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William F. Hoppe

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HYDROCARBON POTENTIAL AND STRATIGRAPHY OF THE PICTURED CLIFFS, FRUITLAND AND OJO ALAMO FORMATIONS IN THE NORTHEASTERN SAN JUAN BASIN, NEW MEXICO

WILLIAM F. HOPPE
Robert L. Bayless, Producer, P.O. Box 168, Farmington, New Mexico 87499

Abstract—The northeastern portion of the San Juan Basin has had far less drilling activity than the central producing areas. Recent methane gas discoveries in the Ojo Alamo Sandstone, Fruitland coal seams and Pictured Cliffs Sandstone have increased interest in this area of the basin. Exploiting effective natural fractures is necessary for commercial production from the Pictured Cliffs and most likely from the Fruitland coals. In both the surface and subsurface, the Fruitland coal interval has been intruded by igneous rocks. The Ojo Alamo produces from primary porosity and permeability in a probable stratigraphic-structural trap. Explorationists must be adept in mapping lineament trends and will probably find numerous faults and folds in the subsurface.

INTRODUCTION

The study area is located in the northeastern portion of the San Juan Basin of northwestern New Mexico (Fig. 1). Compared to the main oil and gas producing trends of the San Juan Basin, this area of the basin is relatively undeveloped. There has been economic justification for this lack of interest. Rough terrain, low productivity, deeper reservoirs and land problems associated with the San Juan National Forest and Jicarilla Apache Reservation combine to limit drilling activity. During the initial drilling phase (1953–58), 55 wells were drilled. It took until 1981 for another 55 wells to be drilled. In the past several years numerous coal bed methane wells have been drilled, mostly in T29–32N, R4W.

Most of the production in the study area is from Fruitland coal and Pictured Cliffs reservoirs, with the deeper Mesaverde, Gallup and Dakota intervals contributing minor amounts of gas. Excluding coal bed methane tests, only 24 wells, mainly Pictured Cliffs producers, have cumulative production greater than 400 mmcf. Several highly productive Fruitland coal gas wells are located in east-central T32N, R4W. Recent completions in the Ojo Alamo have produced methane and hydrogen sulfide.

SURFACE GEOLOGY AND INTRUSIVES

Outcrops of the Lewis, Pictured Cliffs, Fruitland and Ojo Alamo formations are located near Dulce, New Mexico (Fig. 2). These strata, which dip approximately 10° southwest and west, outline the northeastern portion of the San Juan Basin and are only 8–10 mi from production in T31–32N, R4W and T30N, R3W. The most striking surface features are the biotite-hornblende lamprophyre dikes that trend N5°E to N10°E (Dane, 1948) and extend from southern Colorado to the vicinity of T26N, R2W, New Mexico. The dikes are Miocene in age and are slightly younger than the augite-andesite sill of Archuleta Mesa near Dulce. The dikes are 1–30 ft thick, mostly nearly vertical, and bordered by a thin chill zone (Dane, 1948). Well exposed on the north side of Amargo Arroyo west of Dulce are two thin sills and several dikes. Here the intrusives are often present within or in contact with the Fruitland coals. The coal has been altered to coke in places and original sedimentary structures have been disrupted. Near Dulce (sec. 36, T32N, R2W; Fig. 2), a sill within the Lewis Shale contains free oil in vesicles (Fassett et al., 1977). The oil is "believed to have been transported upward as a volatile" (E. A. Riggs, personal comm. 1992).

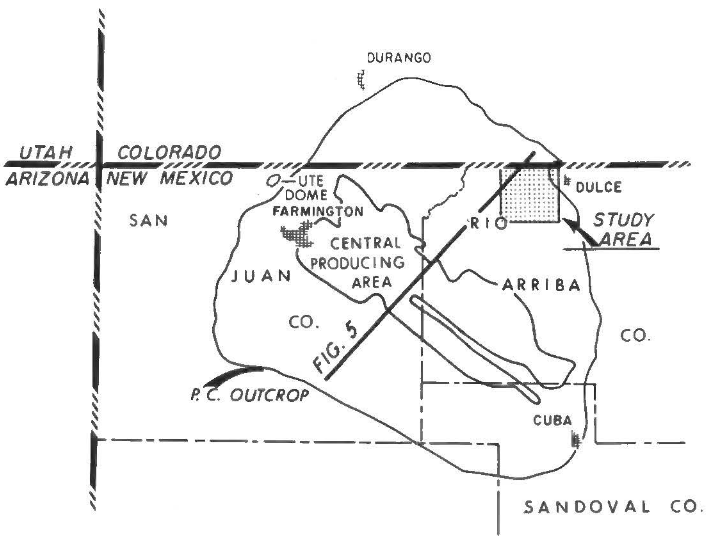

FIGURE 1. Index map of San Juan Basin as defined by the Pictured Cliffs outcrop, showing study area, diagrammatic cross section trace, and central producing area of the Pictured Cliffs (after Brown, 1973).

In Dulce, the interval from the base of the Ojo Alamo to the top of the Pictured Cliffs, essentially the Fruitland Formation, is approximately 100 ft thick (Fassett et al., 1977) whereas the same interval in the Bayless Jicarilla 459 No. 2 (NW¼ sec. 20, T30N, R3W) is 310 ft thick. The "lower" Pictured Cliffs Sandstone is not seen in the outcrop.

Several circular anomalies in T31–32N, R3W are prominent on topographic maps and satellite imagery. The origin of these features is unknown but they might be related to the intrusives.

Intrusives are widely found in the subsurface, as outlined in Fig. 2 and illustrated on the cross sections (Figs. 3, 4). Both the Pictured Cliffs and Fruitland Formations have been intruded. A core through the intrusive and coal intervals was recovered from the Amoco Jicarilla Tribal 531 No. 1 (SW¼ sec. 5, T31N, R3W). Results of thin section analyses revealed that the samples contain fine-grained igneous rocks. Alteration and replacement of the original minerals makes classification of the rocks difficult and they are therefore called pheno-basalts.

Small, elongate, tabular crystals, most of which are arranged in a fan-like shape, comprise much (42%) of the samples. These crystals appear to be plagioclase, which may be an alteration product. Secondary replacement minerals are abundant. These include pyrite (28%), phyllosilicates (chlorite 8.4%, others 10%), carbonate (6.0%), titanium oxides (2.4%) and quartz (0.4%). Pyrite is heterogeneously distributed in large clusters and often lines fractures. Calcite is present in fractures and as replacements of blocky crystals that may have been mafic minerals such as pyroxene. Authigenic smectitic/illitic clay partially to completely fills some of the fractures in the coal. Samples from drill cuttings effervesce and fibrous crystals and pyrite are usually observed.

Total core porosity of 2.8% consists mostly of fractures and microporosity. Fractures range from closed and filled to uncemented and open. Many of the fractures in the intrusive rock are surrounded by microporous matrix for most of their length. A 0.2-mm-thick, nonporous chill zone in the intrusive rock is present immediately adjacent to the sharp contact with the coal. Fractures in the coal are distributed

