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OIL AND GAS EXPLORATION IN THE RATON BASIN

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INTRODUCTION

The history of exploration for oil and gas in the Raton Basin has been cyclical and is currently in a relatively quiescent stage. The Raton Basin has long been considered one of the better frontier areas for petroleum exploration in the Rocky Mountains. Yet at the present time it is the only major Laramide-aged structural and stratigraphic basin in the Rockies that does not have commercial production. It has great thicknesses of organic-rich marine shales to serve as source beds for petroleum generation. These beds overlie, underlie and interfinger with massive sandstones of beach and nearshore origin that could serve as reservoir beds. These sands are in turn interbedded with coastal plain, paludal, estuarine and lagoonal sediments with both source and reservoir potential. The geological history of marine transgression and regression which deposited this rock sequence is an integral part of the same Late Cretaceous sequence which produced the majority of oil and gas accumulations in the Rocky Mountains. The deeper Mesozoic and Paleozoic possibilities can be only speculative, as the subsurface control within the confines of the deeper Basin is limited to the data provided by only thirteen tests which penetrated below the Jurassic beds.

The geologic factors point primarily toward stratigraphic entrapment, but there are also structural possibilities. All of the obvious structural features have been drilled, but in several cases cannot be said to have been adequately tested. In addition limited drilling has suggested less obvious structural controls which will become apparent when the drilling density is increased. This low drilling density is probably the single most important reason why there is no production in the Raton Basin today. There are approximately 2,150 mi^2 within the area of the Raton Basin as defined by the Trinidad Sandstone outcrop-1,194 in Colorado and 956 in New Mexico (Fig. 1). All of the recorded holes penetrating at least to the Cretaceous Trinidad Sandstone within the same area number less than 100. This figure includes a substantial number of coal exploration holes which are clustered in limited areas. Utilizing these figures, the drilling density is about one test per 20 mi^2, an extremely low density compared to other productive Rocky Mountain basins.

This paper discusses the structure and stratigraphy of the Raton Basin, its drilling history and problems associated with the drilling, and the potential of some of the more favorable stratigraphic horizons.

REGIONAL STRUCTURE AND PHYSIOGRAPHY

The Raton Basin is a structural basin situated in Las Animas and Huerfano counties of southeastern Colorado, and Colfax County of northeastern New Mexico. As defined in this study (Fig. 2), the Basin is encompassed by the Trinidad Sandstone outcrop and does not include those structural portions which adjoin it on the north and south. These related portions are the Huerfano Park area on the north and the Las Vegas subbasin on the south. The Basin is bounded on the west by the Sangre de Cristo Mountain range and on the east by two subsurface positive elements, the Apishapa Arch and the Sierra Grande Uplift. The Apishapa Arch is a northwest-southeast oriented structural extension of the Wet Mountain Uplift which terminates the basin on the northeast, whereas the Sierra Grande Uplift is a northeast-southwest oriented subsurface arch, that forms the basin's southeastern margin.

The Sangre de Cristo mountains are a structurally complex block having a Precambrian igneous core that is bounded by major, high-angle reverse faults and highly contorted, steeply dipping to overturned sedimentary beds of Paleozoic and Mesozoic age. The range resulted from uplift and eastward thrusting during the Laramide orogeny commencing in Late Cretaceous time and continuing intermittently to possibly late Tertiary time (Wanek and Read, 1956).

The Sierra Grande Uplift is manifested in the subsurface by a Precambrian high which is unconformably overlapped by arkosic Permian beds and thin Triassic beds. The presence of Pennsylvanian and older beds off its flanks indicate that it has been a positive element since Paleozoic time. The present structural arch represents a Laramide rejuvenation of a portion of this older uplift. The axis of the uplift apparently extends further northeastward to merge with the Las Animas Arch of southeastern Colorado. The present Apishapa Arch had a similar history to its New Mexico counterpart. It is a Paleozoic positive element which underwent later Laramide rejuvenation. The ancestral Apishapa Uplift branched southeastward from the Central Colorado Range of Pennsylvanian time and joined the Sierra Grande positive. Both units became almost

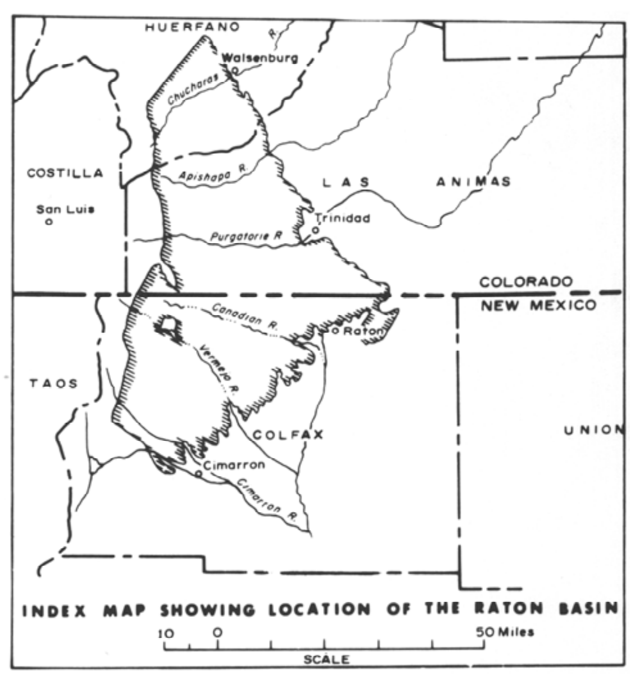

Figure 1. Index map showing location of the Raton Basin.

