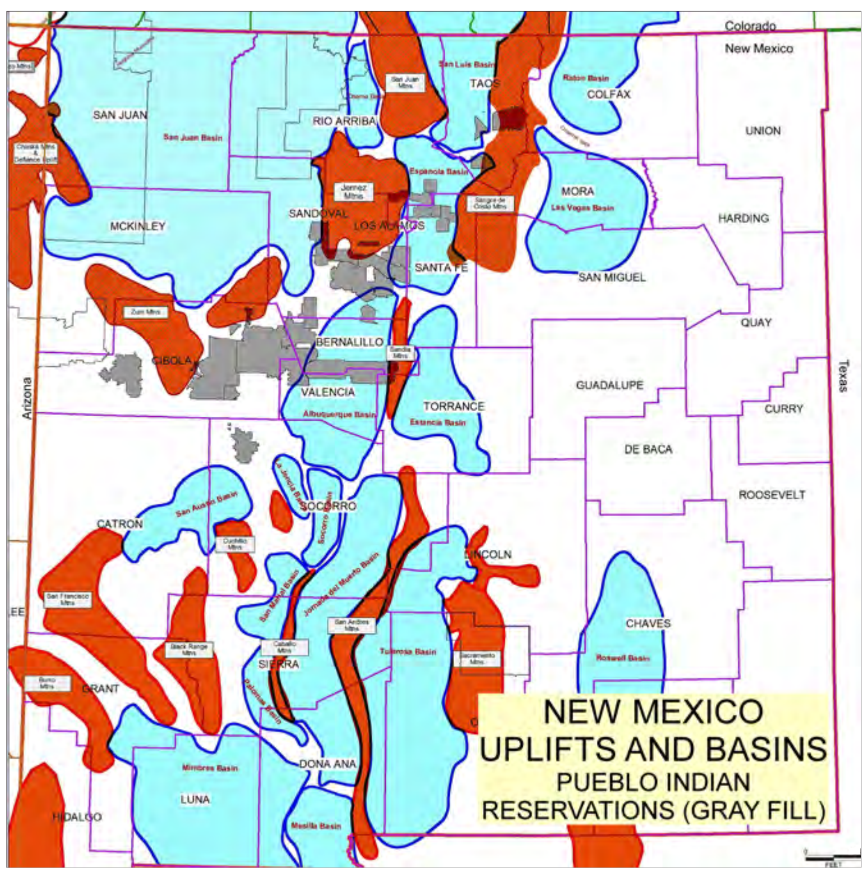

Figure P-1.1. Outline of major geologic basins in New Mexico with respect to the Pueblo Indian Reservations (modified after Land et al, 2016).

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-2.1). 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-2.2). 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-2.2).

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.

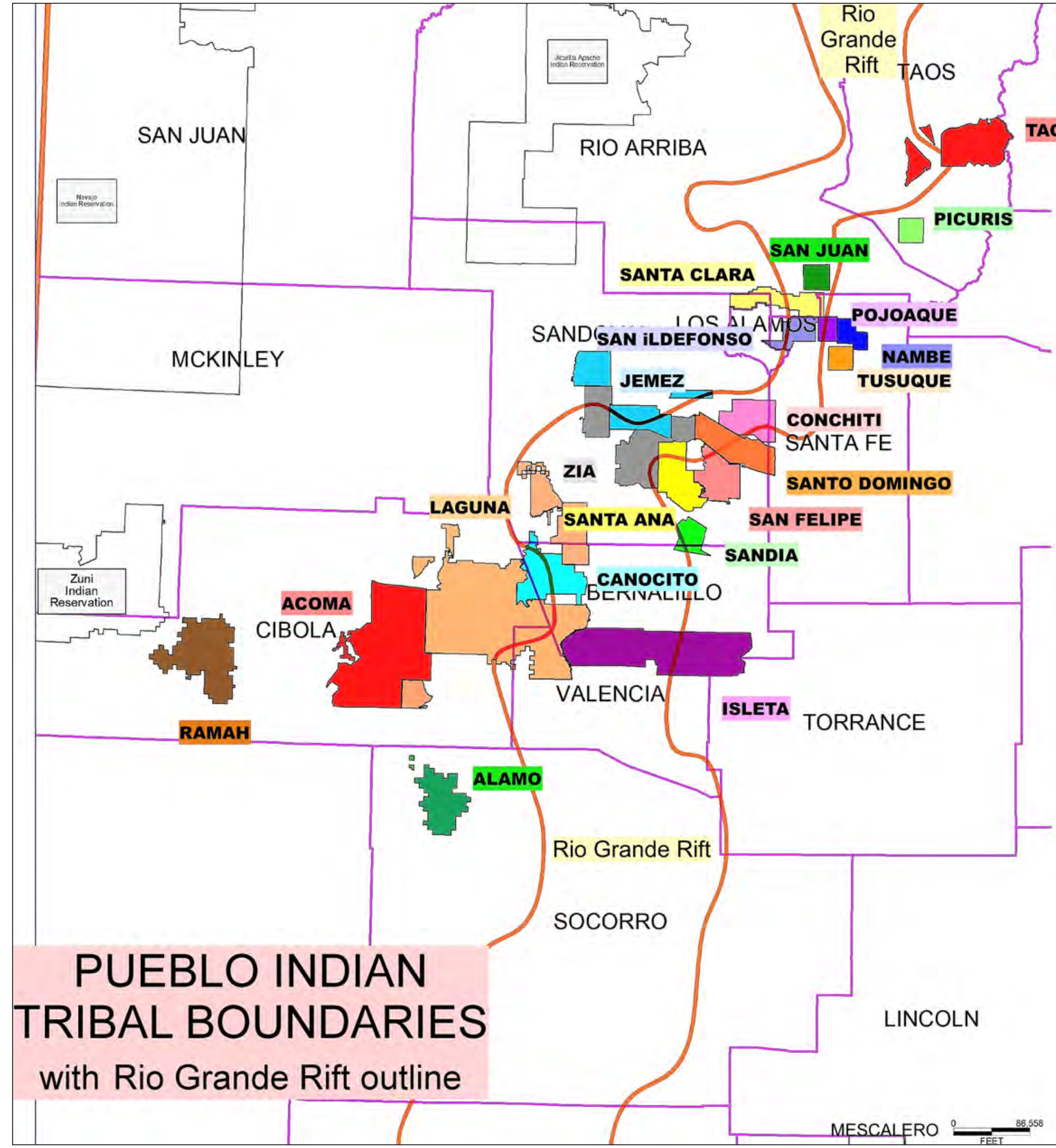

Figure P-1.2. Location of Pueblo Indian Reservations with location of the Rio Grande Rift in New Mexico).