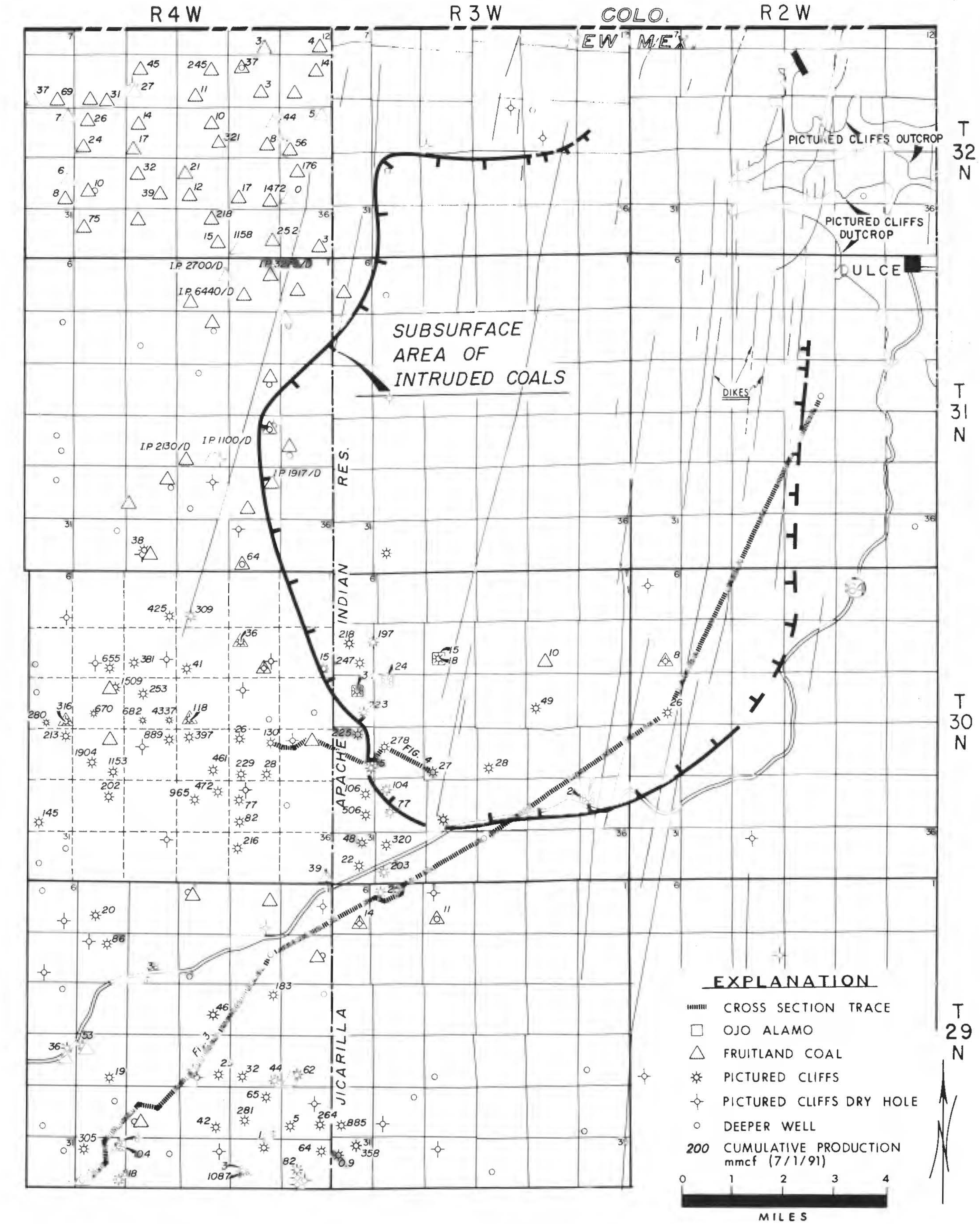

FIGURE 2. Regional study area showing outcrop of Pictured Cliffs and intrusives, well locations, cumulative production, subsurface area of intruded coals and cross section traces.

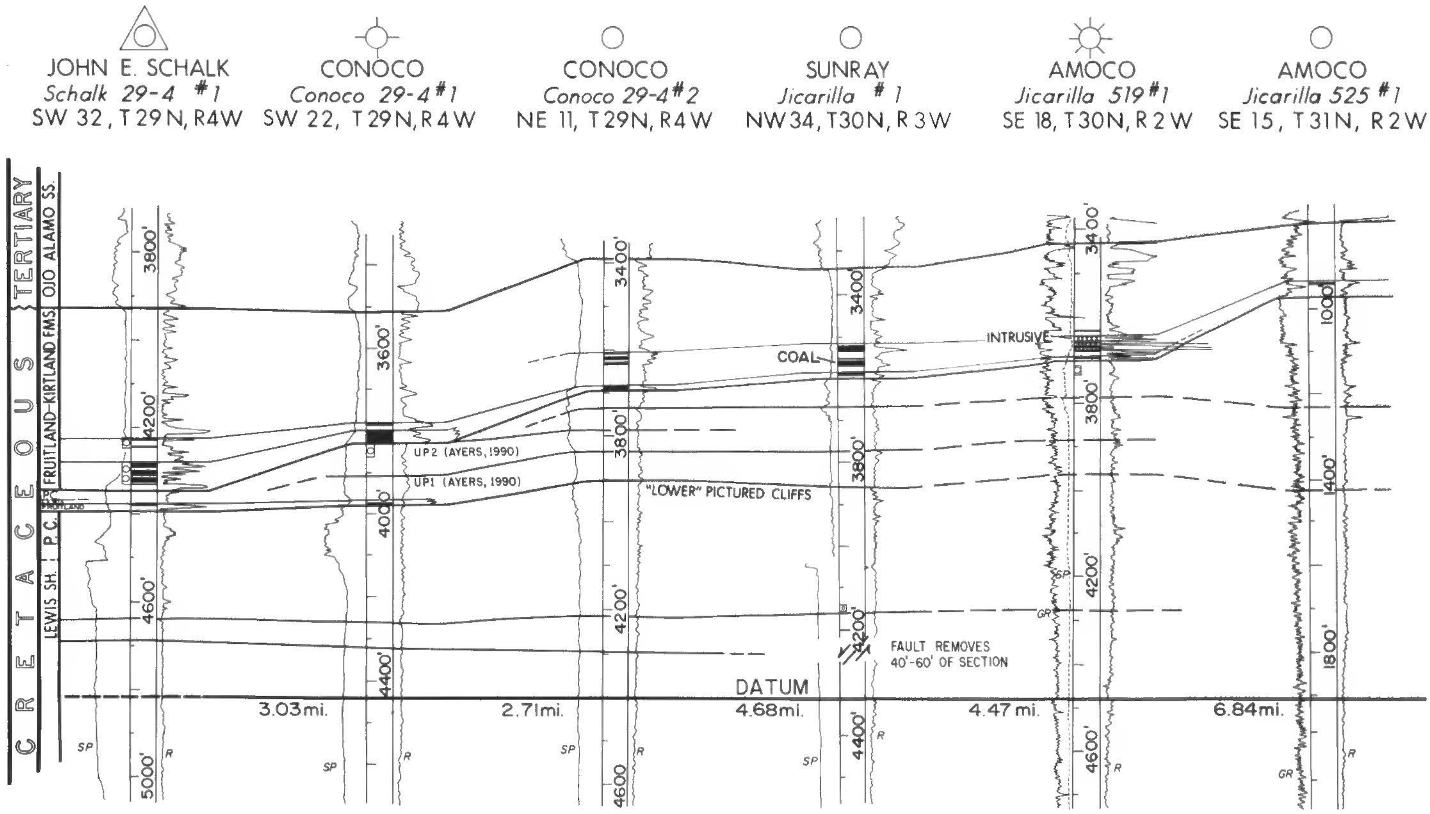

FIGURE 3. Regional southwest-northeast cross section. Cross section trace shown on Fig. 2.

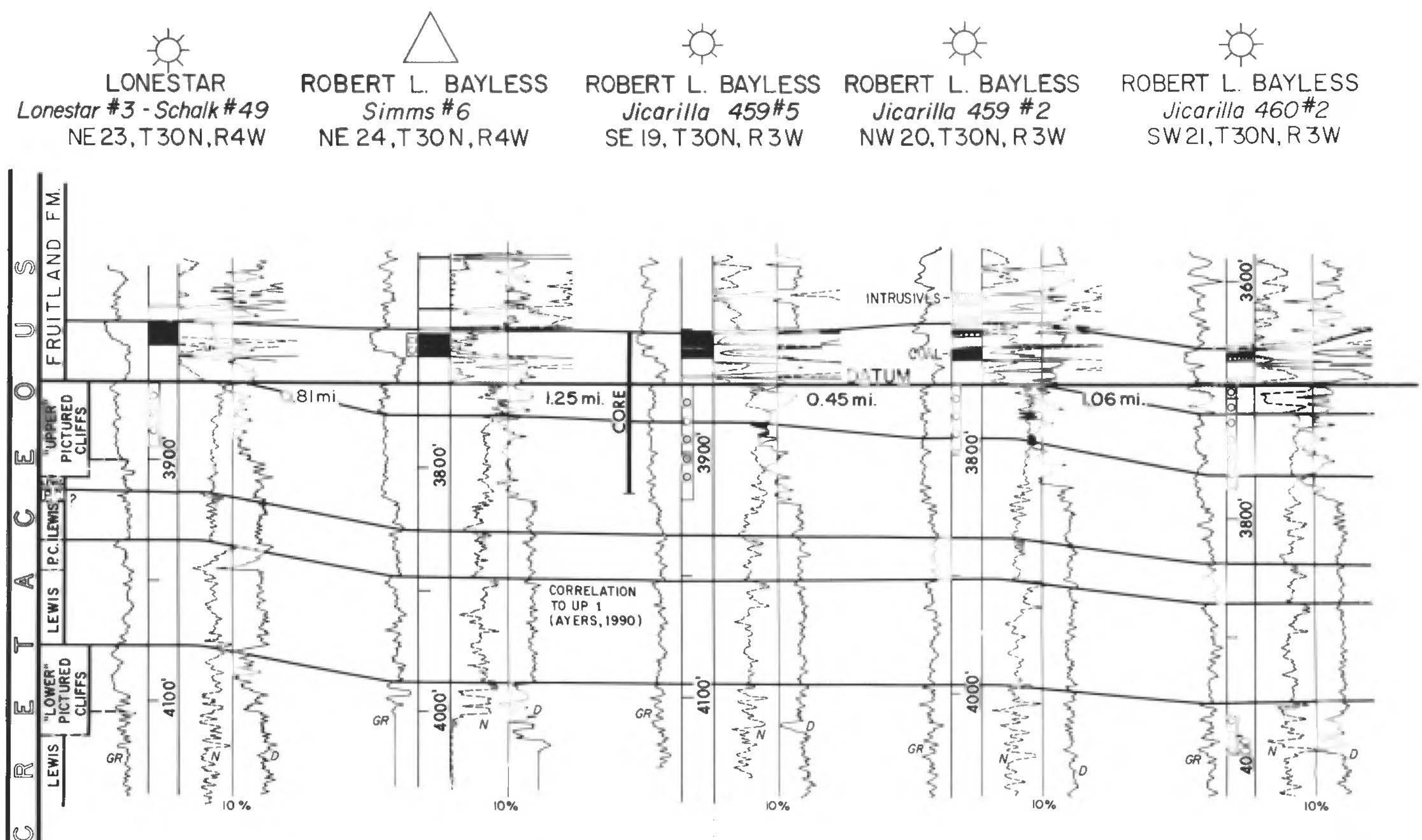

FIGURE 4. Detailed west-east cross section. Cross section trace shown on Fig. 2.

throughout the sample and appear to be variably interconnected. It is unknown whether the intrusives have affected the reservoir properties of the coal seams.