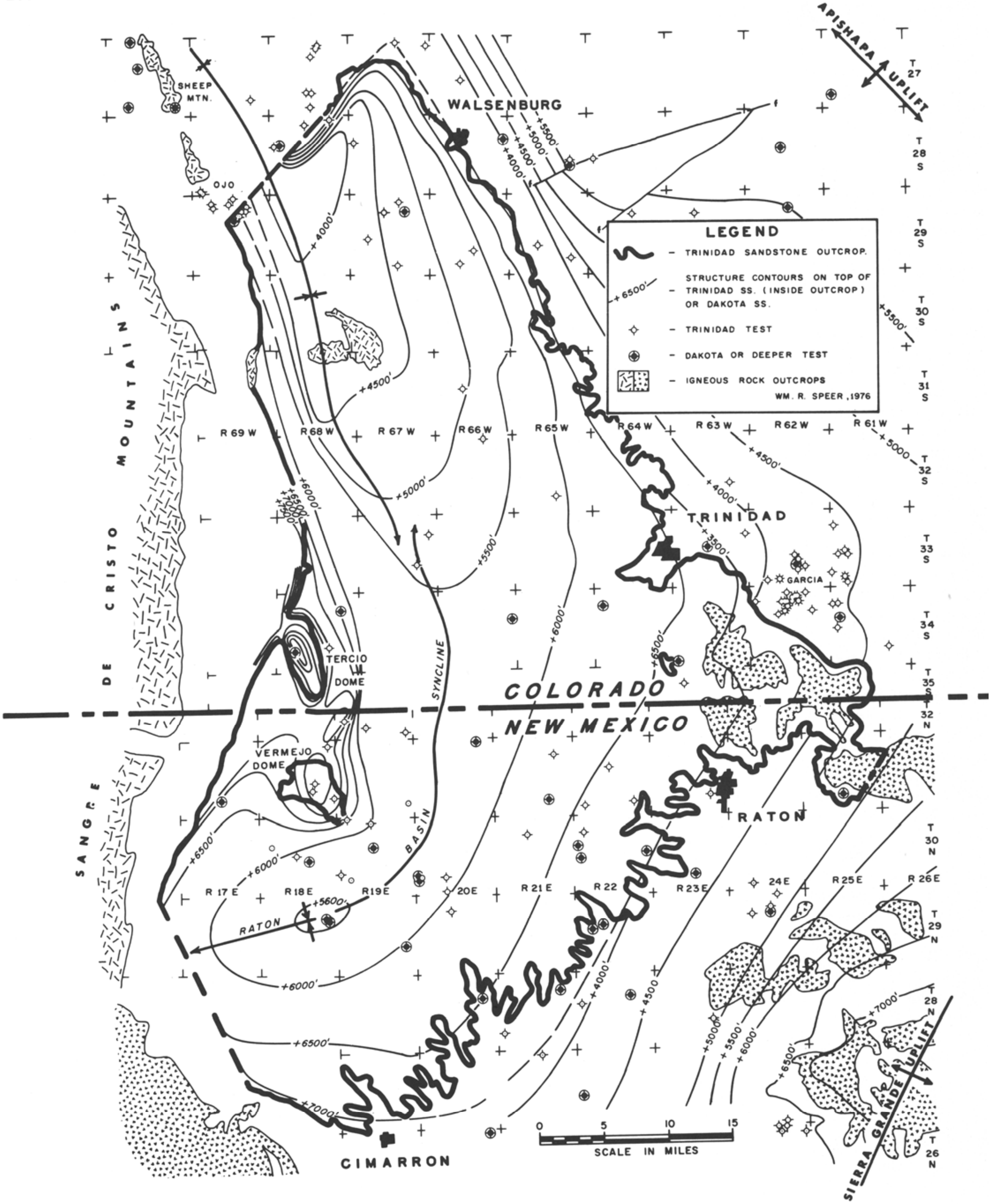

Figure 2. Geological structure map of Raton Basin, New Mexico and Colorado, showing location of oil and gas test wells.

buried by coarse sediments during late Pennsylvanian-Permian time as the ancestral mountains were worn away. They remained as shallow to slightly emergent positive igneous masses awash in a sea of continental, fluvial sediments during most of Mesozoic time until their actual inundation by the Cretaceous epicontinental seas. The retreat of these seas was followed by a period of discontinuous vertical uplift of these positives throughout Late Cretaceous to mid-Tertiary time.

The present structural axis of the basin generally parallels the Sangre de Cristo Mountain front, being arcuate with a northeast trend in New Mexico and a northwest trend in Colorado. It plunges slightly northward such that the basin's deepest portion is in the northern end. Near the town of La Veta, Colorado, the axis bifurcates with its westward extension continuing into Huerfano Park and its eastward arm trending northeastward as the Delcarbon syncline to its termination against the Apishapa Arch. Immediately north of the axis bifurcation, the Trinidad Sandstone is cut out by an angular unconformity and does not extend into Huerfano Park. The Park itself contains a substantial thickness of later Tertiary continental sediments which have little petroleum potential and which have buried those sediments with potential to excessive drilling depths.

A broad, minor east-west saddle occurs across the axis of the basin just south of the state line and drilling has indicated the presence of subsidiary basins in the southern end of the restricted Basin. On the south end, the axis of the Raton Basin syncline terminates against an apparent angular unconformity in which Tertiary beds overlap an upturned Cretaceous sequence. This unconformity also cuts out the Trinidad Sandstone in a manner similar to the occurrence in the northern end of the Basin. The geology of the southern end is obscured generally by the presence of late Tertiary igneous intrusives which were injected not only into the sedimentary sequence, but also into the Precambrian igneous rocks along this margin (Smith and Ray, 1943).

The basin is asymmetrical, with a west limb which dips steeply ($> 50^\circ$) to the east and an east limb which dips gently (1 to 5°) westward off of the Sierra Grande and Apishapa positives. The eastern margin of the Basin, as restricted in this study, is marked by a prominent escarpment which is composed predominantly of cliffs of sandstones including the Trinidad. Surficially the central part of the basin is a large, highly dissected plateau or tableland composed of beds of Late Cretaceous and early Tertiary age. In New Mexico this physiographic feature is called the Raton Mesa and is drained southeastward by the perennial, through-flowing Canadian, Vermejo and Cimarron Rivers. In Colorado, where the feature is named the Park Plateau, drainage is to the east and northeast by the Purgatoire, Apishapa and Cucharas Rivers.

The continuous escarpment forming the eastern edge of the basin is also the physiographic boundary between the Southern Rocky Mountain Province on its west and the High Plains section of the Great Plains on its east. To the east of the escarpment are gently rolling hills with broad drainage valleys which are imposed on soft, marine shales of Late Cretaceous age. The rolling plains are interrupted by basalt-capped mesas and volcanic cones which originated in late Tertiary time and were injected into and flowed out onto a pediment surface which originally extended from the mountain front on the west to the plains further east. These flows and cones uphold mesas east and southeast of the town of Raton as erosional remnants of the old pediment surface.