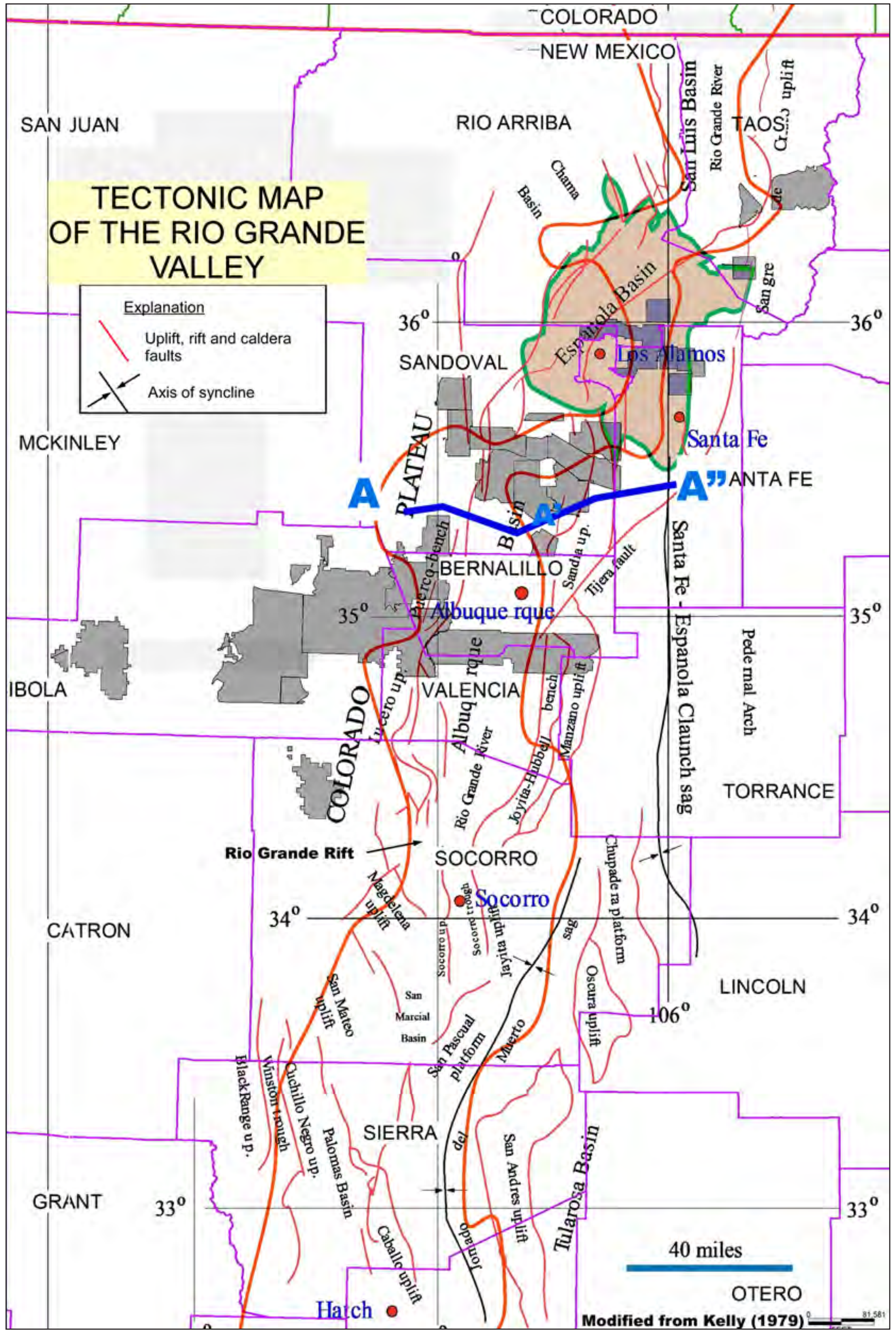

Figure P-2.1. Tectonic map of the Rio Grande Valley in North-Central New Mexico (modified after Kelley, 1979).

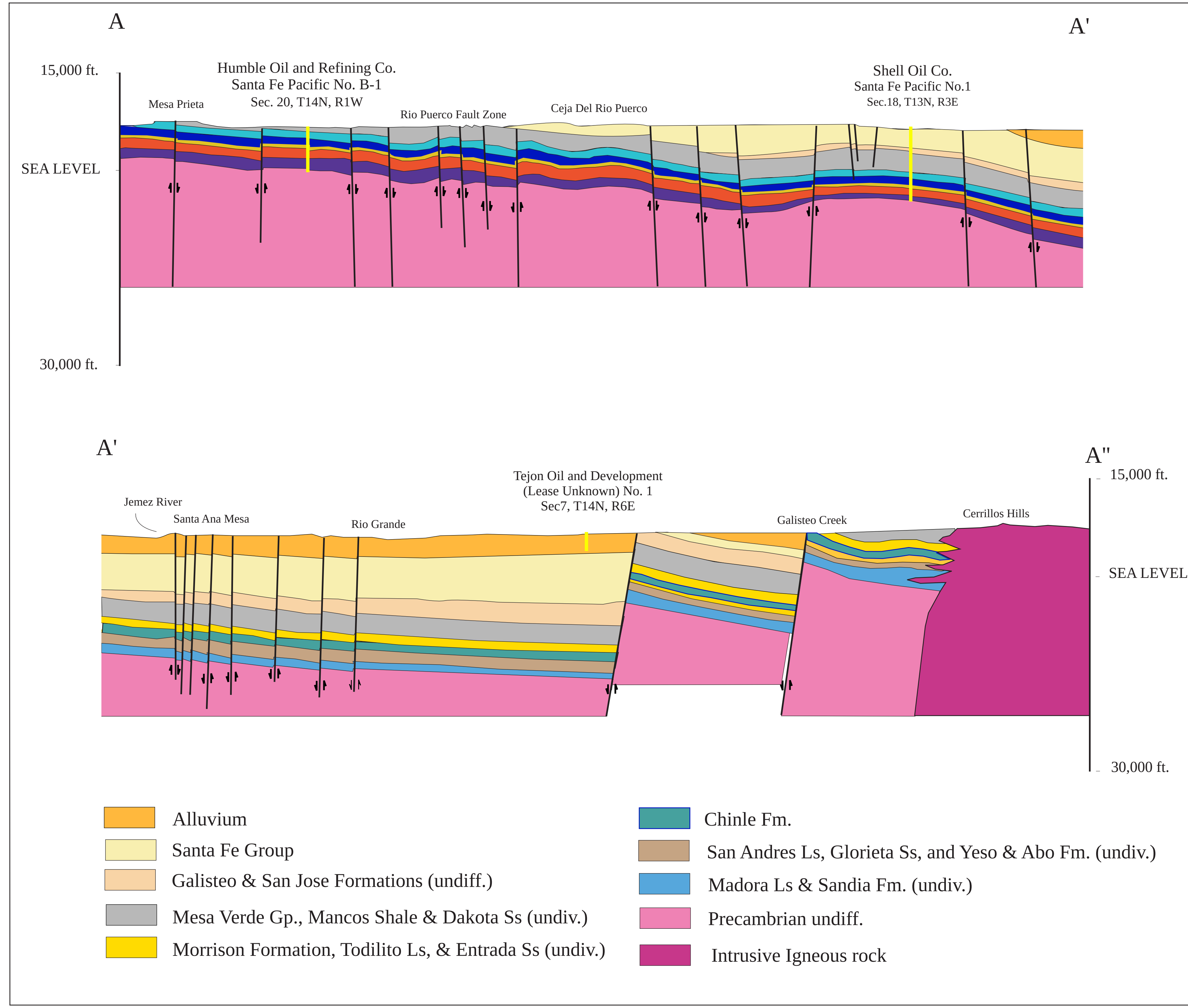

Figure P-2.2. Geologic cross-section across the northern part of the Albuquerque Basin and the southern part of the Espanola Basin (Figure P-2.1 and 4.1) (modified after Black and Hiss, 1974).

STRATIGRAPHY

The Albuquerque-San Luis Rift Basin contains rocks ranging in age from Precambrian to Recent (Fig. P-3.1). 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-3.2 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-4.1 and P-4.2 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).