STRATIGRAPHY

As has been documented by many authors (Fassett and Hinds, 1971; Fassett, 1977; Brown, 1973; Ayers et al., 1990), the Pictured Cliffs Sandstone represents a littoral deposit in a wave-dominated system in the final northeasterly regression of the Cretaceous sea. Stratigraphically below and intertonguing with the Pictured Cliffs is the marine Lewis Shale. In the study area there are two main Pictured Cliffs intervals; the lower Pictured Cliffs and an upper unit consisting of one to three sandstone tongues. The general relationships of the Lewis–Pictured Cliffs–Fruitland strata are illustrated in Fig. 5. Note that the major thickening of the Pictured Cliffs–Lewis interval occurs above the Huerfanito Bentonite Bed datum and above the lower Pictured Cliffs.

The lower Pictured Cliffs is an upward coarsening sandstone sequence that is the stratigraphic equivalent of the productive interval in the central San Juan Basin (Fig. 5). Fassett (1968) described the lower Pictured Cliffs from a core in the El Paso Gasbuggy No. 1 (SW¼ sec. 36, T29N, R4W), as a very fine- to fine-grained, fairly well sorted, salt-and-pepper sandstone. The dark grains consist mostly of glauconite, mica and carbonaceous shale. Interbeds of the Lewis Shale are present in the lower part of the interval but become fewer and thinner upward.

Deposited above the lower Pictured Cliffs is the intertongued, nonmarine Fruitland Formation, which consists predominantly of coal and/or carbonaceous shale. A thin coal is present on the southwestern portion of the regional cross section (Fig. 3). This coal is thicker southwest of the study area and pinches out to the northeast. The area was then transgressed by the Lewis sea. The process of transgression is very destructive and probably eroded some of the intertongued Fruitland.

The Lewis sea reached the T29N, R5W area, where it began to regress and transgress with one to three widespread upper Pictured Cliffs–Fruitland sequences deposited. Few of the Fruitland coals and carbonaceous shales remain and these sequences are identified by noting the coarsening upward character shown on the wireline logs (Fig. 4). There is considerable stratigraphic complexity in the area between sections 22 and 11 in T29N, R4W on Fig. 3. In sec. 22, units UP 1 and UP 2 are identified according to Ayers and Ambrose (1990). These units (UP 1, UP 2) are each considered by Ayers and Ambrose to be tongues of the upper Pictured Cliffs. A core of the upper Pictured Cliffs from the Bayless Jicarilla 459 #5 (SE¼ sec. 19, T30N, R3W; Fig. 4) was described as a gray, salt-and-pepper, very fine-grained to fine-grained, moderately sorted, subangular to subrounded, slightly calcareous sandstone with clay matrix, and occasional small fractures. *Ophiomorpha* casts and molds are also commonly present.

The Fruitland Formation lies stratigraphically above the Pictured Cliffs Sandstone. The Fruitland consists of sandstone, limestone, shale, carbonaceous shale, coal and volcanic ash, and represents the numerous environments of the coastal plain. Fruitland environments can change quickly laterally and include rivers, overbank deposits, floodplains, swamps and tidal deposits. The lower Fruitland Formation, including the coal, is sometimes intruded by igneous rocks in T30–32N, R2–4W. In one instance, the Bayless Jicarilla 31-3-32 No. 1 (SW¼ sec. 32, T31N, R3W), no bulk density measurement from high resolution wireline logs is less than 1.75 gm/cc. Sample examination revealed only coaly shale and intrusives. The isopach of net coal (Fig. 6) varies from 0 to 21 ft in thickness, reflecting the wireline measurements of bulk density in a consistently clean gamma ray interval (Fig. 4).

The geometry of the coals in a stratigraphic dip section is illustrated in Figs. 3 and 4. Three major seams are recognized above the upper Pictured Cliffs. These seams appear to terminate or thin at stratigraphic rises. In T30N, R3W (Fig. 4), the main 15–20-ft-thick coal seam interval can be 20–30 ft above the Pictured Cliffs, indicating deposition some distance behind the shoreline. Generally, the depositional strike of the coals is northwest-southeast, paralleling that of the Pictured Cliffs.

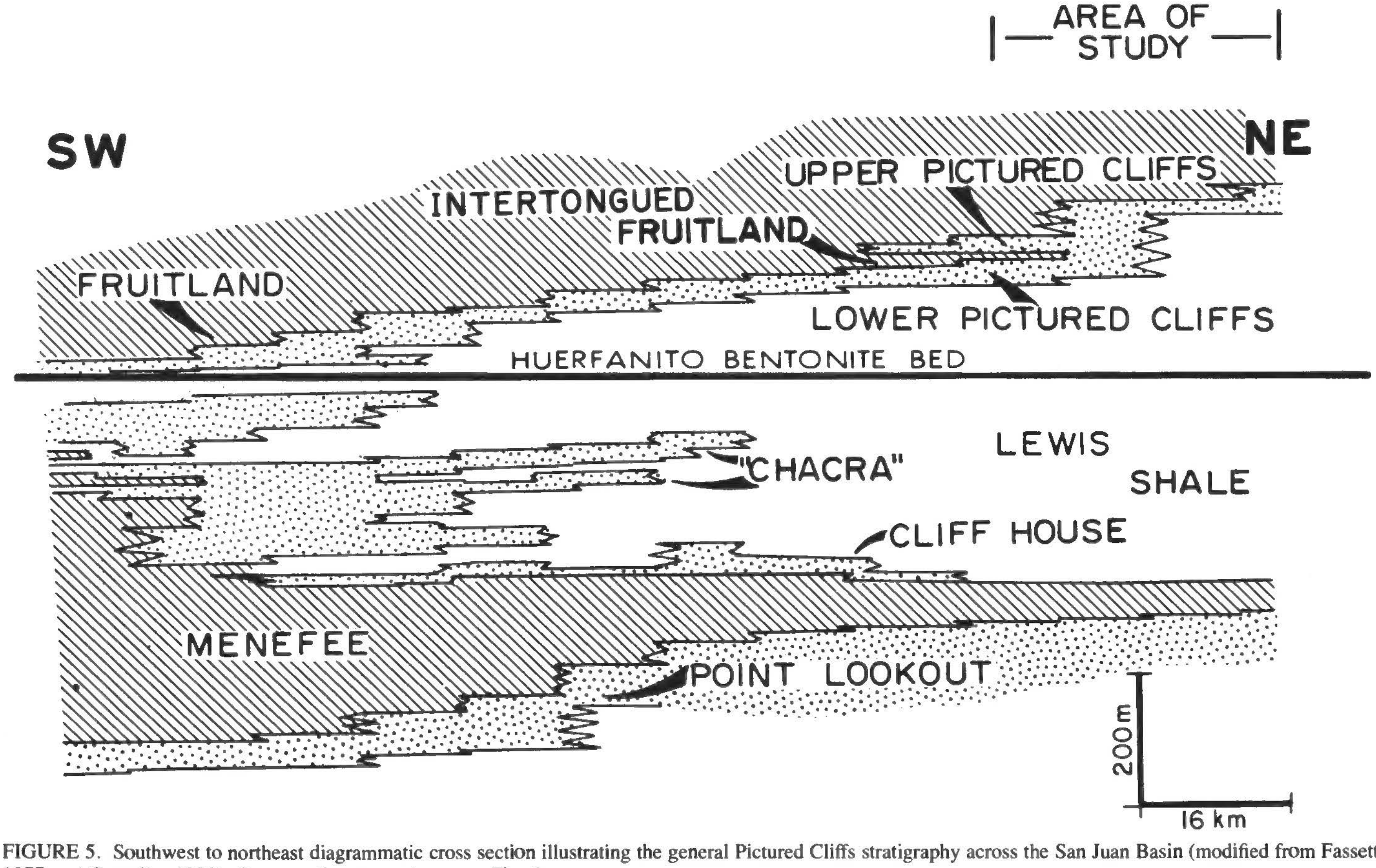

FIGURE 5. Southwest to northeast diagrammatic cross section illustrating the general Pictured Cliffs stratigraphy across the San Juan Basin (modified from Fassett, 1977 and Cumella, 1981). Cross section trace shown on Fig. 1.

The Kirtland Shale, lying conformably above the Fruitland, was deposited on the upper coastal plain. It consists mainly of shale, siltstone, sandstone and carbonaceous shale. Most of the Kirtland has been eroded in the study area.