Prominent secondary structural features include Vermejo Dome and Tercio Dome, both located in the central portion of the Basin on its eastern limb. The former is in New Mexico and the latter in Colorado, both ringed by outcrops of Trinidad Sandstone. Vermejo Dome has at least 1,400 ft of closure, while the companion Tercio Dome has 1,700 ft. Subsurface data indicates a northward extension of the Vermejo Dome axis, which apparently has some subsidiary closure. The dip of the east flank of these structures is extremely steep, but flattens abruptly at about the +6,000 Trinidad Sandstone sea-level datum. The apex of Vermejo Dome was drilled to a depth of 4,411 ft in 1926 and was reported to have penetrated "a great thickness" of igneous rock. A second test drilled about a mile away had the same results. Although old reports indicate these tests penetrated the Precambrian, Bates (1942) stated that "neither well seems to have reached the Dakota Sandstone," and that "the heart of the dome is occupied by an igneous intrusion." Drilling since 1970 on the flanks of the structure have verified the intrusive nature of the dome's core, while also indicating deep-seated thrust faulting associated with emplacement. In contrast, Tercio Dome appears to have no igneous core, having been drilled in 1948 to a depth of 7,457 ft, bottoming in beds described as Permian in age without having reached any identifiable igneous rock.

STRATIGRAPHY AND PALEOGEOGRAPHY

A composite stratigraphic column of rocks underlying the Raton Basin is presented on page xiv of the Guidebook for reference. Much of the discussion pertaining to the Paleozoic and earlier Mesozoic is taken from Baltz (1965). The Cretaceous data is derived from Johnson (1956, 1959) and Kaufman (1969), whereas Upper Cretaceous and Tertiary data is from Johnson (1956, 1958, 1959) and Pillmore (1969). The author is responsible for the interpretative analysis.

Paleozoic

During early Paleozoic time most of the area of the present Raton Basin was occupied by the broad, structurally positive "continental backbone" which received very little sedimentation. The oldest identified rocks are thin, high-shelf marine rocks of probable Late Devonian age, the *Espiritu Santo Fm.* The older Cambrian, Ordovician and Silurian rocks are not present in the immediate area of the Basin, probably as a result of non-deposition rather than pre-Devonian erosion. On the extreme northern end of the Sangre de Cristo Mountains some 50 miles north of the Basin both Ordovician and Devonian dolomites have been mapped, indicating some high-shelf marine invasion to the northwest. Unconformably overlying the Espiritu Santo dolomitic limestones in the basin area are the relatively thin limestones and limestone breccias of the Mississippian *Tererro Fm.* identified in the nearby Sangre de Cristo Mountains. The first indications of the structural formation of the ancestral Raton Basin occurred during Pennsylvanian time when the present site of both the eastern portion of the Basin and that of the Sangre de Cristo Range was downwarped into the Paleozoic Rowe-Mora Basin, a deep, narrow intermontane structural and sedimentary basin. This basin was filled by the Pennsylvanian Madera Formation and Permo-Pennsylvanian Sangre de Cristo Formation. The *Madera Formation* is the upper, marine sequence of the *Magdalena Group,* as named further south and is a zeugogeosynclinal facies with thick gray and black shales predominant over limestones and sandstones. The formation's presence in the deeper part of the basin is speculative, but is projected to occur in the southern portion, mainly on the basis of more than 600 ft of Madera logged in a well (Sec. 26, T. 31 N., R. 21 E.) on the southeastern flank. The *Sangre de Cristo Formation* is dominantly fluvial in origin with red and green shales and arkosic sandstones and conglomerates. This thick sequence ranges in age from late Pennsylvanian to Early Permian and marks the continuous infilling of the Rowe-Mora Basin as the surrounding uplifts remained active, supplying abundant detritus.

The return of shallow seas to the southern portion of the area is indicated by the remainder of the Permian section. The *Yeso Formation, Glorieta Sandstone* and *San Andres Limestone* are all relatively thin and indicative of a marginal marine environment of deposition. In the northern part of the Basin terrestrial sedimentation, including all or part of the Lykins Formation, occurred simultaneously during Leonard to Guadalupian time. The youngest Permian unit, the *Bernal Formation,* is a thin unit of red and pink siltstones, shales and fine-grained sandstones of probable Guadalupian age.

Mesozoic

After a period of non-deposition and slight erosion, the fluvial sands and muds of the Triassic *Dockum Group* were deposited, thinning northward in the Raton Basin. Evidence of later Jurassic upwarping and mild erosion is indicated prior to the deposition of the nearshore eolian *Entrada* or *Exeter Sandstone* and the shallow marine *Wanakah Formation* gypsiferous sandstones and shales. The overlying *Morrison Formation* consists of green, gray, maroon and brown fluviatile sandstones and red and green shales derived apparently from a southwestern source area.

During Cretaceous time the entire area became a part of the Western Interior Seaway as epicontinental seas invaded the central portion of the U.S. from both the Gulf of Mexico and the Arctic Ocean regions. More than 4,100 ft of dominantly marine beds were deposited during this inundation. This sequence and that of the immediately overlying Tertiary beds is of primary interest for petroleum (Fig. 3).

The initial beach and nearshore sands deposited by the transgressing sea advancing to the west constitute the *Purgatoire* and *Dakota Formations.* The latter and possibly a portion of the former may be of Early Cretaceous age, although sedimentation was apparently continuous across the Early-Late Cretaceous boundary. Continuous transgression

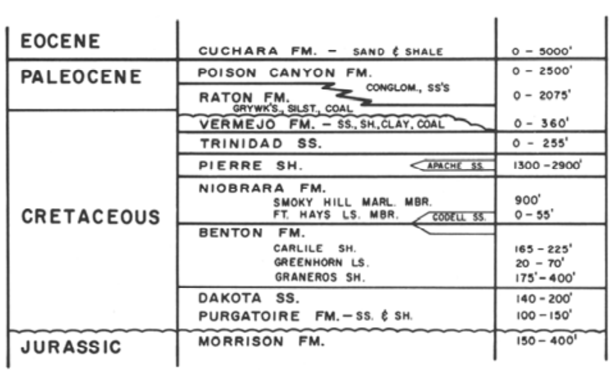

Figure 3. Partial stratigraphic column of central Raton Basin, showing formations of greatest hydrocarbon potential.

causes time boundaries to transgress the lithologic boundaries. The Purgatoire, as described in surface exposure in Colorado, consists of a sequence of conglomeratic sandstones interbedded with carbonaceous shales and occasional coals indicative of a coastal plain and deltaic environment. The Dakota may be described in this manner; however, the sandstones are generally finer-grained and better sorted as a result of a closer association with a transgressing littoral environment. The two formations are difficult to differentiate in the southern portion of the Basin but are separated by a recognizable shale interval in the northern portion. These units are overlain by a substantial thickness of marine muds and silty limes as the shoreline advanced further westward. These sediments formed the Graneros Shale, Greenhorn Limestone and Carlile Shale; all members of the *Benton Formation.* The overlying *Niobrara Formation* is also of marine origin and consists of a basal limestone member, the Ft. Hayes Limestone, and a thick silty, calcareous mud sequence, the Smoky Hill Marl. The Pierre Shale lies on the Niobrara Formation and is composed of a thick sequence of dark gray, sandy, non-calcarous marine shales.