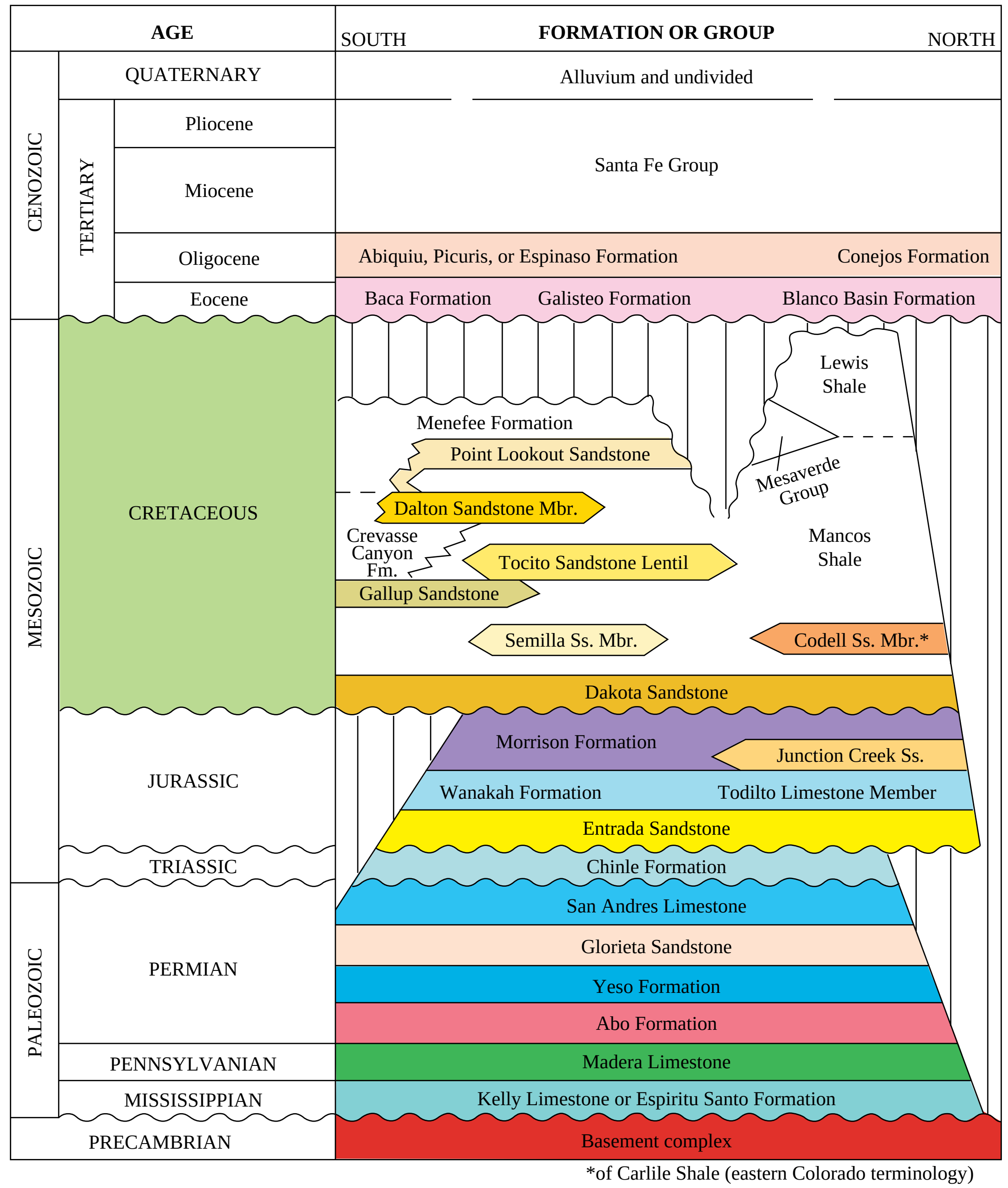

Figure P-3.1. Stratigraphic section depicting bedding relationships within the Albuquerque-Santa Fe Rift Geologic Province (modified after Gautier et al., 1996).

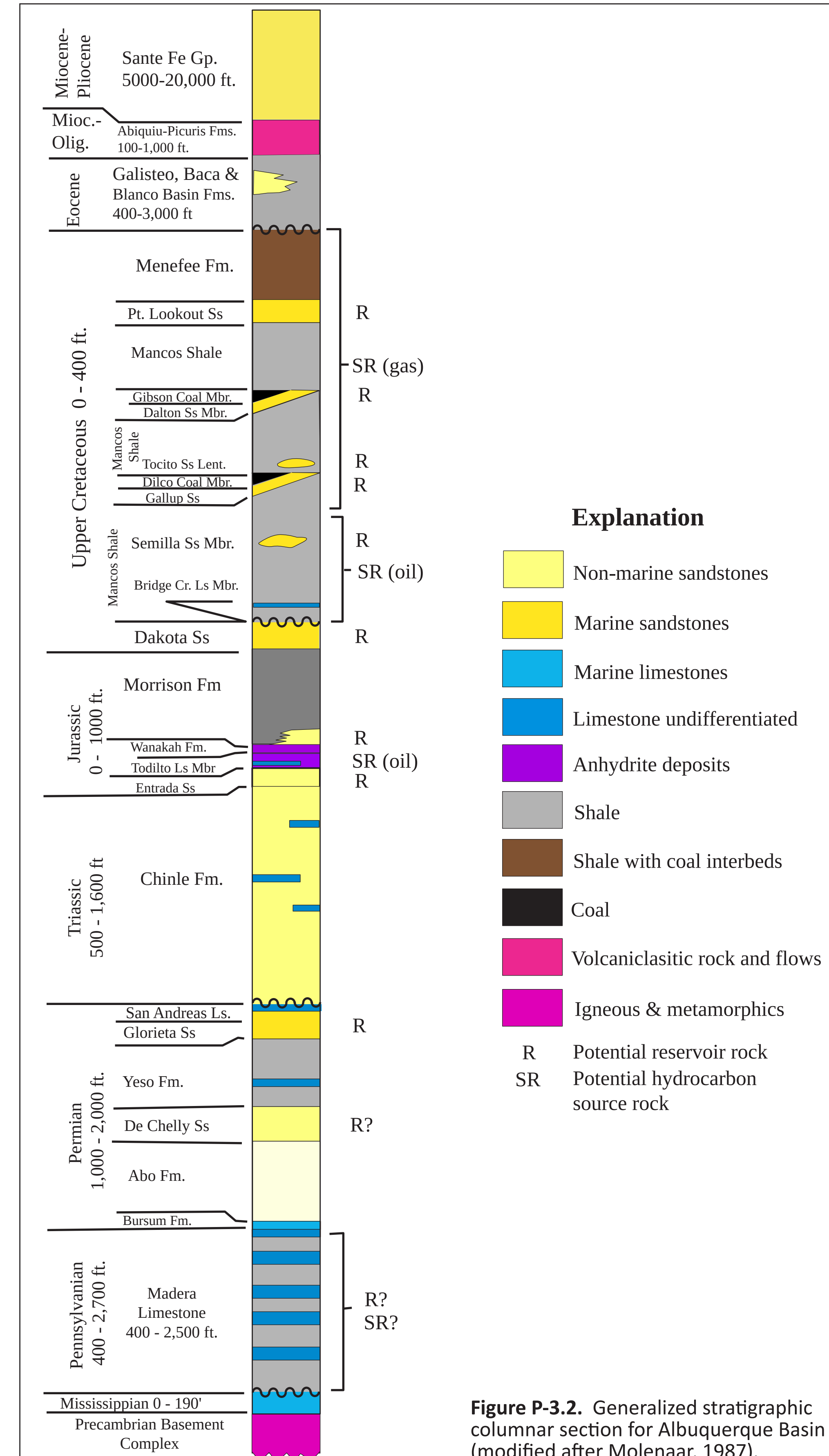

Figure P-3.2. Generalized stratigraphic columnar section for Albuquerque Basin (modified after Molenaar, 1987).