The Ojo Alamo Sandstone lies unconformably on the Kirtland, and their contact approximates the Cretaceous-Tertiary boundary. The Ojo Alamo was deposited in a fairly high energy braided stream environment. The erosional nature of the contact is partially illustrated by the thinning of the Fruitland-Kirtland interval from 1300 ft near Farmington, New Mexico, to 150–500 ft in the study area and by basinwide cross sections by Fassett and Hinds (1971) and Ayers and Ambrose (1990). In the area of Fig. 3 this interval thins from 420 ft to 170 ft. The Ojo Alamo is believed to have a source to the west-northwest.

Fassett (1968, p. 26–27) described the Ojo Alamo Sandstone from a core in Gasbuggy No. 1 (SW¼ sec. 36, T29N, R4W) as follows: "It is composed of poorly sorted arkosic sandstone and a few thin shale interbeds and papery carbonaceous partings. Beds of claystone pebbles as much as 0.3 foot in diameter occur at random throughout this unit. Grain size of the sandstone ranges from very fine to very coarse. Some parts of the formation contain as much as 20 percent feldspar."

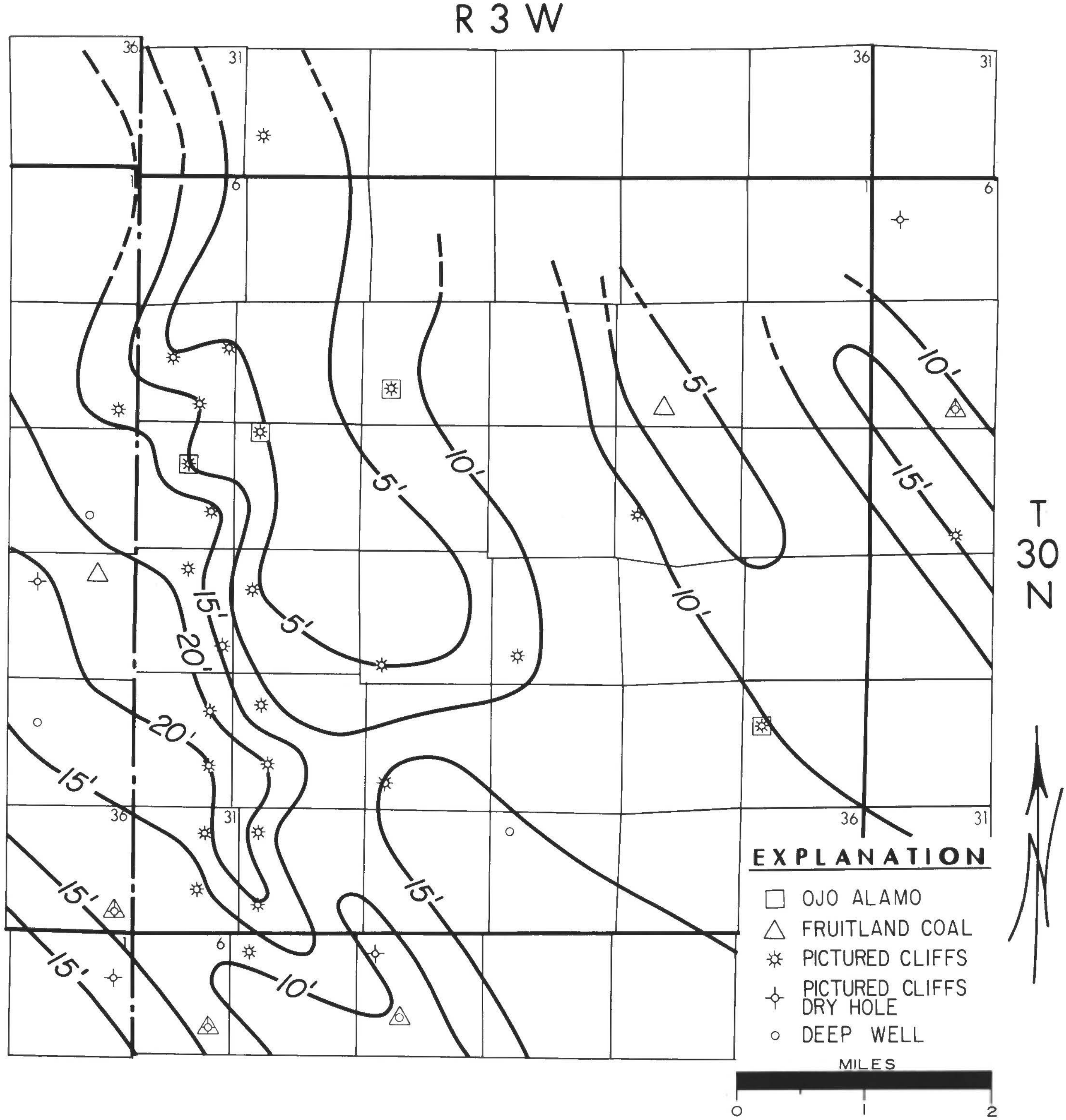

FIGURE 6. Isopach of net Fruitland coal based on clean gamma ray, bulk density <1.75 gm/cm³, resistivity of >60 ohms.

The overall continuity of the Ojo Alamo is well established. In detail, the individual sandstone beds are usually discontinuous between wells. Even the major shale breaks within the Ojo Alamo in T30N, R3W, where the gross section is fairly uniform, cannot be correlated with confidence. This variability is to be expected in a braided stream depositional environment. Laterally shifting channels are constantly eroding previous channels, and continuity of individual deposits does not usually occur. Porosity and permeability barriers may also exist at these channel-to-channel erosion surfaces.

STRUCTURE

The San Juan Basin is almost circular as outlined by the Pictured Cliffs outcrop (Fig. 1). It is bounded by hogbacks on three sides, with only the south side lacking an abrupt structural boundary. Structural contours of the Huerfanito Bentonite Bed (Fassett and Hinds, 1971, fig. 15) show that the basin is asymmetrical, with the deep axis trending northwesterly on the northeast side of the basin. The edge of a large synclinal feature several miles wide appears in the southwest portion Fig. 7; it may be part of the axis of the basin. Thus, the detailed study

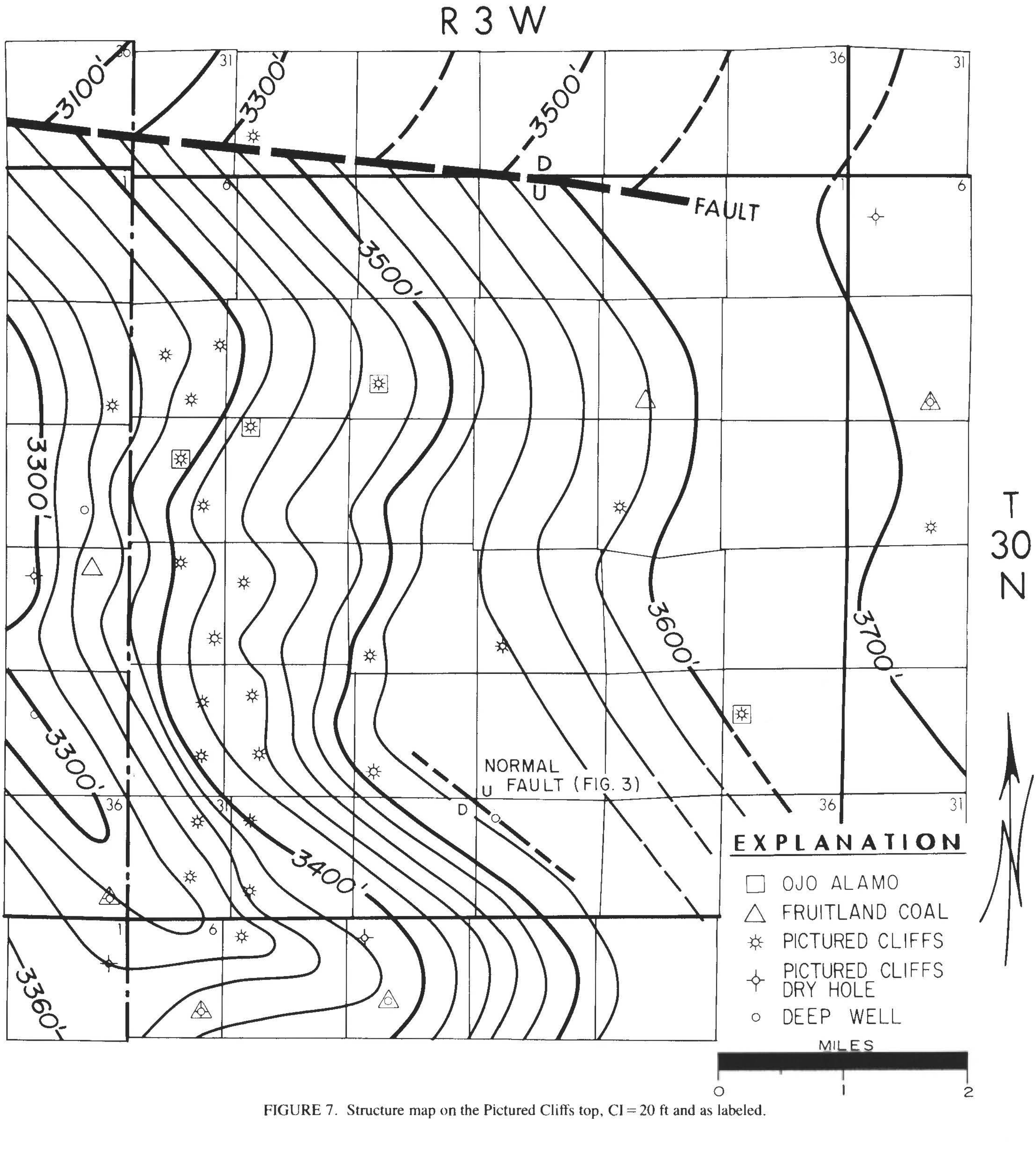

FIGURE 7. Structure map on the Pictured Cliffs top, CI = 20 ft and as labeled.

area is on the east side of the basin, with structure contours rising steeply to the outcrop approximately 14 miles northeast.

