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.

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 (Greis, 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 down-dropped 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-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).

- Humble Oil and Refining Co.
  - Santa Fe Pacific No. B-1
  - Section 20, T14N, R1W
  - Mesa Verde Group
- Shell Oil Co.
  - Santa Fe Pacific No. 1
  - Section 16, T13N, R6E
  - Caja De Rio Puerco fault zone

- Tejon Oil and Development
  - Lease Unknown No. 1
  - Section 7, T14N, R6E
  - Cerrillos Hills

- Sea Level

- 15,000 ft.
- 30,000 ft.

- Alluvium
- Santa Fe Group
- Galisteo & San Jose Formations (undiv.)
- Mesa Verde Gp., Mancos Shale & Dakota Ss (undiv.)
- Morrison Formation, Todilto Ls, & Entrada Ss (undiv.)
- Intrusive Igneous rock

- Chinle Fm.
- San Andres Ls, Glorieta Ss, and Yeso & Abo Fm. (undiv.)
- Madora Ls & Sandia Fm. (undiv.)
- Precambrian undiff.

- Sea Level
- 15,000 ft.
- 30,000 ft.
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 interbedded 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 of Mesozoic and Paleozoic strata, the petroleum prospective part of the section, are missing in the northern half of the basin because of Pennsylvanian-Premian 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 Española 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 those of the well-explained 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 Mesaverde Group (western Colorado terminology) 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 (Gries, 1985).

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 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).
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.

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).
Conformably above the Niobrara is the marine Pierre Shale, subordinate thin interbeds of gray limestone and sandy shale. The Smokey Hill Marl, made up of calcareous shale with 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 Trinidal 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. Matouzak (1969) interpreted the Trinidal Sandstone as beach, nearshore, and offshore deposits formed by a regressive sea retreating toward the northeast. Occasional pauses in regressions or transgressions toward the south west 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-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).**

**Figure P-11. Stratigraphic section depicting log relationships within the Raton Basin-Sierra Grande Uplift Geologic Province (modified after Gautier et al., 1996).**
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 to the Early Cretaceous. The constrained basin, in combination with long-term eustatic sea level changes along the margin of the Cretaceous sea, 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 late Turonian time resulted in various tongues with intertongued marine and non-marine sediments (Mellere, 1994). Figure P-13 illustrates a hypothetical paleogeographic reconstruction of the Twowells Tongue during highstand, lowstand, and transgressive phases.

**PRODUCTION OVERVIEW**

Oil and gas production in north central New Mexico was described in the 1995 National Assessment of United States Oil and Gas Reserves (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 (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.
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.

<table>
<thead>
<tr>
<th>Reservation: Pueblo Indian Reservations</th>
<th>Geologic Province: Albuquerque-Santa Fe Rift Province, South-Central New Mexico Province, and the Raton Basin-Sierra Grande Uplift Province</th>
<th>Province Area: Approximately 7,000, 39,900, and 18,800 square miles, respectively</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Play Types</strong></td>
<td><strong>Conventional Plays</strong></td>
<td><strong>Unconventional Plays</strong></td>
</tr>
<tr>
<td><strong>Description of Play</strong></td>
<td><strong>Oil and Gas</strong></td>
<td><strong>Known Accumulations</strong></td>
</tr>
<tr>
<td>1. Albuquerque Basin Play</td>
<td>Structural and Stratigraphic</td>
<td>Gas and Minor Oil</td>
</tr>
<tr>
<td>2. Hagan-Santa Fe Embayment Play</td>
<td>Structural and Stratigraphic</td>
<td>Minor Oil</td>
</tr>
<tr>
<td>3. Espanola Basin Play</td>
<td>Structural and Stratigraphic</td>
<td>Minor Oil</td>
</tr>
<tr>
<td>4. San Luis Valley Biogenic Gas Play</td>
<td>Stratigraphic; biogenic gas from lacustrine deposits</td>
<td>Minor Oil</td>
</tr>
<tr>
<td>5. Upper Cretaceous-Lower Tertiary Play</td>
<td>Stratigraphic</td>
<td>Gas (7,998 BCFG)</td>
</tr>
<tr>
<td>6. Jurassic-Lower Cretaceous Play</td>
<td>Stratigraphic</td>
<td>Minor Gas and Oil</td>
</tr>
<tr>
<td>7. Southern Raton Basin Play</td>
<td>Coal-bed gas within fractured coal</td>
<td>Gas</td>
</tr>
<tr>
<td>8. Acoma Basin Play</td>
<td>Structural</td>
<td>Gas and Minor Oil</td>
</tr>
</tbody>
</table>