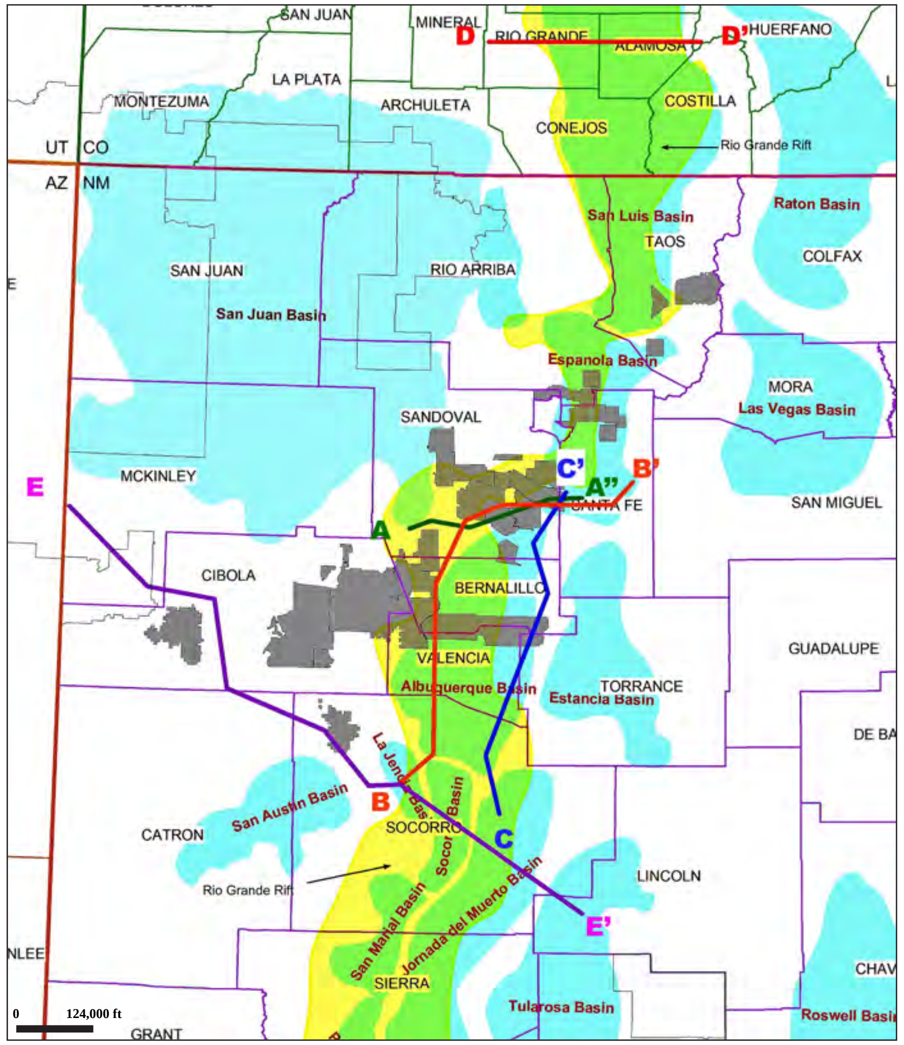

Figure P-4.1. Location of cross-sections through study area (modified after Molenaar, 1987; Black, 1982; and Woodward, 1984). Pueblo reservations are shown in gray color.

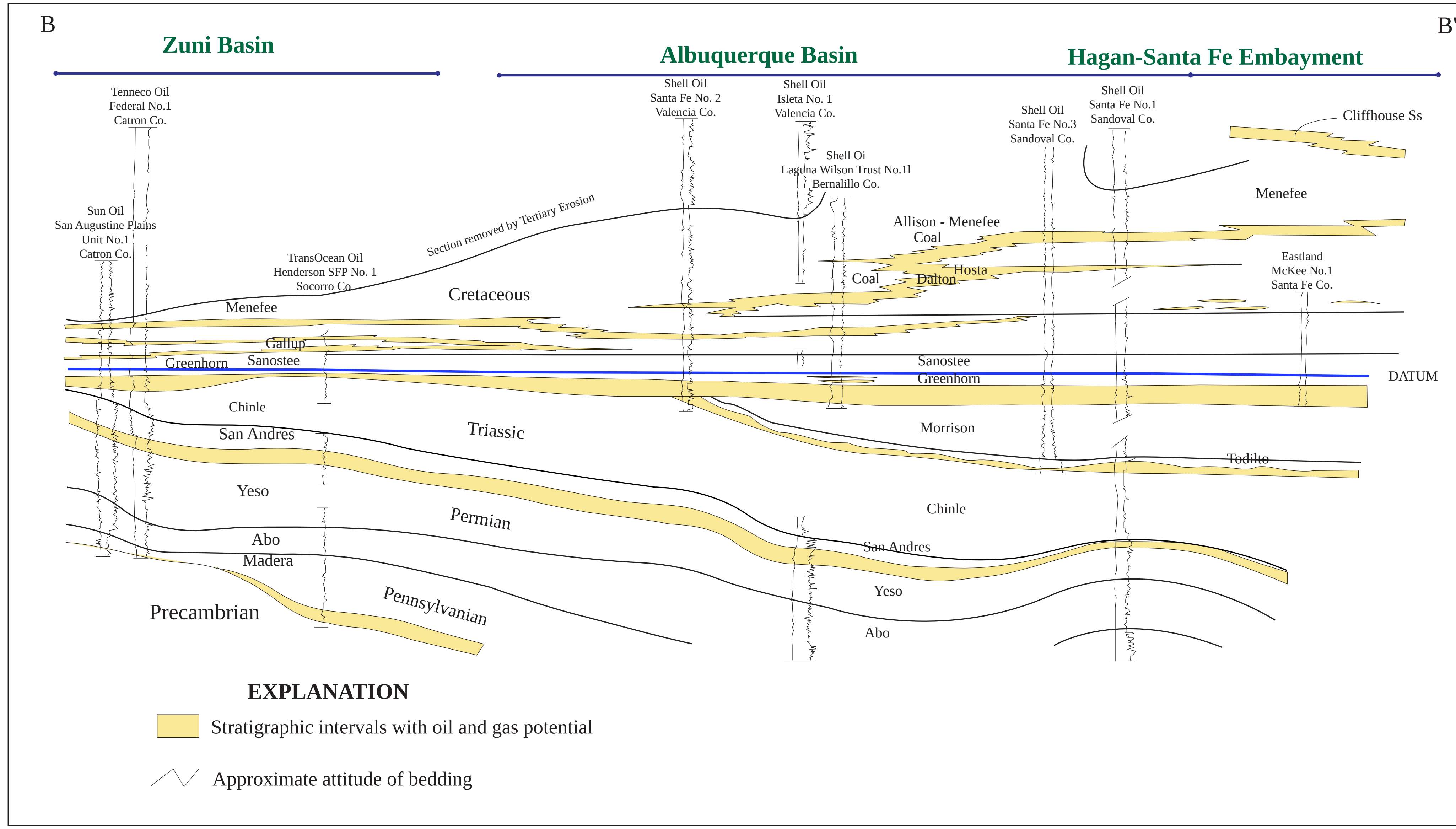

Figure P-4.2. Stratigraphic cross-section from outcrop along the Zuni and Acoma basins (Figure P-4.1) (modified after Molenaar, 1974).

RATON BASIN

GEOLOGIC STRUCTURE

The Raton Basin is asymmetrical with a steep western limb and a gently dipping eastern limb (Figure P-4.3). 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.

Tectonic 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 margin 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).

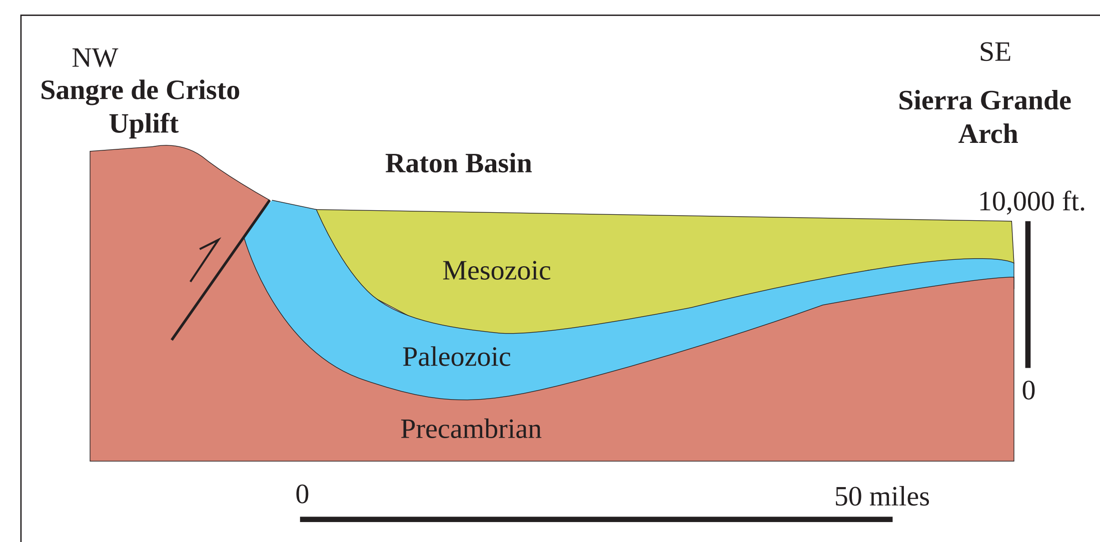

Figure P-4.3. Geologic cross-section across the Raton Basin illustrating the asymmetrical syncline associated with the Sangre de Cristo Uplift (modified after Woodward, 1984).