Fig. 7 also illustrates a broad, shallow, west-trending anticline and two faults. This anticline is influential in the Ojo Alamo gas accumulation. In the Sunray Jicarilla No. 1 (NW1/4 sec. 34, T30N, R3W; Figs. 3, 7), an apparently northwesterly trending, down-to-the-west, normal fault has probably caused the contours to widen in this area. This well gauged 1550 mcfd during drilling and was subsequently completed and abandoned in this interval. This fault subparallels many of the structures on the east flank of the basin, such as Dulce and Monero Domes (T31N, R1W). Studies of topographic maps and satellite imagery did not reveal surface expression of this fault.

Prior to the drilling of the Jicarilla 31-3-32 No. 1 (SW1/4 sec. 32, T31N, R3W), a fractured area was predicted for the southwest portion of T31N, R3W. This prediction was based on a structural contour map and satellite imagery. As a result of this well, the fault has been mapped. However, use of these techniques did not identify several fields of existing fracture production. It is interesting to note that the trend of the dikes (Fig. 2) does not parallel the best productive trends in T30N, R3W, but does subparallel the trend between the prolific Fruitland coal bed methane wells in T32N, R4W and the Pictured Cliffs wells in T30N, R4W. Other faults are undoubtedly present on the eastern side of the basin, and will be important in evaluating the hydrocarbon potential of the area.

HYDROCARBON POTENTIAL

Pictured Cliffs Sandstone

The physical properties and productive capabilities of the Pictured Cliffs Sandstone vary considerably in the San Juan Basin (Brown, 1973; Cumella, 1981). Based on these differences, the basin can be divided into three general areas. These areas (Cumella, 1981) are (1) the northeast (area of study)—low permeability, gas saturated, production dependent on fractures; (2) central producing zone—production dependent on primary porosity and permeability with fracture enhancement; and (3) southwest—permeable, mostly water saturated. Since the depositional environments of the Pictured Cliffs are similar throughout the basin, the change in physical properties of the reservoir have been strongly influenced by diagenesis.

Fassett et al. (1978) reported that the basinwide average permeability of Pictured Cliffs cores is 2.96 md. Brown (1978) stated that the average permeability is 5–6 md in the central producing area. Several core analyses of Pictured Cliffs zones normally completed within the study area are listed in Table 1. These permeabilities range from 0.6% to 42% of the basinwide average, with most of the core data at approximately 7% of average.

The low permeability values in the northeast are probably due to diagenetic changes. Petrographic and x-ray diffraction studies of two samples from the Jicarilla 459 No. 5 (SE1/4 sec. 19, T30N, R3W) indicate that these sandstones are cemented by authigenic and detrital clays, dolomite cement and quartz overgrowths. Porosity and permeability in these samples have been significantly reduced by the deformation of ductile framework grains (sedimentary and volcanic rock fragments) and/or the precipitation of authigenic clays (illite and/or mixed-layer illite-smectite) and dolomite in the pore system. Permeability measurements for these samples ranged from 0.02–0.11 md. This confirms data from Cumella (1981) who examined numerous outcrop and subsurface (Gasbuggy No. 1, SW1/4 sec. 36, T29N, R4W) samples. His conclusion, based on scanning electron microscopy, x-ray diffraction and thin section data was that authigenic clays (mostly mixed layer illite-smectite) occur as a pervasive grain coating throughout the entire Pictured Cliffs interval. This contrasts with his finding in the central producing area where the grain-coating clay is prevalent only in the lower, thinly bedded portion of the Pictured Cliffs, thereby preserving permeability in the upper productive intervals.

TABLE 1. Pictured Cliffs Sandstone core permeabilities and locations.

LOCATION OF CORE	PERMEABILITY (md) Range	Average
Conoco 29-4 No. 7		
NW 1/4 sec. 20, T29N, R4W		
Lower section of upper Pictured Cliffs	0.05-0.44	0.17
Silty-shaley zone of lower Pictured Cliffs	<0.01-0.08	0.02
Schalk 29-4 No. 6		
SW 1/4 sec. 25, T29N, R4W		
Upper Pictured Cliffs	0.01-9.6	1.25
Lower Pictured Cliffs	0.06-0.97	0.21
Gasbuggy No. 1		
SW 1/4 sec. 36, T29N, R4W		
Upper Pictured Cliffs	<0.01-0.17	0.04
Lower Pictured Cliffs	<0.01-0.77	0.25
Jicarilla 459 No. 5		
SE 1/4 sec. 19, T30N, R3W		
Upper Pictured Cliffs (Fig. 3)	0.02-0.11	0.05
Jicarilla 31-3-6 No. 2		
SW 1/4 sec. 6, T31N, R3W		
Sidewall core of upper Pictured Cliffs	-	0.035

As Brown (1973) stated, the Pictured Cliffs sandstones in the northeast part of the basin are difficult to recognize on wireline logs due to the effect of the shale and water bound to the shale. Indeed, the spontaneous potential and resistivity curves lack the configuration observed in the central producing area.

Cumulative production trends (Fig. 2) in the area also highlight the naturally fractured nature of the reservoir. The most productive Pictured Cliffs wells are located in central T30N, R4W (1.0 to 4.3 Bcf) and the southern portion of T29N, R3–4W (0.6 to 1.1 Bcf). Wells drilled offsetting these prolific wells are, in comparison, far less productive. Production tests in the southwestern part of T30N, R3W have indicated the possibility of communication between at least two wells, Bayless Jicarilla 464 No. 8 (SW1/4 sec. 29) and No. 2 (NW1/4 sec. 32). Since these wells were drilled in 1987–88 and have produced low gas volumes (77–320 mmcf), it is unlikely that communication in this low permeability reservoir could have been established without natural or mechanically induced fractures. Thus, if a good gas well is completed, close offsets may not be the best plan of development. In addition, the narrow trend of the more productive wells in T30N, R3W may indicate the presence of a naturally fractured area.

Numerous wireline parameters were mapped in T30N, R3W, in an attempt to correlate logs to production and possibly identify fractures. Wireline measurements will not positively identify effective natural fractures, but the best indicators are the neutron and density porosity curves. An advantage in T30N, R3W was the consistency of these data due to recent, similar log suites. Thus, these data can be easily normalized.

Density porosity isopachs for the net lower (Fig. 8) and net upper (Fig. 9) Pictured Cliffs illustrate that while the lower Pictured Cliffs pinches out in T30N, R3W, there is considerable porosity in the upper Pictured Cliffs. Well-site sample logs confirm that the best gas shows are in the upper interval. To locate the best areas, a cutoff of 14% porosity was applied to the upper Pictured Cliffs. This reveals a thick, porous sandstone buildup of low permeability that only partially correlates to the most productive wells. Since deflection of the neutron curve to low porosity values often signifies the presence of gas, an isopach of this deflection was constructed (not shown). This map removes much of the subjectivity of a neutron-density crossover isopach. A combination of the density porosity and neutron deflection highlights the most gas productive areas in T30N, R3W. Stratigraphy does not appear to play the most important role in the productivity of wells in T30N, R3W or in the entire study area. Rather, the wireline measurements are subtle indicators of enhanced productivity via natural fractures, and provide a measure to assist in the evaluation of new wells. Extension of these wireline trends may follow fracture permeability.

Fruitland coal

Numerous Fruitland coal seam gas wells have been drilled and completed over the past several years within the study area (Fig. 2). Most of this activity has occurred in T29–32N, R4W, with Nassau Resources, Meridian Oil, Parker and Parsley, and Falcon Seaboard being the main operators. Amoco (1984), Frontier Energy (1984), Southland Royalty (1987) and Bayless (1988) were the first to gather coal data from wells in this area.

Judging by the number of coal seam tests and the range of producibility of these tests, it is apparent that drilling for coal bed methane remains a statistical gamble. Since cleating is not pervasive, the key to commercial wells is in finding areas where cleating is preserved or in locating effective natural fractures. Neither of these options has been successfully executed in this area. In some instances calcite has filled or partially filled cleats. Extensive diagenesis has affected the intrusives and permeability of the underlying Pictured Cliffs, which would imply similar changes in the Fruitland. As previously discussed, a trend of highly gas-productive coal seam wells in east-central T32N, R4W, southward to prolific Pictured Cliffs producers in central T30N, R4W, suggests a naturally fractured zone. This trend parallels the orientation of the surface dikes.

Generally the area is hydrostatically underpressured and water production is moderate to low; usually less than 50 barrels per day. Vitrinite reflectance and proximate analysis data indicates a range of coal rank from medium volatile to high volatile B bituminous. Desorption analyses range from approximately 75 to 350 ft^3/ton, with the higher values generally in the north and west within the study area.