During the deposition of this entire sequence of shallow marine muds, the shoreline, which lay to the west in a sinuous, generally north-south orientation, was fluctuating in response to changes in sea-floor subsidence, rate of sediment supply, or combinations of the two. While the transgression and regression of the shoreline during this period never brought the shoreline back into the area of the present southern Raton Basin, it closely approached it during the deposition of the Mesaverde Formation sequence in the San Juan Basin immediately to the west. This approach coincides in time with the presence of a calcareous sandstone sequence found in the middle Pierre shale as described from surface outcrops near Walsenburg, Colorado (Cobban, 1956). This sandy zone was called the *Apache Sandstone* in early reports and is believed to represent an offshore sand equivalent of the Mesaverde Formation deposited at the distal point of the Mesaverde shoreline reversal.

The *Codell Sandstone Member* of the Carlile shale is a possible nearshore sand unit deposited in an otherwise uninterrupted sequence of marine, offshore muds. It was originally described from exposures in southwestern Kansas and was subsequently extended into eastern Colorado at Huerfano Park as the uppermost member of the Carlile. It has been described also as the first regressive sandstone unit in the marine sedimentary cycles of the Cretaceous epicontinental sea (Weimer, 1972 and Kaufman, 1969). In several older reports of the subsurface in the northern part of the Raton Basin, a sandy zone in this stratigraphic position has been called Codell and hydrocarbon shows were reported. The fact that an unconformity has been documented at the Niobrara-Carlile contact in several surrounding areas (Dane, 1960; Kaufman, 1969) suggests that the same marine unconformity may exist as a shale-shale contact in parts of the Raton Basin. The subsurface "Codell" actually may be a thin basal depositional unit laid down on this erosional surface, as an offshore terrace deposit or a turbidite. This would account for its apparent discontinuous nature in the Raton Basin.

The final retreat of the Western Interior Sea from the area is recorded in the deposition of the *Trinidad Sandstone.* The upper portion of the underlying Pierre Shale becomes increasingly sandy as the shoreline began its northeastward regression.

There is no sharp contact of the Trinidad and Pierre, but the change occurs through a 50 to 100 ft transitional zone composed of siltstones and thin, very fine grained sandstones interbedded with sandy shales. The Trinidad Sandstone is a light gray, fine- to medium-grained, well-sorted argillaceous sandstone deposited in a beach and nearshore environment. The massive portion of the Trinidad, excluding the transitional zone, has a relatively consistent thickness, despite the fact that it intertongues with the overlying Vermejo Formation. Evidence indicates that the withdrawal of the seas from the Basin area was a relatively steady and rapid event, although some still-stands or minor regressions could have occurred, as indicated by the interbedded relationships of tongues of Trinidad which extend laterally into lowermost Vermejo beds (Lee, 1924; Johnson and Wood, 1956). Fossils indicate that the retreat of the seas across the Raton Basin occurred during a relatively short time period compared to the 36 million years of marine deposition occurring after the initial Dakota transgression (McGookey and others, 1972).

The *Vermejo Formation* consists of poorly sorted greywacke sands, gray, carbonaceous, silty shales, and thin- to thick-bedded, lenticular coal beds. The sediments forming the Vermejo Formation were deposited in the lagoonal, coastal swamp and flood plain environments immediately adjacent to the littoral environment of the Trinidad sandstone. As the Trinidad shoreline migrated, the continental coastline environment of Vermejo sediments migrated in concert with and parallel to that shoreline. Accordingly there is intertonguing of the two formations and a crossing of time boundaries by the lithologic contacts.

As the coastline retreated northeastward beyond the confines of the present Basin in the final stages of the Late Cretaceous, local positive areas began to become active. During most of Cretaceous time prior to this period the orogeny which affected sedimentation lay considerably to the west in what had previously been the Cordilleran Geosyncline of the Paleozoic era. This uplifted geosyncline lay in Nevada, Idaho, western Utah and southern Arizona. The earlier orogeny consisted of periodic thrusting of geosynclinal plates onto the shelf platform to the east, accompanied by major volcanic outpourings; however, near the end of the Cretaceous period (Campanian-Maastrichtian) and into the Paleocene-Eocene, scattered vertical uplifts began to dominate the areas east of the deformed geosyncline. The Sierra Grande Uplift seems to have become mildly active first, causing the exposure and beveling of the Vermejo Formation and possibly some portion of the Trinidad Sandstone. Shortly thereafter the Sangre de Cristo range began to rise and supply coarse detritus to the east, laying down a basal conglomeratic sandstone on the beveled Vermejo Formation surface. The Vermejo is thus a wedge which thins to a zero edge near the eastern edge of its outcrop.

Tertiary

The conglomeratic sandstone unconformably overlying the Vermejo Formation is the basal bed of the *Raton Formation.* It is included in a basal sandstone sequence some 100 ft thick that consists of friable, fine- to medium-grained, fluvial sandstones. This basal unit is overlain by a coal-bearing shale sequence, a thick, coarse-grained sandstone sequence and another coal-bearing shale sequence, totaling as much as 2,000 ft of strata in some areas of the basin. Deposition was continuous across the Upper Cretaceous-Tertiary boundary, which has been located by palynological evidence at about 270 ft above the base of the Raton Formation (Brown, 1943). Because the sedimentation is a terrestrial flood plain sequence the bedding is very irregular, lenticular and varies considerably in unit thickness. The overall thickness of the Raton Formation ranges from 830 ft to as much as 2,075 ft. The variance is due to interbedding, overlapping and gradation of the Raton Formation into the *Poison Canyon Formation.* The Poison Canyon Formation represents the piedmont facies that was deposited simultaneously along the Sangre de Cristo mountain front to the west. It consists of coarse, poorly-sorted, conglomeratic arkose sandstones interbedded with thin yellow clay siltstones. These deposits mark the termination of deposition with marine affinities and the end of those formations with good petroleum potential.