Table 1. Summary table of oil and gas plays that are located in or near the Pueblo Reservations.
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 Colorado (Fig. P-16). The east-west width of the province ranges from 15 to 65 miles and the eastern and western boundaries are mostly uplifted mountain blocks exposing Precambrian and Mesozoic rocks generally 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 Source rocks: In the province, source rocks are in Cretaceous carbonaceous shales and coals. The major source rock is the Mancos Shale, which is the major source of oil and gas. Secondary source rocks are in the Jurassic Entrada Sandstone and Paleozoic shelf sandstones and carbonates. All these potential reservoirs are along depositional strike with the source rocks. Secondary source rocks are in the Jurassic Entrada Sandstone and Paleozoic shelf sandstones and carbonates. All these potential reservoirs are along depositional strike with the source rocks.

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 1970s and early 1980s. There is no production in the province from these wells. 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 Source rocks: In the province, source rocks are in Cretaceous carbonaceous shales and coals. The major source rock is the Mancos Shale, which is the major source of oil and gas. Secondary source rocks are in the Jurassic Entrada Sandstone and Paleozoic shelf sandstones and carbonates. All these potential reservoirs are along depositional strike with the source rocks. Secondary source rocks are in the Jurassic Entrada Sandstone and Paleozoic shelf sandstones and carbonates. All these potential reservoirs are along depositional strike with the source rocks.

Albuquerque Basin Play (USGS 2301)

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 structures 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-16) and is bounded on the east by the Sandia, Manzano, and Los Picos Mountain ranges, which are composed of Paleozoic and older rocks. The west side is bounded by the Pueblo Reservations, composed of Cretaceous 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 uplifts in the vicinity of Socorro.

General Characteristics

Reservoirs: The primary objective 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 in the Jurassic Entrada Sandstone and Paleozoic shelf sandstones and carbonates. All these potential reservoirs range in thickness, but are generally less than 100 feet thick. Recoveries on drill-stem and production tests of Cretaceous sandstones in wells in the play area in ducate low permeabilities for these potential reservoirs (Molenaar, 1993).

Source rocks: Old-prone source rocks are in the basal marine part of the Cretaceous section (Greenhorn 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 maturation ranges from immature to marginally mature along the shallow and 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 maturation.

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

<table>
<thead>
<tr>
<th>Well No. and Name</th>
<th>Location</th>
<th>Completion Date</th>
<th>Total Depth (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell SFP No. 1</td>
<td>18-13N-3E</td>
<td>6-19-72</td>
<td>11,045</td>
</tr>
<tr>
<td>Shell Laguna-Wilson</td>
<td>8-9N-1W</td>
<td>9-21-72</td>
<td>11,115</td>
</tr>
<tr>
<td>Shell SFP No. 2</td>
<td>29-6N-1W</td>
<td>3-29-74</td>
<td>14,305</td>
</tr>
<tr>
<td>Shell Isleta No. 1</td>
<td>7-7N-2E</td>
<td>10-25-74</td>
<td>16,346</td>
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<tr>
<td>Shell SFP No. 3</td>
<td>26-13N-1E</td>
<td>4-19-76</td>
<td>10,276</td>
</tr>
<tr>
<td>TransOcean Isleta</td>
<td>8-8N-3E</td>
<td>10-4-78</td>
<td>10,378</td>
</tr>
<tr>
<td>Shell Isleta No. 2</td>
<td>16-4N-2E</td>
<td>11-23-79</td>
<td>21,266</td>
</tr>
<tr>
<td>Shell West Mesa</td>
<td>24-11N-1E</td>
<td>12-30-80</td>
<td>19,375</td>
</tr>
</tbody>
</table>

Table 3. Summary table of eight deep test wells in Albuquerque Basin (modified after Molenaar, 1987).
Hagan-Santa Fe Embayment Play
(USGS 2302)

General Characteristics

The Hagan-Santa Fe Embayment is in the southern part of the Espanola Basin, but be cause of the different play attributes, this hypothetical play is split off from the Toca nola 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 vol canic-covered end of the Albuquerque Basin, on the east by the southern plunge of the San ger 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.