The effects of the intrusives on the producibility of the coals is

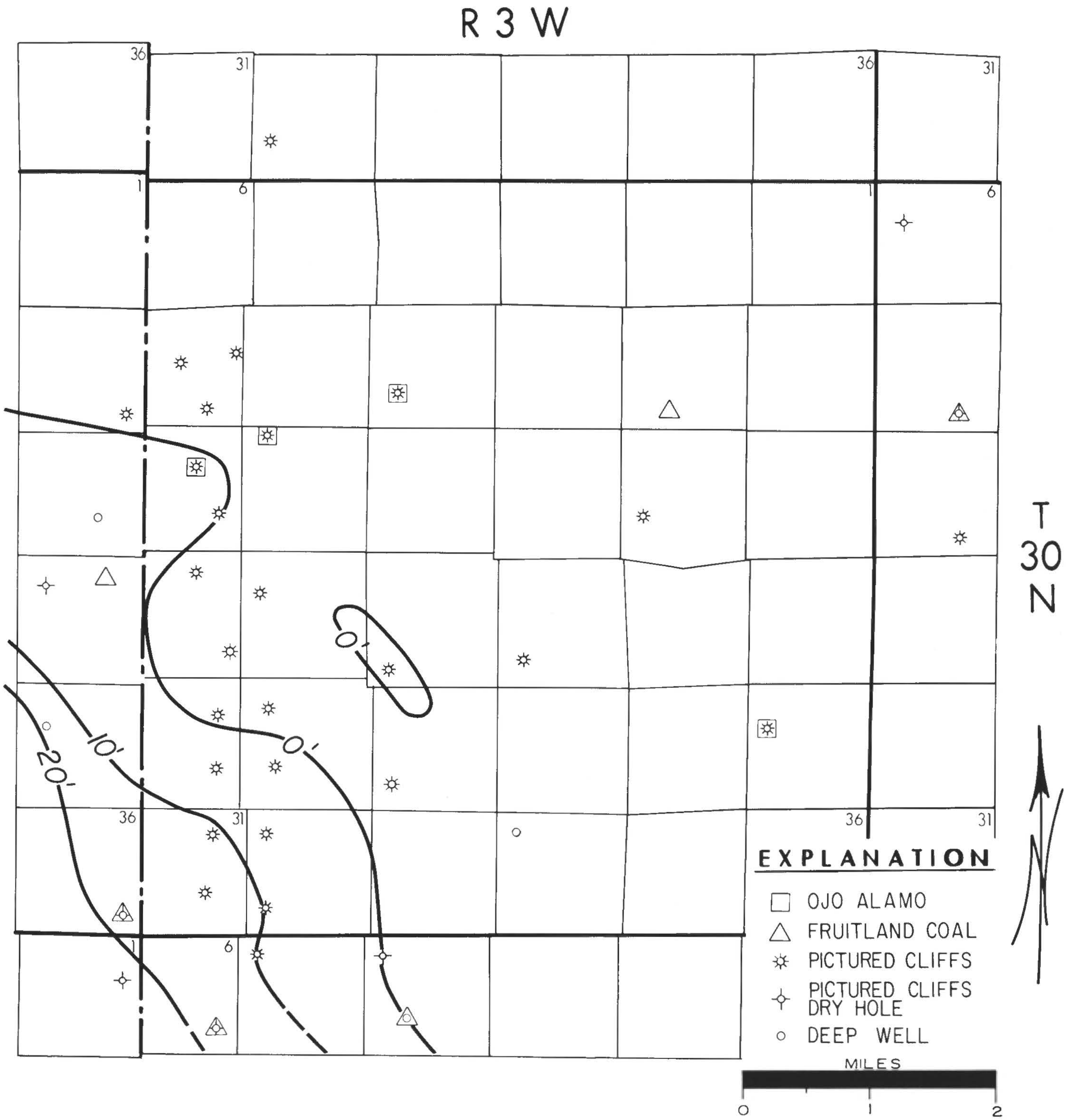

FIGURE 8. Isopach of lower Pictured Cliffs Sandstone, density porosity >10%, CI = 5 ft.

unknown. Well-site gas shows are always associated with the coal interval, even if the seam is totally intruded. To date, there have not been enough tests to fully evaluate the potential of the coal seams within the intruded area. Only two wells in T30N, R2–3W, and three wells in T31N, R4W, have been completed in zones in which intrusives are present. Data from the two productive wells (T30N, R2–3W) are not conclusive, due to long shut-in periods and lack of water disposal facilities. The other three wells have been completed, one with an initial potential of 1917 mcfd (NE1/4 sec. 26, T31N, R4W), but are not yet producing.

Ojo Alamo Sandstone

Four wells in T30N, R3W (Fig. 2), have been recompleted in the Ojo Alamo by Robert L. Bayless beginning in 1989. Prior to this activity, the Ojo Alamo had been considered an aquifer throughout much of the San Juan Basin. The discovery and confirmation wells were completed primarily as a result of interpretation of wireline logs and mudlogging shows by Bayless. The produced gas contains up to 7000 ppm (0.7%) hydrogen sulfide (H_2S), which differs from Cretaceous age reservoirs in the basin. Water is not produced in significant amounts.

The Ojo Alamo has a considerable thickness of neutron-density cross-

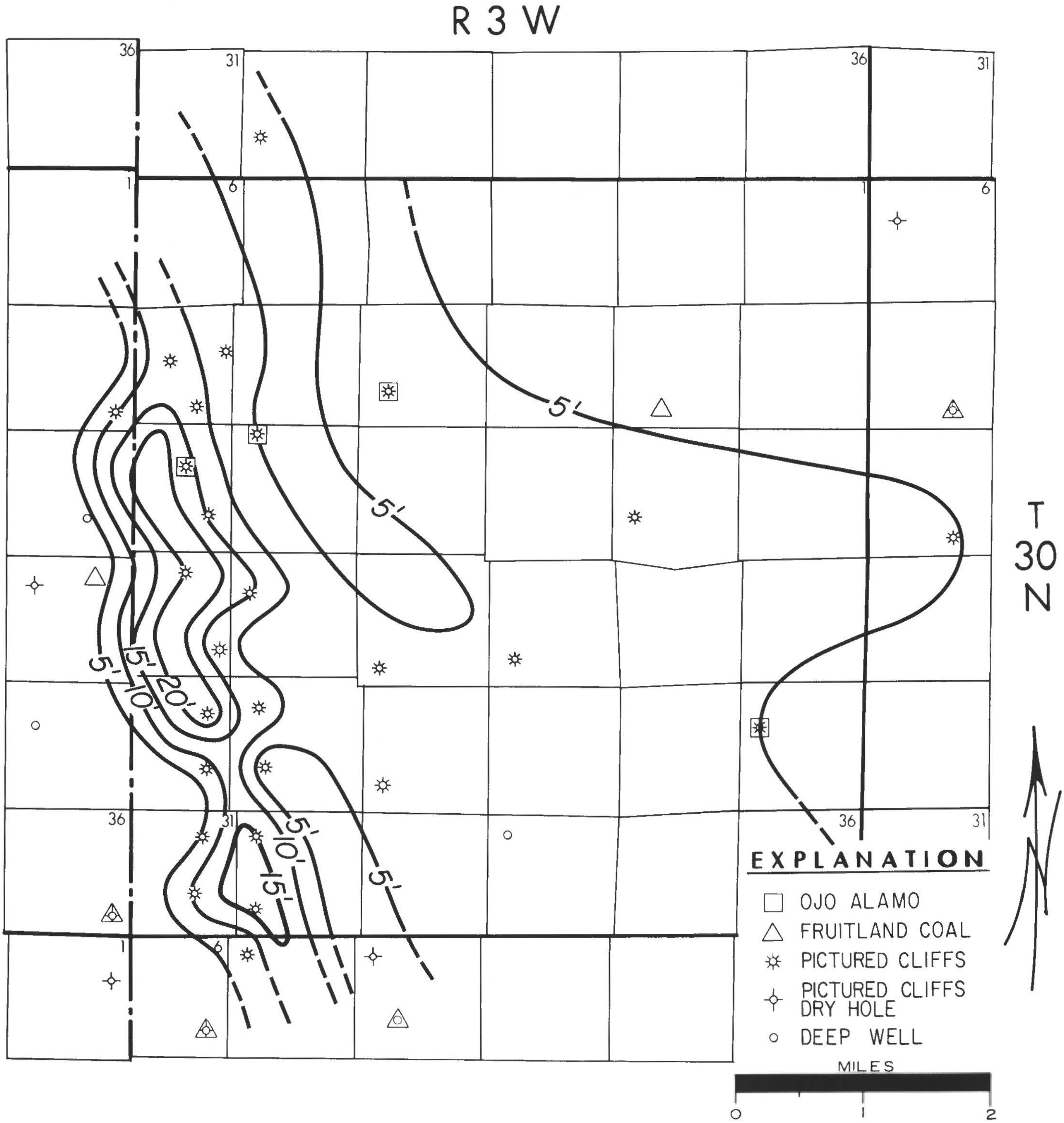

FIGURE 9. Isopach of upper Pictured Cliffs Sandstone, density porosity >14%, CI=5 ft.