STRATIGRAPHY

Pueblo tribal boundaries lie between the San Juan Basin on the west and the Raton basin to the east. Stratigraphic correlations of well logs from the San Juan Basin into the Rio Grande Rift region show a decidedly San Juan Basin stratigraphic bias. However, depositional systems outside of the basinal boundaries are influenced by the stratigraphic relationships within the adjacent basins. On that note, the following paragraphs give a description of the stratigraphy for the San Juan and Raton basins.

RATON BASIN

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-5.1 shows the gamma ray log of the Cretaceous strata in the Raton Basin. Figure P-5.2 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.

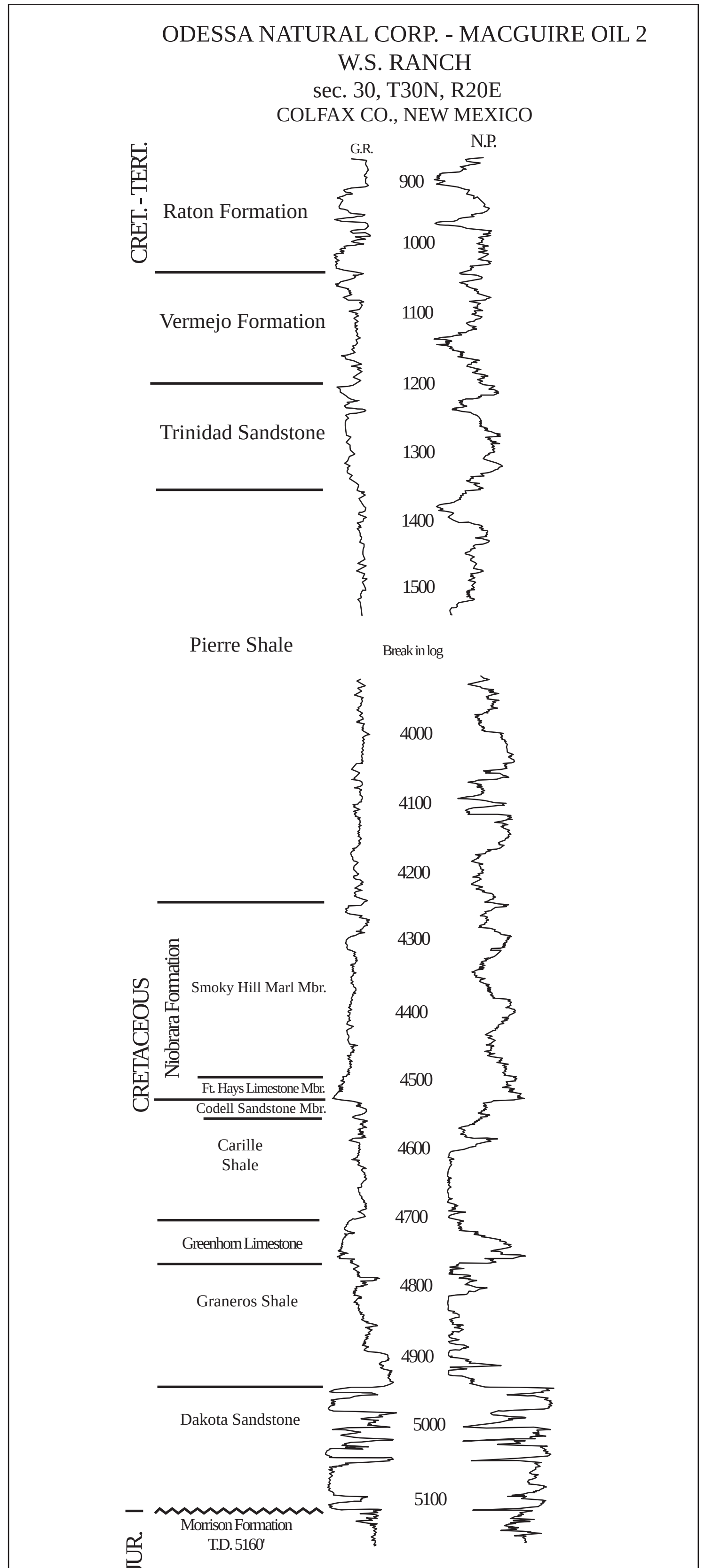

Figure P-5.1. Gamma ray-neutron porosity log showing Cretaceous strata of Raton Basin, New Mexico. Log from Odessa Natural Corporation-Maguire Oil No.2, W.S. Ranch; sec 30, T30N, R20E (modified after Woodward, 1984).

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, 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) interpreted 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.

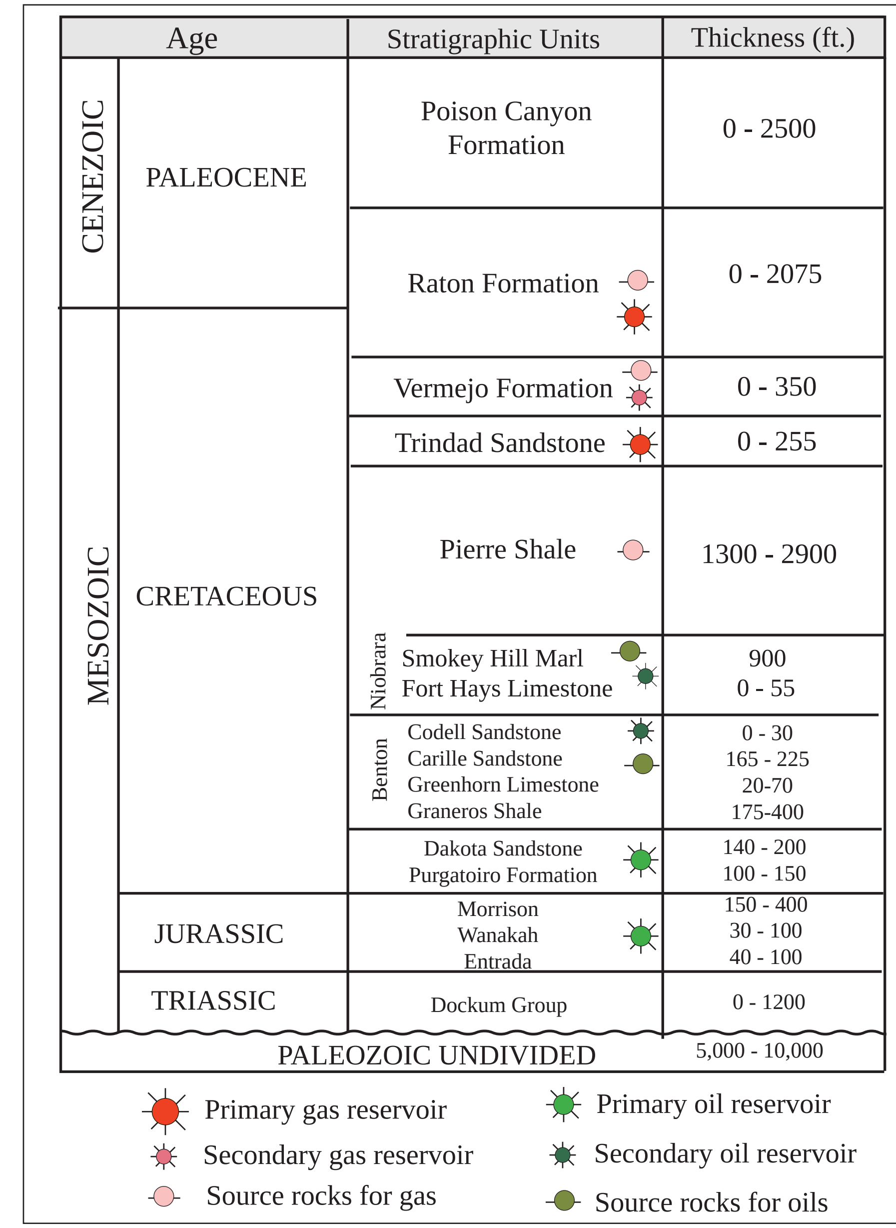

Figure P-5.2. Stratigraphic section depicting bedding relationships within the Raton Basin-Sierra Grande Uplift Geologic Province (modified after Gautier et al., 1996).