The Sangre de Cristo Mountains continued to rise episodically during the remainder of the Tertiary and to supply a great thickness of coarse, fluvial sediments to the adjacent basin. These sediments form the *Cuchara* and *Huerfano Formations* (Eocene), the *Farasita Conglomerate* (probably Oligocene) and the *Devil's Hole Formation* (probably Miocene). All of these formations, a substantial thickness of sediments, are present only in the Colorado portion of the Basin, and only the Cuchara Formation is present in the restricted portion of the basin as defined in this report by the Trinidad Sandstone truncation. The balance of the formations are confined to the Huerfano Park area, where they were first named and described (Johnson, 1959, 1969). These beds were undoubtedly present at one time in the restricted Colorado portion but were removed by post-Miocene erosion.

The epeirogenic uplift of the entire region occurred in late Tertiary time and caused widespread erosion. It was accompanied by extensive volcanism which emplaced most of the plugs, dikes and sills found in the Basin today. The basaltic cones and extruded basaltic lava flows which centered along the axis of the Sierra Grande Uplift and uphold portions of Raton Mesa as erosional remnants today, were late stage events which occurred after the general area had been reduced erosionally to a gently eastward sloping pediment surface. The *Ogallala Formation,* an important aquifer which crops out in the plains to the east of the mapped area, was deposited as a pediment gravel on this surface but is not present in the area of this study.

DRILLING HISTORY

The earliest wells were drilled in 1892 on the Garcia structure in T. 33 S., R. 62 W. in Colorado, and gas production was obtained from fractured shales at relatively shallow depths. The first well in the New Mexico portion of the basin was drilled on Vermejo Dome at the Vermejo Ranch headquarters in about 1906. It probably was drilled in search of water, but as it spud near the top of the Pierre Shale and bottomed at 2,300 ft still in the Benton shales, it was a failure. The next wells were drilled in 1926 also on Vermejo Dome, by Union Oil of California near the apex of the structure in search of petroleum.

Scattered drilling also occurred in the late 1920's in Colorado, notably in the Ojo, Alamo and Garcia structural areas which resulted in some relatively minor production. This production was of sufficient interest to stimulate additional tests during the mid-1950's and recently. The later drilling resulted in the discovery of additional small amounts of gas at Ojo Alamo and Sheep Mountain. In 1933 Continental Oil drilled on Tercio Dome with a 1,360 ft cable-tool test which bottomed in the water-bearing Dakota Formation.

The first concentrated exploratory drilling effort designed to test all possibilities was conducted by Continental Oil Company in the mid-1950's. They drilled 11 significant tests on properties of the St. Louis, Rocky Mountain and Pacific Fuel Company in the east-central portion of the Basin. Included were four Precambrian tests, one Permian Glorieta test, one Jurassic Entrada test and six Dakota tests. All were in New Mexico except two Dakota wells just across the line in Colorado. The tests were all plugged, but at least seven reported significant shows of oil or gas in the Dakota Formation.

In the late 1950's Pan American Petroleum, now Amoco Petroleum, began a comprehensive stratigraphic test program designed to test the possibilities of the Trinidad Sandstone. In Colorado 10 tests were drilled along the eastern flank of the Basin extending from the vicinity of Trinidad, Colorado, to beyond the Trinidad Sandstone truncation west of Walsenburg. Two of these tests were drilled northwest of the truncation and help to define this erosional overlap. None of the tests were productive, although cores and drill stem tests were taken in various formations in eight of the holes, and hydrocarbon shows were reported in five of the tests. The Trinidad Sandstone had oil or gas indications in four of the wells, but a completion attempt on one (the #1-M State, sec. 33, T. 29 S., R. 66 W.), resulted in formation water and no oil or gas, despite an earlier fluorescent core. Shows were also reported in the basal conglomeratic sandstone of the Raton Formation, with tests in three different wells and a core in a fourth. These tests showed only formational water or drilling mud.

At the same time in the New Mexico portion of the Basin, Pan American conducted an eight well Trinidad Sandstone testing program in the Canadian River drainage area on the former St. Louis, Rocky Mountain and Pacific Fuel leases, which had only recently been acquired by the Kaiser Steel Corporation. This program was located mainly on the eastern flank of the Basin, but three tests (T. 32 N., R. 19 E.) were across the basinal axis and defined the northern extension of the Vermejo Dome axis. One of these tests (sec. 33, T. 32 N., R. 19 E.) had sufficient gas shows in the basal Trinidad sandstone to attempt a sand-water hydraulic fracturing treatment at a depth of 2,408 to 2,424 ft. The results of swabbing afterward were slight shows of gas and formational water. Pan American finished the New Mexico portion of their program in 1959 with an unsuccessful Dakota well (sec. 19, T. 30 N., R. 22 E.) immediately south of a previous Continental Oil Dakota test.

In the first half of the 1960's only one significant test was drilled, the Gourley #1 Vermejo (sec. 27, T. 31 N., R. 17 E.). This well, drilled by the owner of the Vermejo Ranch on the western flank of the basin was in an important location for structural control and went deep enough (6,012 ft) for vital stratigraphic information. It penetrated to the Triassic Dockum Group without significant shows, but did show how rapidly the steep dips along the extreme western margin of the basin flattened. In 1965 and 1966 Kaiser Steel conducted a series of scattered coal exploratory holes in York, Salyers and Van Bremmer Canyons of the Vermejo Ranch and adjoining properties. Several of these tests penetrated the Trinidad Sandstone while checking the overlying basal Vermejo Formation coal beds. These holes provide control in delineating the basinal axis and its subsidiary depression in the southern Raton Basin. In the late 1960's Pan American drilled another Dakota test (sec. 11, T. 28 N., R. 20 E.) on coal properties owned by the Phelps-Dodge Corporation, and W. J. Gourley drilled a second test (sec. 16, T. 30 N., R. 18 E.) to the Dakota Formation on the Vermejo Ranch. In the opposite end of the basin, Clark and Perkins drilled the first and only test in the Colorado portion to go below the Dakota since the two Continental wells of the late 1950's. This test (sec. 11, T. 29 S., R. 67 W.) bottomed at 6,605 ft in the Permian Sangre de Cristo formation and is the only well penetrating below the Trinidad in the whole northern half of the restricted Raton Basin.

In the early 1970's two exploratory programs were conducted adjacent to the Purgatoire River drainage in Colorado. The Peabody Coal Company initiated a shallow Vermejo Formation coal program immediately west of the town of Trinidad and the Alamo Petroleum Corporation, also operating as the Los Angeles Petroleum Corporation, drilled two Trinidad test wells on a surface Tertiary structure in T. 33 S., R. 67 W. It is questionable whether the structural feature mapped by the U.S.G.S. on beds in the upper Raton Formation reflects the structural configuration of the deeper Tertiary and Cretaceous beds.