Seals: The primary seals are the overlying Mancos Shale for Cretaceous reservoirs, Todilto Anhydrite in the latter in the case of lenticular Semilla and Tocito Sandstone Members (Fig. P-23). 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 these 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 of all the wells. A small amount of oil has been produced in one well from the Tocito Sandstone Lentic 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.

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

Stratigraphy & Hydrocarbon Potential

Figure P-26. Block diagram of the Española 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).
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 Arikara 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-Cambrian 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 ternigenous Permian-Pennsylvanian strata, largely sandstones and red beds. Triassic red beds (approximately 1,000 feet thick) overlie about 500 feet of ternigenous 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 cherts, marls, and organic-rich shales of the Benton and Niobrara Groups. This sequence is overlain by ~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/Paleogene coal-bearing Raton Formation overlies the Vermejo. Tertiary sediments of the Pocono-Canyon Formation overlying these strata are highly variable, and represent continental ternigenous 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 fields were developed. Measurable amounts of gas were produced from the Niobrara Formation (Fig. P-34) and from Cretaceous age rocks in Huerfano County. The Glorieta Field (Fig. P-34) was abandoned in Las Animas County, Colorado, and was not commercially productive. In the New Mexico portion of the basin, the Sandia Gas Field (Fig. P-35) was also abandoned, and the Upper Cretaceous-Lower Tertiary Play (4101) and Jurassic-Lower Cretaceous Play (4102) are not currently active.

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 CO₂ 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 CO₂. The Bravo Dome [Buenrostro Field] (Fig. P-36) has produced 118 BCF of CO₂. This field is estimated to contain more than 16 TCF of CO₂ 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: 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-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: Stratigraphic; anticline
- Initial Production: 1.5 MCFD
- Cumulative Production: NA
- Gas Characteristics: 26.5 g/SCF, gravity API
- Type of Drive: Low pressure
- Average Net Pay: v
- 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 Dakota Ss Field

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).
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. It is possible that a few new discoveries will exceed 6 BCFG. A number of small gas fields possibly could be found. This is a high-risk play; undiscovered resource potential is estimated to be of small size.

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 have a porosity of 15-25 percent. Most of the gas has been found in the upper Dakota Sands.

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.

Source rocks, timing, and migration: Shale and coal are possible sources within the Purgatoire-Dakota sequence. 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.

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.

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

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.

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

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 recharge at 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 streams and drainage areas (Geldam, 1989; Stevens et al., 1992). The primary fracture (trend clear) trend in the Raton Basin coals is perpendiculat to the local trend of the Sangre de Cristo thrust front and thus enhances groundwater flow and the potential for artesian water (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 MCFD 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 nitrogen injection project for coalbed gas wells has been approved (Rice and Finn, 1995).
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, concentrations of gas in place are about 8 BCF/square mile or less. The reservoir potential of this play is also regarded as good (Rice and Finn, 1989).

Small, northeast-trending rift basins are the predominant physiographic feature of the South-Central New Mexico Province. As much as 10,000 feet of alluvium and volcanic rocks fill these extensional basins, obscuring a moderately thick section of Paleozoic strata. This province has a complex geologic history, having been deformed 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 environments. Epeiric seas generally transgressed from the south, and nascent opening of the Gulf of Mexico 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 (Chihuahua Trough) deposited as much as 750 feet of marine Jurassic sediments in the south-southwest; about 3,000 feet of this section is preserved. Laramide compression from the southwest rejuvenated older fault-bounded structures and other paleo-zones of weakness (for example thrust faults) and created basement-cored uplifts. Plutons, with attendant rich mineralization, intruded the province. Early Tertiary uplift provided cyclic alluvial-fan gravels and deltaic clastics to continental interior-drained basins and small lakes.

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

Two hypothetical conventional plays were assessed in this frontier petroleum 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 Reservation. A brief description of the production within the Acoma Basin is presented in the following section.
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 significant 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 reservoir 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).

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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-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).

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