The Raton Formation is Cretaceous and Paleocene in age and consists of very fine to coarse-grained sandstone, arkose, and graywacke 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.

SAN JUAN BASIN

The oldest formation in the subsurface of the San Juan Basin is the Upper Cambrian Ignacio Quartzite, which unconformably overlies Precambrian metamorphic and igneous rocks (Fig. P-6.1). The Ignacio is as thick as 150 feet in the northern part of the basin and thins to about 30 feet in the Piedra River Canyon about 20 miles west of Pagosa Springs, Colorado. It consists mainly of white, reddish-brown, and light-brown conglomerate; feldspathic and quartzoes sandstone; purple to green, burrowed, micaceous mudstone and siltstone; and minor dolomite. The sandstone is very coarse to fine grained. Bedding is thin to thick in tabular layers with small to medium scale crossbeds. The lower Ignacio Quartzite was deposited subaerially in streams and on alluvial fans. The upper Ignacio Quartzite is a shallow-shelf assemblage of strata that was deposited by the eastward transgressing sea. There is no production of hydrocarbons or any other economic resource from the Ignacio in the vicinity of the Reservation.

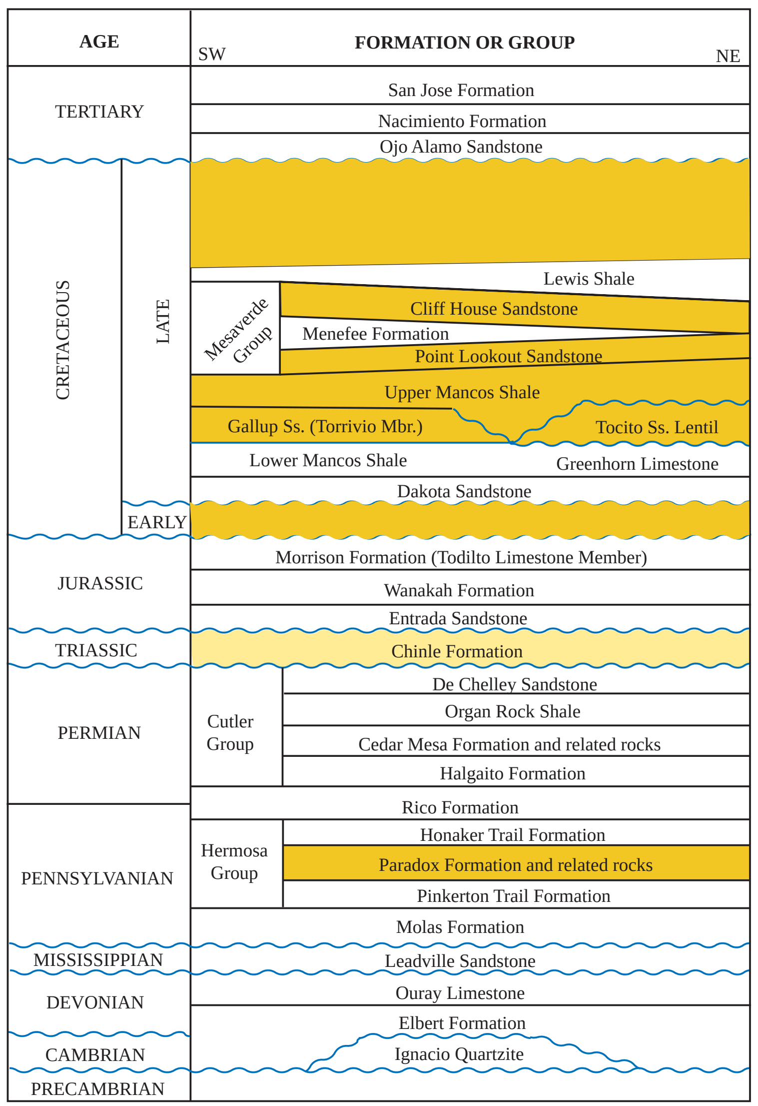

Figure P-6.1. Geochronologic chart for the San Juan Basin (modified after Gautier et al., 1996).

CAMBRIAN - MISSISSIPPIAN SYSTEM

The Cambrian-Devonian McCracken Sandstone Member and Upper Member of the Elbert Formation unconformably overly the Ignacio Quartzite and basement rocks. The McCracken Sandstone Member ranges from 0 -140 feet thick. The McCracken consists of gray to brown sandstone, brown and gray dolomite, and greenish-gray shale. The dominant lithology is very fine to coarse grained sandstone. It is composed of shallow marine, nearshore sediments that were deposited during a eustatic sea-level rise in the Late Devonian. The Upper Member of the Elbert Formation ranges from 150 to 250 feet thick. It consists of poorly exposed, thinly bedded, brownish-gray, sandy dolomite and sandstone; green to red shale; and minor anhydrite. The sediments were deposited in a shallow, tidal-flat environment.

The Devonian Ouray Limestone conformably overlies the Elbert Formation. The Ouray is generally 100 feet thick and pinches out in the eastern part of the basin. It is composed of dark-brown to light-gray, dense, argillaceous limestone with local green clay partings.

The Lower Mississippian Leadville Limestone unconformably overlies the Ouray Limestone. The Leadville ranges in thickness from nearly zero to about 250 feet going east to west. The Leadville is composed of yellowish-brown and light to dark-gray finely to coarsely crystalline, fossiliferous dolomite and limestone. The Leadville formed during two transgressive episodes in the Mississippian. The sediments were deposited under a variety of depositional environments ranging from shallow water tidal flats to low-energy stable-shelf conditions to high-energy shoals. Another unconformity separates the Leadville Limestone from the Lower Pennsylvanian Molas Formation.

PENNSYLVANIAN SYSTEM

The Molas Formation averages 60 feet thick. The Molas Formation is composed of three members; the Coabank Hill Member, the Middle Member, and the Upper Member. They range from shale to conglomerate with some fossiliferous limestone.

The Hermosa Group conformably overlies the Molas Formation. Thicknesses range from 400 feet to more than 2,000 feet. The Hermosa Group consists of (from oldest to youngest) the Pinkerton Trail Formation, the salt-bearing Paradox Formation and the Honaker Trail Formation. The Paradox Formation is composed of four main cycles of Desmoinesian deposition; the Ismay, Desert Creek, Akah, and Barker Creek Stages. These are cyclic deposits of dolomite, limestone, and black, carbonaceous shale. Porosity is 10% and more, which has made these cycles important as an oil and gas reservoir.

PENNSYLVANIAN AND PERMIAN SYSTEMS

The Rico Formation averages about 200 feet thick. It is composed of conglomeratic sandstone and arkose interbedded with greenish-, reddish-, and brownish- gray shale and sandy fossiliferous limestone. The Rico Formation represents the transition between the Cutler Group and the Hermosa Group.

LOWER PERMIAN SYSTEM

The Cutler Group ranges from 1,200 to 1,700 feet thick. It is mostly nonmarine red shale, siltstone, mudstone, sandstone, and conglomerate. It is composed of (from oldest to youngest) the Halgaito Formation, Ceder Mesa Formation, Organ Rock Shale, and the De Chelley Sandstone.

TRIASSIC SYSTEM

The Chinle Group ranges in thickness from about 900-1,200 feet. It is composed mostly of interbedded red to purplish-red, very fine to coarse grained sandstone, conglomerate, siltstone, and mudstone. The Chinle is interpreted to be fluvial-channel, flood plain, lacustrine, and eolian sand-sheet deposits.