In early 1972 a comprehensive Dakota testing program was initiated by Odessa Natural Corporation on the W. S. Ranch properties in the southern portion of the Raton Basin. Odessa Natural's program was predicated on the possibility that the numerous gas shows recorded in both the Trinidad and Dakota sandstones of previous tests on the eastern flank of the Basin might develop into commercial gas accumulations deeper in the Basin, where the fine-grained sediments had been subjected to rapid burial and higher overburden pressures during the early periods of possible hydrocarbon formation and migration. Odessa undertook to drill five Dakota tests in the deeper portion of the southern basin in order to test this theory. Due to drilling problems Odessa Natural was obliged to drill offset wells to two different wells, and thus drilled a total of seven tests penetrating the Dakota. In addition an unsuccessful completion attempt was made on the Dakota formation in the then five year old Gourley #2 Vermejo well (sec. 16, T. 30 N., R. 19 E.) and a partnership well was drilled to the Trinidad Sandstone near the #5 W. S. Ranch well (sec. 22, T. 30 N., R. 18 E.) to evaluate shows found in that well. No producing wells resulted from the program, but the drilling technique employed allowed a thorough and positive testing of all formations drilled and a number of good petroleum shows were encountered in several different formations.

DRILLING TECHNIQUES

Drilling problems are a factor which have had an important influence on the drilling history of the Raton Basin. Although different areas of the basin present slightly different problems, all have common problems. Lost circulation zones occur in all formations from the Tertiary Poison Canyon and Raton formations to Precambrian igneous rock. Returns are lost to sandstones in the Raton, Vermejo, Trinidad, Dakota, Morrison, Entrada, Glorieta and the Sangre de Cristo formations. They have been lost in shale fractures in the Raton, Vermejo, Pierre, Niobrara and Benton formations in wells drilled to date. Attempts have been made to carefully control mud weights and composition in anticipation of lost circulation. Mud has been lightened by diesel oil and aeration and has been loaded with various lost circulation materials. Controlled pump pressures have been tried. All of these approaches have met with only limited success or, more often, with outright failure.

The Odessa Natural Corporation program was designed to avoid the lost circulation problems by the use of air as the circulating medium, rather than drilling mud. The advantages of the air drilling technique include (1) faster penetration rates, (2) avoidance of lost circulation problems, and, most importantly, (3) continuous open-hole test of possible producing formations which were known to have low-permeability and, hence, low-pressure characteristics. The disadvantages proved to be (1) poor quality, contamination or lack of adequate drill cuttings to identify formations, (2) the too-rapid penetration rates producing hole problems (excessive deviation and out-of-gauge size) and lack of precise control on the depths of formations and zones of gas or fluid entry, (3) the considerable additional expense of intermediate casing and air compression, (4) the general lack of success in coring, when attempted, and (5) the less-than-satisfactory suite of geophysical logs that can be run in a dry or cased hole.

The initial problem in Odessa's air drilling program was that of excessive water from the shallow Raton Formation sandstones. It had been anticipated that the entry of formational water into the holes in volumes which additional air compression could not overcome would require the use of air-mist drilling techniques. This proved to be the case. The air-mist technique, while still allowing essentially a continuous open-hole test, has some drawbacks. These include slowed drilling time, sample contamination and discontinuity, and difficulties in determining the depths and amount of any additional zones of water entry. More important is the fact that exposed, water-sensitive formations are subjected to wetting and consequent swelling and sloughing. The thick bentonitic shale sections below the Trinidad were found to be extremely water-sensitive and caved-in on two of the wells, causing hole loss and the necessity of drilling offset wells. Odessa revised their original drilling plan of attempting to maintain an open hole from the top of the Vermejo Formation to total depth, to one in which an intermediate casing string was set through the Trinidad Sandstone, followed by the air drilling of the thick, underlying shale section and the Dakota. When water was encountered in the Dakota, it was decided that a second intermediate casing string would be set off of the top of the Dakota which would protect the shale section from wetting. This procedure was used successfully during the balance of their program.

RECENT DRILLING ACTIVITY

Since the Odessa Natural program in 1972-73, four additional areas of the Raton Basin have been explored. In the southern portion of Huerfano Park in Colorado, beyond the northern limits of the restricted Basin, three companies have been involved in exploration on the flanks of the Sheep and Little Sheep Mountains. These mountains are silicic intrusives of probable Eocene age which have bowed up sedimentary beds of the Tertiary Poison Canyon Formation and the unconformably underlying Cretaceous Pierre Shale into an elongate anticlinal structure which is cored by the intrusive. Beds down to the Jurassic Entrada have been tested and one well (sec. 35, T. 27 S., R. 70 W.) was reported to have tested inert gas in volumes up to 5 MMCFPD in the Dakota and small volumes of flammable gas from an igneous sill and the Codell Sandstone.

In New Mexico a shallow test program was conducted by Amoco Production in the plains area immediately south and east of Koehler on the lower slopes of Eagle Tail Mountain. Four of the five tests were scheduled as Ft. Hays Limestone tests, while the fifth, the deepest at 1,221 ft, was a Morrison test. All wells were located structurally along the northwestern flank of the Sierra Grande Arch and all were plugged and abandoned without reported shows. Further south, in the Las Vegas sub-basin and on the western flank of the same Arch, another shallow-test program discovered flammable gas in the Dakota at depths of less than 500 ft. In the southern Basin proper an extensive coal-drilling program has been conducted since 1973 by the Kaiser Steel Corporation on their properties on the southeastern margin of the Raton Mesa adjacent to the extensively mined area at Koehler. While the program was directed at Vermejo Fm. coals generally at less than 1,000 ft depth, several of the holes exceeded 1,500 ft, all were drilled into the Trinidad for stratigraphic control purposes and several reported methane gas shows.

Perhaps the more important program for oil and gas consideration was the series of five test wells and one workover that was drilled by the American Fuels Corporation under a farm-out agreement with Odessa Natural Corp. on the W. S. Ranch properties. All tests were located on the flanks of Vermejo Dome and three were located near tests previously drilled by Odessa. Although two of the wells were originally scheduled as Morrison tests, none of the holes reached the Dakota. The initial well was drilled in the valley of the Vermejo River, where it breaches the southeastern flank of Vermejo Dome. It was intended as a Dakota test, but after encountering a series of ten silicic igneous sills 2 to 28 ft thick at a depth of 300 to 3,970 ft the well was abandoned at 4,167 ft in 163 ft of igneous rock. The second and third tests were a workover and an offset to previously drilled Odessa wells designed to attempt completions of what the operator apparently thought were incompletely tested zones in the Trinidad and basal Raton formations. The attempts were unsuccessful and American Fuels then drilled two Trinidad tests in Van Bremmer Canyon a few miles both northwest and southeast of these attempts. Casing was run to total depth on both of these tests, but perforations in the Raton and Vermejo Formations produced no significant hydrocarbon indications.