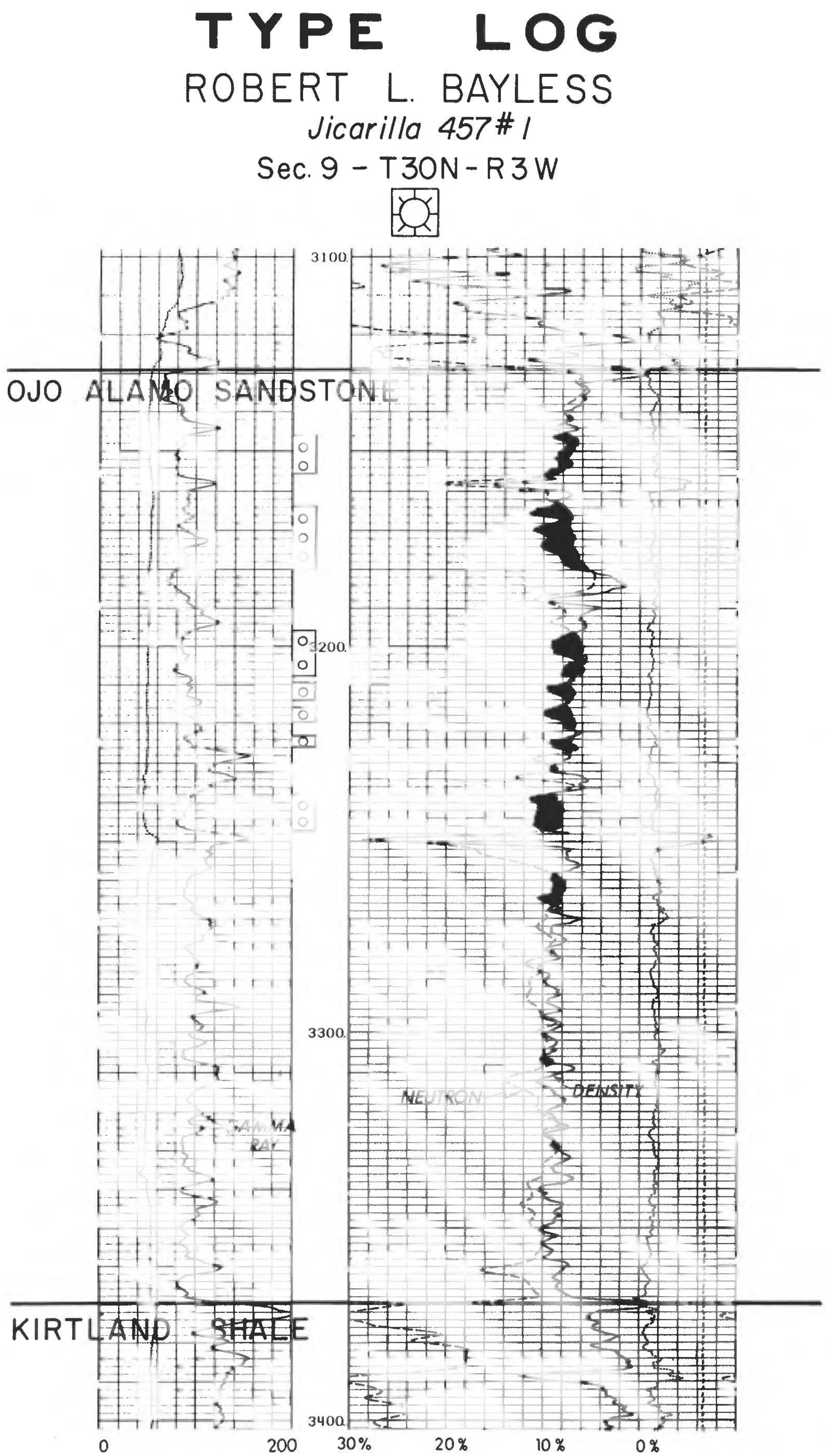

FIGURE 10. Type log of Ojo Alamo Sandstone. Note neutron-density porosity crossover. Perforated intervals are in upper portions of formation.

over usually within the upper portion of the formation (Fig. 10), indicating the possible presence of gas. Fig. 11 is an isopach of the crossover porosity "gas effect." In T30N, R3W, several well-site sample logs indicate that the gas shows correspond to crossover, high density porosity values, and high resistivity values on wireline logs. Thus, when used with caution, crossover on wireline logs is useful in outlining the potential gas producing area of the Ojo Alamo.

Outside of this area, the neutron-density curves tend to parallel each other, with infrequent minor crossover, indicating the probable presence of water. Numerous well-site sample logs in T29N, R4W, confirm the lack of gas shows in the Ojo Alamo. In the El Paso Sparks No. 1 (NE1/4 sec. 19, T30N, R4W), two DSTs conducted in 1952 over the Ojo Alamo each recovered over 1100 ft of sulfur water and no hydrocarbons.

Although the Ojo Alamo is present throughout the area, Fig. 12 illustrates that the porosity and probably the permeability are not. Rather, the porosity is located in distinct bands that may represent the main channel systems. Production testing of the Bayless Jicarilla 457 No. 1 (SW1/4 sec. 9) and the Jicarilla 459 No. 3 (NE1/4 sec. 18) indicate permeabilities of 0.2 millidarcies and 0.5 millidarcies respectively. Some

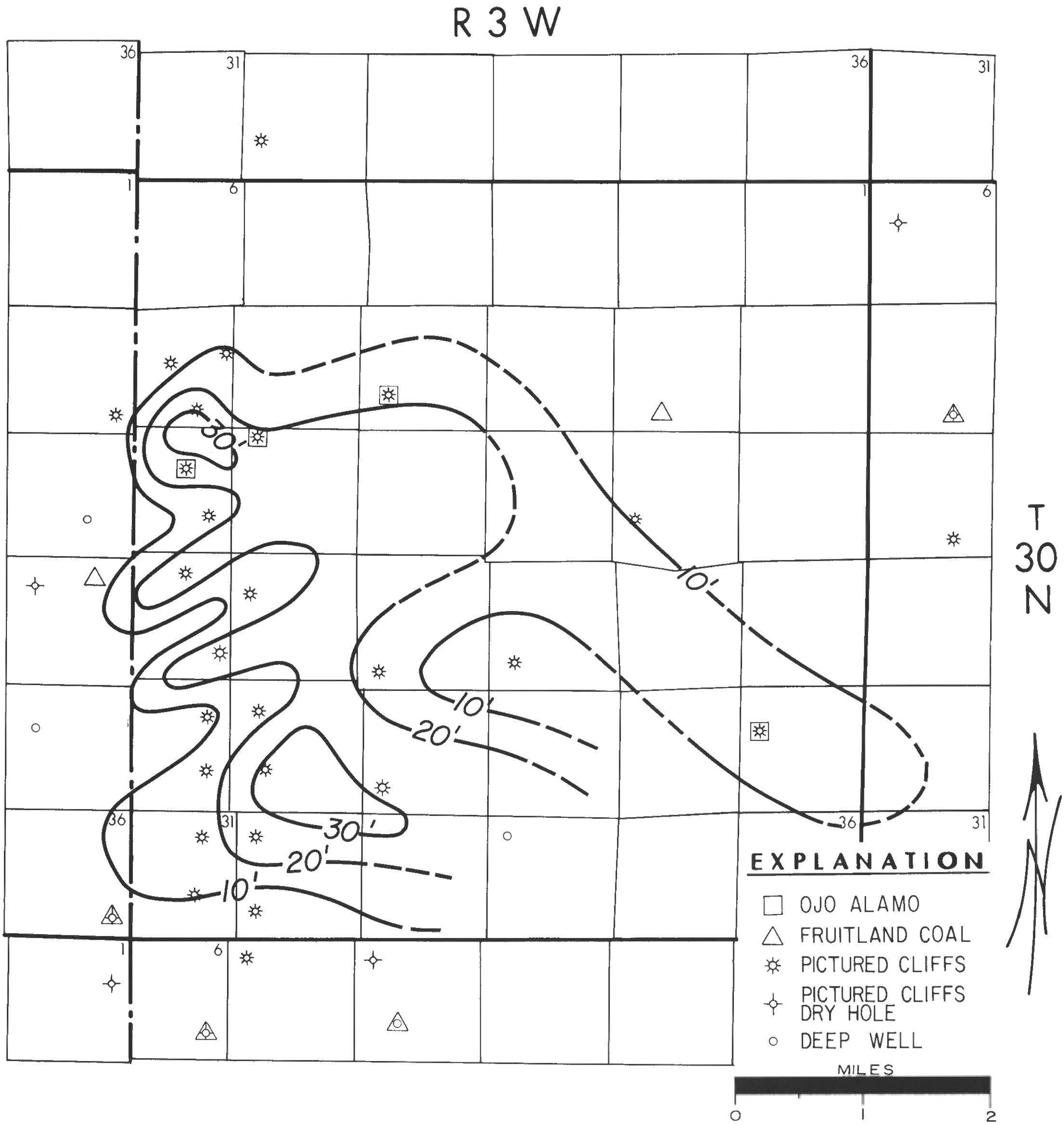

FIGURE 11. Isopach of Ojo Alamo Sandstone, neutron-density porosity crossover with density porosity >10%, CI = 10 ft.

discontinuity in the reservoir was also detected during the tests. Since both wells have only been perforated and acidized and are capable of producing between 100–250 mcfd, a permeable reservoir is present. However the other two wells, the Bayless Jicarilla 459 No. 8 (NW1/4 sec. 17) and the Jicarilla 463 No. 1 (NW1/4 sec. 25), have both been hydraulically fractured after poor production results were obtained after acidizing. These two wells are now capable of producing approximately 100 mcfd and 10 mcfd, respectively.