JURASSIC SYSTEM

The Entrada Sandstone unconformably overlies the Triassic and is composed of light-gray, cross-bedded sandstone. Maximum thickness is about 250 feet. The overlying Morrison Formation is composed of two members, the Salt Wash Member, which is mostly sandstone with interbedded claystone and mudstone. The overlying Brushy Basin Member is mostly varicolored claystone and mudstone. Maximum thickness of the Morrison Formation is about 800 feet.

CRETACEOUS SYSTEM

The Early Cretaceous Burro Canyon Formation disconformably overlies the Morrison Formation. It is about 1000 feet thick in the basin and consists of lenticular conglomerate and conglomeratic fluvial-channel sandstone bodies.

The Late Cretaceous (Cenomanian) Dakota Sandstone lies either disconformably over the Burrow Canyon Formation or unconformably over the Morrison Formation (Fig. P-6.2). It was deposited in response to the initial transgression of the upper Cretaceous epeiric sea. The Dakota formed in a variety of environments and consists of a basal alluvial unit that is overlain by deltaic, marginal-marine, and marine rocks in different parts of the basin. Its thickness varies from 200-400 feet thick.

The Late Cretaceous Mancos Shale conformably overlies the Dakota Sandstone and intertongues with the overlying Point Lookout Sandstone. It underlies the entire San Juan Basin and outcrops in all directions. It is mostly a dark gray marine shale and its maximum subsurface thickness in the basin is about 2,400 feet. The lower part, about 500 feet thick, containing thin limey shales and limestones in the lower 150 feet. The upper part, about 1,900 feet thick, has sandy limestone and clayey sandstone at its base and contains some limestone or limey beds in its lower 600 feet; it grades upward into fine-grained shaley sandstone.

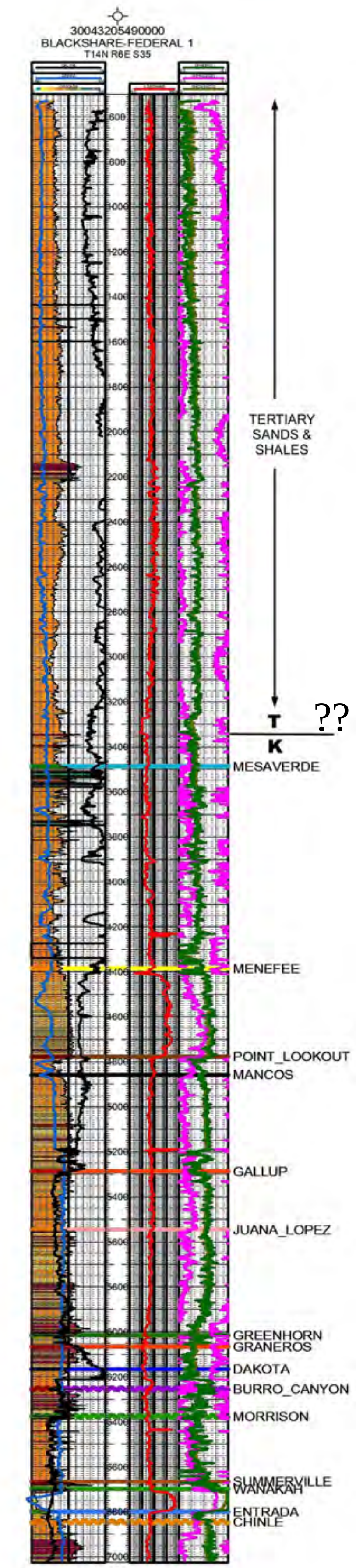

Figure P-6.2. Type log for Pueblo Indian Reservations.

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 (Figures P-7.1, 7.2, and 7.5).

The Sevier orogenic belt and Mogallan Highlands (Fig. P-7.1) 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 eustasy (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-7.4; 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-7.4).

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-7.3 illustrates a hypothetical paleogeographic reconstruction of the Twowells Tongue during highstand, lowstand, and transgressive phases.

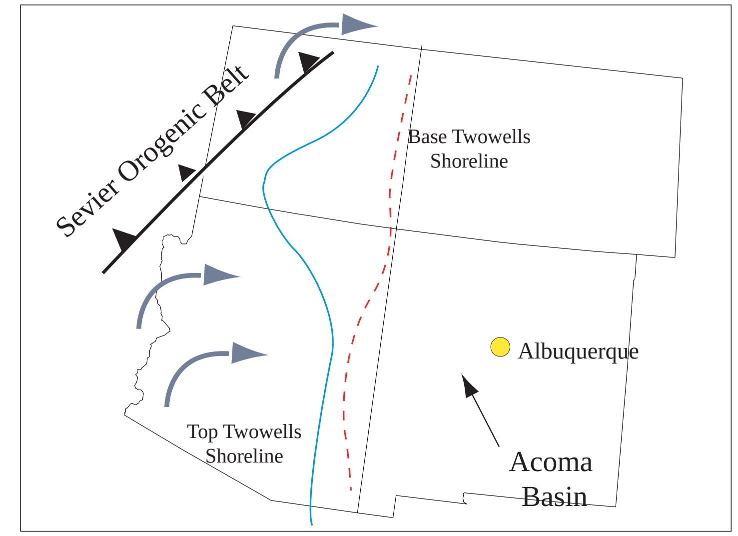

Figure P-7.1. Sediment transport direction (arrows) that filled the Sevier foreland basins during the Cretaceous. Shoreline at the base of the Twowells Tongue and the maximum transgression is shown (mod. - Mellere, 1994; Molenaar, 1983; & Eaton and Nations, 1991).

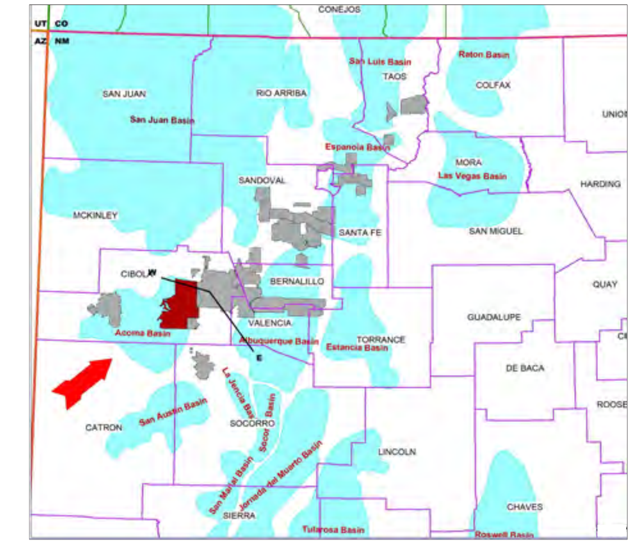

Figure P-7.2. Location map of the Acoma Basin. W - E cross section line shown of the Pueblo Acoma Indian Reservation (with red fill).