The final American Fuels test was a substantial step-out from previous drilling and was located on the eastern flank of Vermejo Dome (sec. 24, T. 31 N., R. 19 E.) near the projected synclinal axis of the Basin. The well was a scheduled Dakota test, but extreme drilling difficulties were encountered and, although the hole eventually was drilled to a total depth of 6,335 ft, it apparently did not reach the Dakota. No mechanical log was run below 3,988 ft but the mud log and drilling time charts indicate that the hole cut a reverse fault at approximately 6,000 ft while in the Graneros and re-entered what is apparently Niobrara shales in which the hole was eventually bottomed. This test closely resembled conditions encountered in Odessa's #5 well (sec. 22, T. 30 N., R. 18 E.) on the south flank of the Dome. In the Odessa well an igneous intrusive was encountered in the Graneros near the top of the Dakota. After penetrating some 60 ft of intrusive the hole entered a repeated section of Greenhorn and Graneros formations and finally topped a highly silicious Dakota section at 6,272 ft. Apparently the hole had cut a reverse fault with some 300 ft of vertical displacement along which an igneous intrusive had been subsequently emplaced. These two wells indicate the structural complexities that might be expected to occur in the subsurface of the central and western portions of the basin.

PROSPECTIVE OIL AND GAS FORMATIONS

Based on current knowledge, the strata considered to have oil and gas potential are considered in descending stratigraphic order.

The *Raton Formation,* being primarily a flood plain-paludal deposit, would not ordinarily offer good possibilities for petroleum accumulation. The sandstones are predominantly coarse grained, poorly sorted, fluvial sandstones which have been shown by log interpretation and actual testing to be consistently water-bearing. Some methane shows have been encountered in the Raton, but usually in direct association with the coal deposits found through the section. From the frequency and extent of oil and gas shows encountered, it is apparent that consideration should be given to the so-called *Raton Formation basal conglomeratic sandstone.* This unit had several encouraging petroleum indications in the Odessa Natural wells. It was cored and tested on the basis of oil staining in at least three wide-spread wells in the Pan American program and was unsuccessfully perforated and hydraulically fractured on two of the American Fuels wells. This conglomeratic sandstone sequence ranges in thickness from approximately 35 to 110 ft. It is variable in character, generally a relatively clean, friable well-sorted quartzose sandstone with minimal conglomeratic material. The unit is usually identifiable on mechanical logs as a cleaner sandstone unit and appears in well cuttings samples to have relatively good reservoir characteristics. Its unconformable relationship with underlying beds presents the possibility of migration of hydrocarbons into this unit from underlying strata.

The *Vermejo Formation* is a wedge of coastal plain and lagoonal sedimentary rocks which thickens to the west from a zero edge on the eastern margin of the Basin. It has been presented in previous publications as offering hydrocarbon reservoir possibilities. It has been likened to its homogenetic equivalent, the Fruitland Formation in the San Juan Basin, which is gas-productive from some of its sandstone units. From a sedimentary stand-point, the two formations are very dissimilar. The Fruitland sediments have been subjected to several still-stands of shoreline which produced sandstones that are relatively clean, permeable and porous. The Vermejo sandstones are extremely "dirty," poorly sorted with abundant feldspar and rock fragments and devoid of good reservoir characteristics in the cores and samples which have been described. The Vermejo Formation, more than any other mapped unit, has been subjected to intrusion by the late Tertiary sills.

From its depositional history as a marine regressive shore and nearshore sandstone unit, the *Trinidad Sandstone* might be expected to offer the best possibility as a hydrocarbon reservoir. It is a massive, thick-bedded, well-sorted, porous quartz sandstone of varying clay content. It has frequently had both oil and gas shows in wells drilled to or through it. It has been likened to its San Juan Basin equivalent, the gas-bearing Pictured Cliffs Sandstone. This analogy is appropriate, although there are still significant differences. The Pictured Cliffs is a prime example of a beach and nearshore deposit which has been subjected to minor transgressions and still-stands of strandline during its overall marine regression. The result of this type of depositional history is a series of elongated, parallel benches or steps of porous and permeable sandstones separated by an impermeable sandstone facies. The clean benches result from periods of shoreline stability in which the waves and shoreline currents had sufficient time to effectively winnow the beach deposits, removing the finer elastic component. The tight sandstone facies are the normal deposits of a steadily retreating sea in which the finer-grained elastics are intermixed with the coarser-grained segment. Gas production from the Pictured Cliffs Sandstone occurs from the clean, porous benches, while the clay and silt-filled, tight sand facies are barren.

An attempt to delineate similar depositional benches in the Trinidad Sandstone by the construction of isopach maps using both surface and subsurface data does not result in any well-defined depositional trends when the thickness of the massive, littoral portion of the sandstone has been carefully selected. Admittedly the lack of sufficient subsurface control points seriously hampers a good definition of depositional trends, but where more widespread subsurface data is available in the southern portion of the Basin, the thickness range is so small that a number of interpretations is possible. An interpretation indicating a northeast-southwest orientation is favored in the southern Basin primarily because it parallels the orientation of elongated buildups of Vermejo coal seams (Pillmore, 1969) which in turn are believed to reflect the original alignment of the Late Cretaceous strandline. An analogy between linear bench clean-ups in the Pictured Cliffs and possible ones in the Trinidad must take into account evidence (McGookey and others, 1972) that indicates the retreat of the Trinidad sea across the Raton Basin appears to have been more rapid and continuous than that of the Pictured Cliffs sea across the San Juan Basin, a fact that seems to be supported by current depositional interpretation. If an analogy is appropriate, it would appear to favor a comparison of the Trinidad depositional environment with that of the regressive Point Lookout Sandstone of the San Juan Basin, rather than that of the regressive Pictured Cliffs Sandstone. Despite comparative differences, the Trinidad does have hydrocarbon reservoir possibilities and its general lithologic characteristics, regional stratigraphic relationships and abundance of subsurface oil and gas indications combine to make it a prime exploratory horizon.