X-ray diffraction of samples from sidewall cores from the Bayless Jicarilla 31-3-6 No. 2 (SW1/4 sec. 6, T31N, R3W) reveal that the Ojo Alamo consists of approximately 50% quartz, 20–25% each of plagioclase and potassium feldspar, and 5% clay minerals. Illite (47%), chlorite (32%) and mixed layer clays (21%) are the major clay constituents. Thin section work was not performed, and thus textural information of the mineral constituents is unknown. The high percentage of feldspars indicates that the Ojo Alamo is fairly immature and has not been subjected to substantial chemical alteration.

The exact nature and configuration of the trap in unknown, but it is probably a combination of stratigraphic and structural factors. A large porosity trend in the Ojo Alamo is present over a low, broad anticline

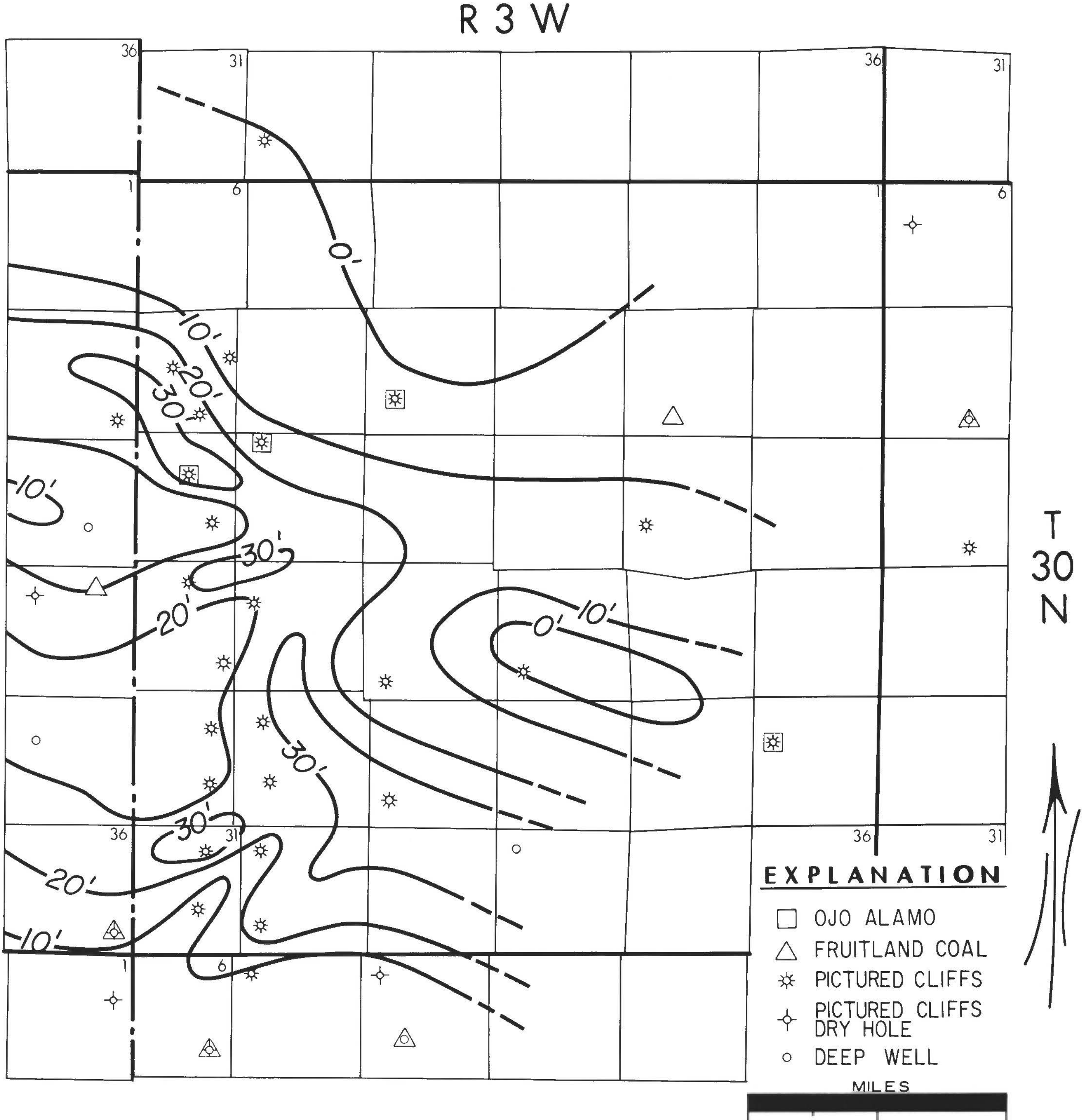

FIGURE 12. Isopach of Ojo Alamo Sandstone, density porosity >12%, CI = 10 ft.

covering much of T30N, R3W (Figs. 7, 12). This combination, together with a local gas source, probably controls the gas accumulation.

Gas analysis indicates methane content of 92–98%, ethane 4–6% and small percentages of more complex hydrocarbons through hexane. BTU content is 1080. Hydrogen sulfide (H_2S), a toxic and corrosive gas, is present in quantities of 1600 (0.16%) to 7000 ppm (0.7%). Each of the wells initially produced sweet gas, but became increasingly sour as greater volumes were produced.

The Jicarilla 457 No. 1 is currently producing with the H_2S removed by a sulfa-check system. Unfortunately, this system is not economic on the other wells. With large volumes of H_2S, an expensive amine plant and gathering system are necessary. At this time, gas prices do not justify this expenditure.

Except for the presence of H_2S, gas composition of the Ojo Alamo, Fruitland coal and Pictured Cliffs is similar. The nearest produced H_2S is from the Pennsylvanian carbonates at Ute Dome (Fig. 1) approximately 12 mi north-northwest of Farmington. The higher concentrations of H_2S in the Jicarilla 459 No. 3 (NE¼ sec. 18, T30N, R3W) may reflect the proximity of sulfur water to the west, such as the water encountered in the DST recovery of the Sparks No. 1 (NE¼ sec. 19, T30N, R4W).

The coincidence of gas in the Ojo Alamo, outcropping dikes, presence of intrusives in the Fruitland coal in the subsurface, and the presence of H_2S allows speculation as to the source of the Ojo Alamo gas. The obvious and most likely process is that igneous solutions intruded the area, heated and forced gas from the coal seams, which then migrated to the structural highs and porous zones of an overlying reservoir—the Ojo Alamo. The hot solutions could also have provided the H_2S; pyrite is common in the samples of the intrusives and coals.

Alternative sources of gas include the Fruitland coal, Lewis Shale, Mancos Shale, Pennsylvanian and older strata, and even more speculatively, the dike itself. The Tertiary, Kirtland and noncoal Fruitland intervals are not considered to be likely hydrocarbon source rocks. Perhaps the lack of porous reservoirs in the Pictured Cliffs and deeper Cretaceous sandstone intervals allows "spillover" to the Ojo Alamo. Unless T30N, R3W is a unique trap, then one might expect more widespread Ojo Alamo and other Tertiary sandstone gas accumulations to be present in this general area. Although unlikely, the Fruitland coal may have begun desorbing due to being underpressured (less overburden), and directly provided gas to the Ojo Alamo and/or to the outcrop. Again, more widespread accumulations in Tertiary sandstones are possible under this scenario.

CONCLUSIONS

The Pictured Cliffs Sandstone, in this study area, is dependent upon natural fractures for commercial gas production, due to extensive diagenetic changes having reduced primary permeability. Production from Fruitland coal seams is most likely also dependent on natural fractures. Numerous tests of the coal seams indicate that cleating is not widespread in the area. In some wells, calcite has been found in the cleat system, indicating diagenetic changes. Also, over a large area, the coal seams have been partially to totally intruded by a basalt-like rock. It is unknown whether the intrusive has affected the producibility of the coal. The coal seams are the most likely source of the methane present in the Ojo Alamo Sandstone. The Ojo Alamo produces from a primary porosity and permeability trend draped across an anticline. Accumulations of hydrocarbons in shallow zones, such as the Ojo Alamo and Fruitland coal, are easily overlooked as operators drill to traditional pay zones without evaluating other possibilities. It is likely that numerous faults and folds are located in the eastern part of the basin. These structures will have a direct effect on the strata's producibility.

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Aerial view of Kutz Canyon from an elevation of approximately 12,000 feet. Badlands here are developed in the Paleocene Nacimiento Formation. Location is south of the east and west forks of Kutz Canyon. Photograph taken morning of 13 April 1992. Copyright © Paul L. Sealey.