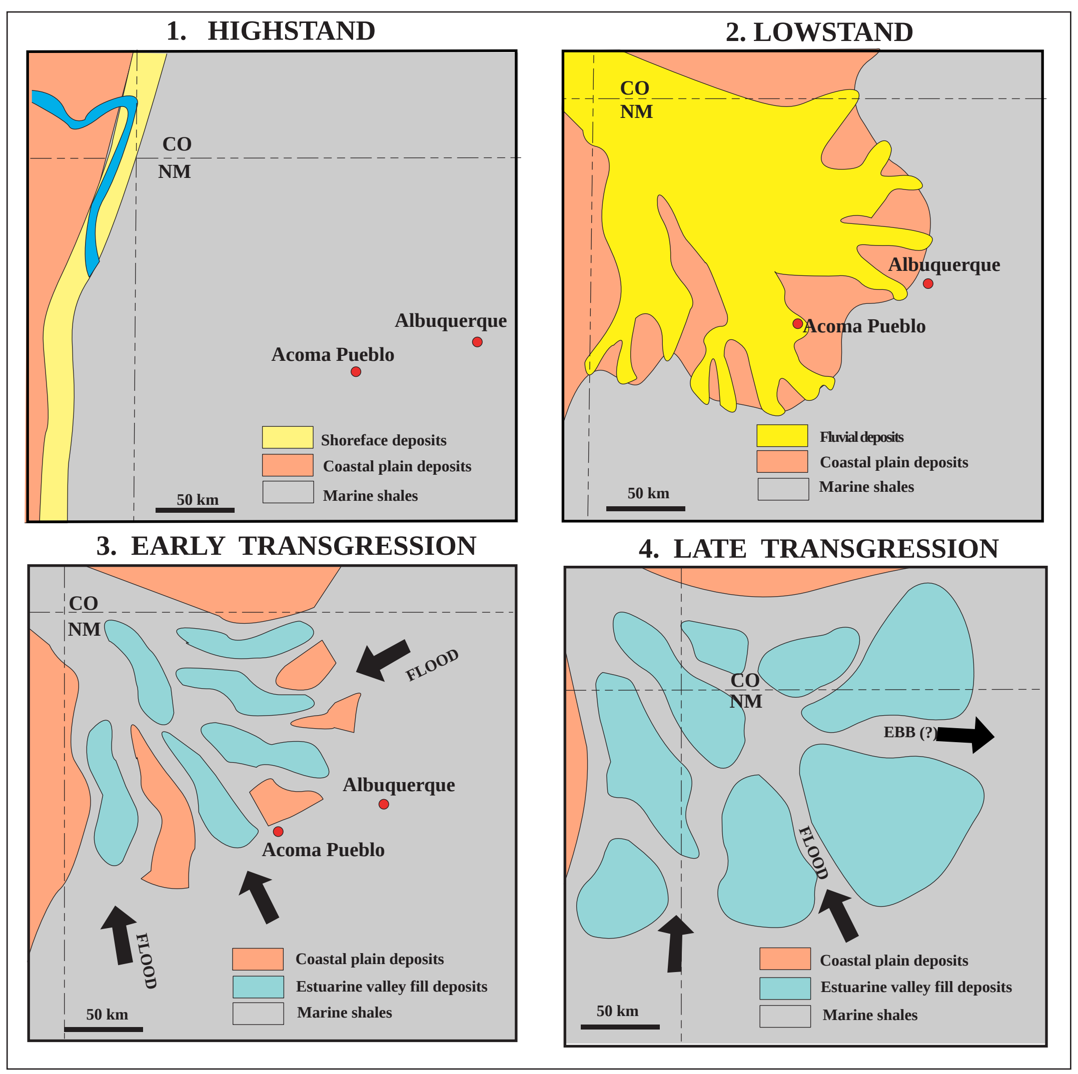

FIGURE P-7.3. Hypothetical paleographic reconstruction of the Twowells Tongue during (1) highstand, (2) lowstand, (3) early transgression and (4) late transgression (modified after Mellere, 1994).

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" combine the research from that publication along with other recent publications of interest to oil and gas in the Pueblo Indian Reservations. The following pages are 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.

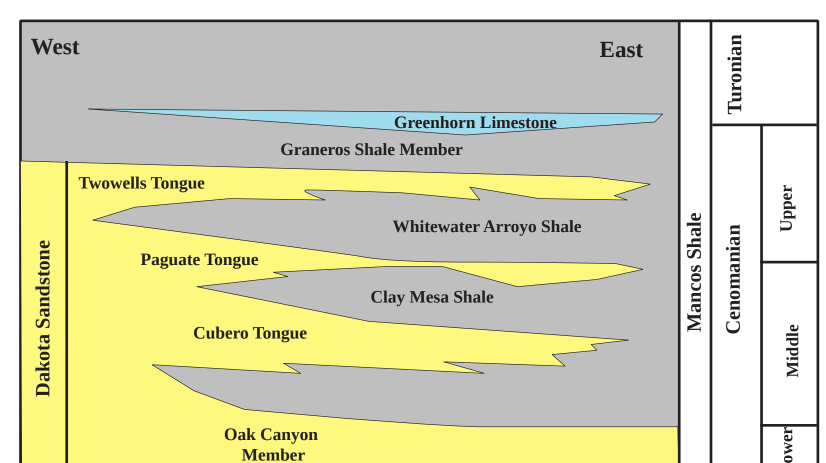

Figure P-7.4. Schematic cross-section of the intertonguing relationships of the Dakota Sandstone and the Mancos Shale in the Acoma Basin (modified after Cobban and Hook, 1989).

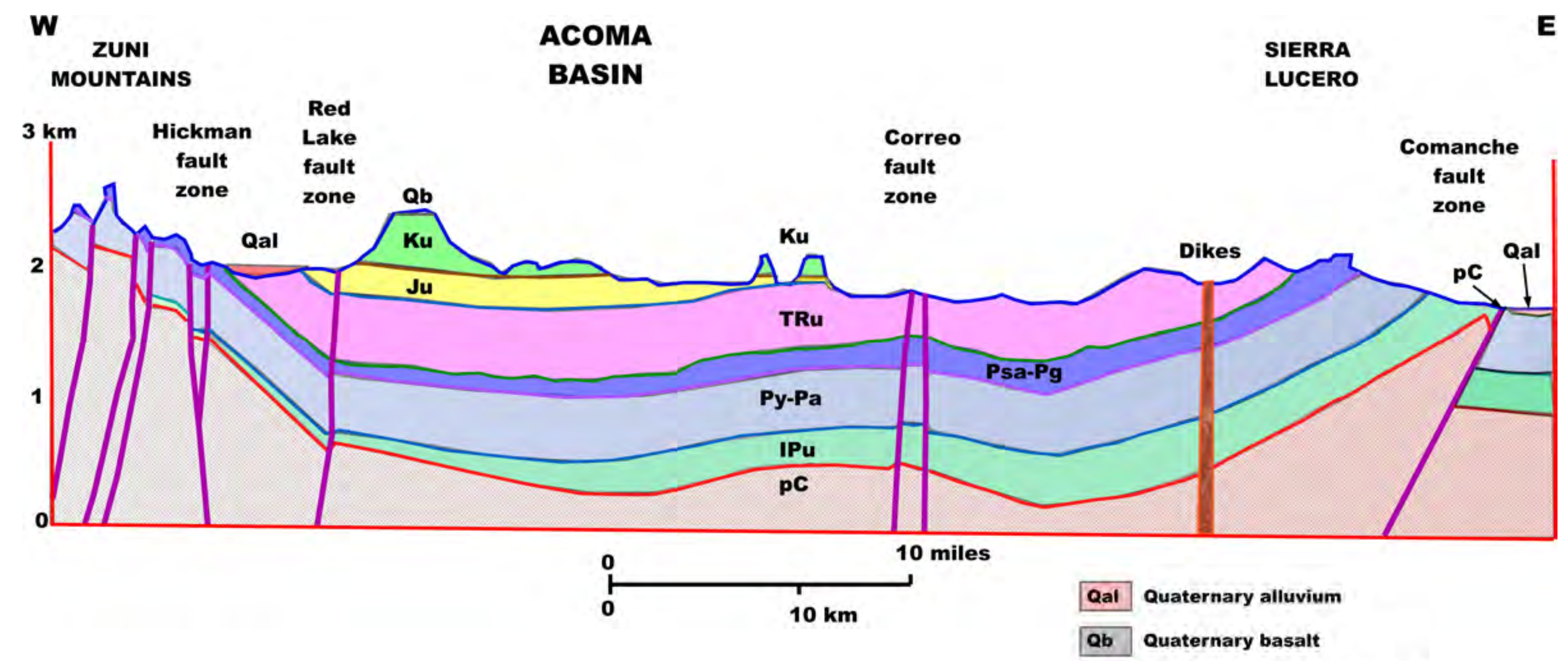

Figure P-7.5. Diagrammatic cross section of the Acoma Basin (modified after Kelly et al.. 2016).