In the 3,000 to 3,765 ft of shale and shaly limestones lying beneath the Trinidad, a number of small, but significant gas shows were encountered by Odessa Natural while drilling the section with air. The only measurable amount (70 MCFPD) was recorded in the Ft. Hays Limestone in the #4 W. S. Ranch well (sec. 12, T. 29 N., R. 19 E.) but was absent in the re-drilled well immediately adjacent. Persistent weak gas shows were recorded in all of the Odessa wells in the middle portion of the Pierre Shale throughout a 630 ft interval. In some cases the shows appeared to be related to an increase in sandiness of the shale, but no specific zones could be correlated between wells. An unsuccessful completion attempt was made on one of the more promising shows on the #3 W. S. Ranch well (sec. 24, T. 29 N., R. 19 E.). Gas was also encountered in the Niobrara Shale, the Carlile Shale, the Greenhorn Limestone and the Graneros Shale sections. The amount was too small to measure and did not appear to be related to any identifiable reservoir rock as determined from samples and mechanical log examination. It is assumed that the gas shows accumulated in fractures in these dense strata. Only at Garcia has gas production been recorded in these shales, but previous wells drilled with mud have reported a high incidence of lost circulation in the intervals, which would appear to give indirect evidence of fracturing. If commercial oil or gas accumulations are to occur in the shale sequence it appears that an extensive, interconnected fracture system would have to be developed and serve as a reservoir. Unfortunately such fracture systems might also have provided natural conduits for either water or the late Tertiary igneous intrusives which are ubiquitous.

The Dakota Sandstone, in the subsurface of the southern half of the Basin where more drilling has occurred, has been disappointing. It has been considered the primary drilling objective in the past, primarily a stratigraphic possibility. Many productive Dakota traps are found throughout the Rocky Mountains, where individual clean beach and nearshore sand units of the formation have undergone facies changes and depositional lens-outs to form stratigraphic traps. The control available in the southern Basin indicates a relatively uniform depositional sequence for the Dakota Formation and what may be Purgatoire Formation. The writer discounts the presence of identifiable Purgatoire in the subsurface of the southern Basin, because the entire sequence above the readily recognizable Jurassic Morrison beds seems to be one of continuous sedimentation. These deposits which fine upwards are best interpreted as deposits of a continuously transgressing sea, with sands grading from a fluvial to a littoral to a shallow neritic environment without significant hiatuses.

The sandstones of the Dakota are excellent reservoir rocks. The upper 30 to 40 ft are tan to light gray, hard, tight, silicious, well-sorted sandstones with sub-rounded, very fine to fine grains of clear quartz. A dark gray, dense to silty, slightly calcareous shale interval about 20-25 ft thick separates this interval from the second sandstone sequence (40-50 ft thick). The second sandstone group is very similar in lithologic characteristics to the upper section, but is somewhat more coarse-grained. The basal sandstone is a massive, very porous, friable sandstone of medium-sized, sub-rounded clear quartz grains. It also contains conglomeratic lenses in its basal portion. The massive basal sandstone invariably is the more porous sandstone as indicated by samples and porosity logs. This general lithologic sequence varies only slightly in all of the wells examined (Fig. 4). There are some changes in the number and thickness of individual sandstone units, particularly in the upper two-thirds, but the lithology and overall thickness remained essentially unchanged. In New Mexico the thickness for the Dakota interval from well control ranges from 115 to 217 ft.

Gas shows were encountered in the upper sandstone section of four of the Odessa Natural Corporation wells. Both gas and oil staining were reported from the Dakota in eight of the Continental Oil Company wells. The Dakota was found to be water-bearing in almost all sandstones, but particularly in the massive basal sandstone unit. Measurable water flows on the order of 20 BPH were encountered with salinities ranging from a relatively fresh 5,000 ppm chloride and 9,800 ppm total dissolved solids upwards to 14,500 ppm and 22,339 ppm respectively. The widespread occurrence of Dakota formation water in the southern half of the Basin suggests that the sand units are hydraulically in communication and that stratigraphic entrapment of petroleum is generally unfavorable. This lithologic continuity would not preclude petroleum entrapment under structural conditions within this area of the Basin.

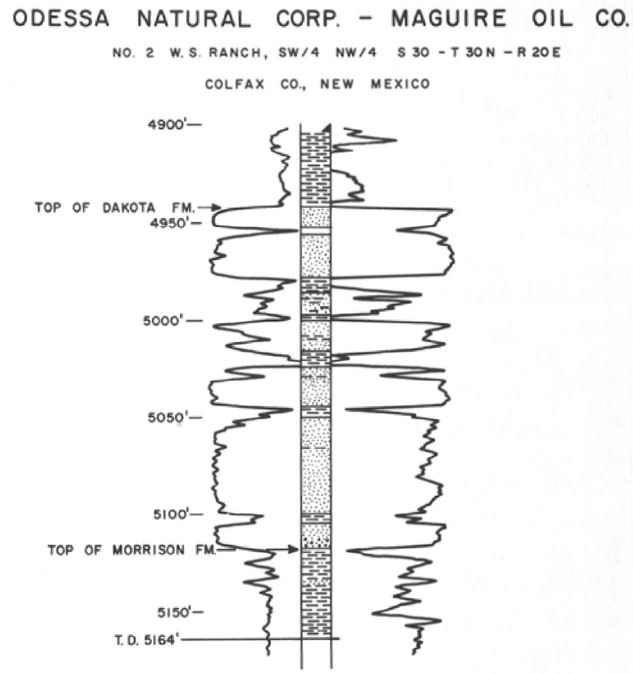

Figure 4. Typical gamma-ray log of Dakota Formation in south-central Raton Basin.

Surface studies indicate that the stratigraphic continuity of sandstone units may not occur in the northern part of the Basin. Unfortunately only one well (sec. 11, T. 29 S., R. 67 W.) has penetrated the Dakota in this half of the Basin, inside the Trinidad outcrop, so that subsurface extensions are purely speculative.

The lack of subsurface data also prevents any evaluation of petroleum prospects below the Dakota formation, but regional studies suggest possible reservoir rocks might include the Jurassic Entrada Sandstone, the Permian Glorieta Sandstone and the Pennsylvanian Madera Formation; however, only the latter is found in association with possible petroleum source rocks of marine origin.

The favorable stratigraphic and structural geological setting, offered by the Raton Basin for the generation and accumulation of hydrocarbons, coupled with its substantial and widespread, though sub-commercial, indications of both oil and gas suggests that the basin still offers opportunities for the discovery of significant reserves.

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