The Upper Mancos Shale in the San Juan Basin: Three plays, Conventional and Unconventional*

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Abstract

The Mancos Shale (Upper Cretaceous) covers approximately 12,000 mi^2 in the San Juan Basin of northwestern New Mexico and southwestern Colorado. From its outcrop belt around the flanks of the basin, the Mancos dips into the subsurface of the basin. The basin is structurally asymmetric with a gentle southern flank and a steep northern flank. Depth to the top of the Mancos exceeds 6500 ft. along the basin axis.

The Mancos is subdivided into two formations, the Upper Mancos Shale and the Lower Mancos Shale, which are separated by an unconformity. The Upper Mancos Shale has been productive of oil and natural gas from both conventional and unconventional reservoirs. The Upper Mancos Shale is 900 to 1600 ft. thick in the San Juan Basin. It is thinnest along the southwestern flank of the basin and gradually thickens to the northeast.

There are three plays in the Upper Mancos Shale: the *Tocito marine bar play*, the *Naturally fractured Mancos Shale play*, and the *Offshore Mancos Shale play*. The *Tocito marine bar play* is a conventional play productive of oil and associated gas from sandstones in the lowermost part of the Upper Mancos Shale. The reservoirs are northwest-southeast-trending shoestring sandstones on the southern flank of the basin; they were deposited offshore of and parallel to the paleoshoreline. Most of the reservoirs were discovered in the 1950's.

The *Naturally fractured Mancos Shale play* is a conventional play located along the southeastern and northwestern flanks of the basin. In these areas, Laramide tectonic uplift that formed the present-day basin outline initiated fracturing of the more brittle lithologies within the Upper Mancos Shale. The open fractures resulted in prolifically productive reservoirs that have been exploited by vertical wells.

The *Offshore Mancos Shale play* is located northeast of the Tocito marine bars. This is the modern unconventional play within the basin. This play extends northeast from the Tocito marine bars into the axial part of the basin. Almost all production and recent exploration is within the lowermost 400 ft of the Upper Mancos Shale (the Mancos C interval). Reservoir intervals are organic-rich marine shales with laminations and very thin beds of very fine-grained sandstones and siltstones. Percentage and thickness of sandstone beds decrease to the northeast with

increasing distance from the paleoshoreline. Current and recent exploratory wells have been drilled horizontally as well as vertically and stimulated with multi-stage hydraulic fracturing.

The Upper Mancos shales are both the source rocks and the reservoirs in the *Offshore Mancos Shale play*. Along the southwestern flank of the basin Upper Mancos shales are thermally immature. Peak oil generation was attained along a trend just northeast of the Tocito marine bar reservoirs. The transition from the oil window to the wet-gas window occurs 8 to 10 miles northeast of the Tocito marine bar reservoirs. The dry gas window is present in the northern part of the basin. Total organic carbon (TOC) content of Mancos C shales ranges from 0.5 to 3.2%. Oil-prone kerogens are dominant in the majority of samples.

Introduction

The San Juan Basin of northwestern New Mexico (Figure 1) has produced natural gas and oil since 1921. Production has been dominantly gas and natural gas liquids. Oil has been produced from relatively small reservoirs. Primary reservoirs have been Upper Cretaceous blanket sandstones with limited permeability and, beginning in the 1990's, Upper Cretaceous coal beds. Oil has been produced primarily from northwest-southeast-trending Tocito shallow marine to marginal-marine sandstones of Late Cretaceous age on the southwestern flank of the basin. These oil reservoirs pass northeast into marine Mancos shales. Mancos shales have produced large volumes of oil from naturally fractured reservoirs along the southeast and northwest flanks of the basin, where brittle, silty and sandy beds have open natural fractures, where upturned along the basin flanks. Scattered vertical wells have produced marginal and generally subeconomic volumes of oil from the Mancos Shale northeast of the main trends of Tocito Sandstone reservoirs. Interest in the Mancos has recently shifted from the conventional Tocito Sandstone reservoirs and the naturally fractured Mancos shales along the southeastern and northwestern basin flanks to Mancos shales located northeast of the Tocito Sandstone reservoirs. Although these shales may be naturally fractured, they do not have the dense network of open fractures that characterizes Mancos Shale reservoirs that have historically produced economic levels of oil from vertical wells on the southeastern and northwestern flanks of the basin. The area of interest is large and encompasses almost all of the Mancos northeast of the Tocito Sandstone trends. This is a summary paper that highlights the major points put forward in the oral presentation made at the 2015 West Texas Geological Society Annual Symposium.

Geologic Setting

The San Juan Basin of northwestern New Mexico (Figure 1) took its present shape as a result of compressive structural deformation during the Laramide (latest Cretaceous to Early Tertiary). During the Late Cretaceous before the basin took its present form, northwestern New Mexico was located on the southwestern edge of the Western Interior Seaway (Figure 2; Blakey, 2014). The Mancos Shale was deposited throughout much of this seaway. Emergent highlands to the southwest were the source areas for sands deposited as beaches, barrier islands, and offshore marine bars along the coastline. Temporally equivalent muddy marine strata to the northeast constitute the Mancos Shale.

Subsequent to deposition of the Mancos Shale and stratigraphically related Upper Cretaceous strata, Laramide compression turned much of the area now occupied by the Rocky Mountains into a series of Laramide-age basins in which Upper Cretaceous strata were preserved. Upper

Cretaceous strata were eroded from intervening uplifts. The San Juan Basin is one of those Laramide basins. Sonnenberg (2011) has identified several emerging unconventional oil plays in the Mancos Shale in Laramide basins of the Rocky Mountain region.

The San Juan Basin is a structurally asymmetric basin that straddles the New Mexico-Colorado border (Figure 3). It is bounded on its western, northeastern and eastern flanks by steeply dipping monoclines. On the west, the Hogback monocline separates the San Juan Basin from Four Corners Platform. To the north lies the San Juan Uplift, formed by the Tertiary-age volcanic rocks that constitute the San Juan Mountains of southwestern Colorado. To the northeast, the monocline is separated from the Chama Basin by the Gallina-Archuleta arch (Woodward et al., 1992). To the southeast, a high-angle reverse fault of Late Tertiary age separates the basin from the Nacimiento Mountains with their exposed Precambrian core. On the south, Cretaceous and older strata gently rise out of the San Juan Basin onto the Chaco Slope. South of the Chaco Slope lies the exposed Precambrian core of the Zuni Mountains. Figure 3 illustrates the structural asymmetry of the basin, with the Mancos Shale and other strata dipping gently into the basin on the Chaco Slope, reaching the deep structural axis of the basin just south of the New Mexico-Colorado border, and then rising steeply to the outcrop in southernmost Colorado.

Mancos Shale Stratigraphy

The Mancos Shale in the San Juan Basin is underlain by the Dakota Sandstone (Upper Cretaceous) and overlain by the Point Lookout Sandstone (Upper Cretaceous; Figures 4 and 5).

Both the Dakota Sandstone and the Point Lookout Sandstone have been prolifically productive of natural gas since the 1950's and constitute two of the most productive stratigraphic units in the basin (Deischl, 1973; Pritchard, 1973; Whitehead, 1993a, 1993b; Fassett and Boyce, 2005). With the exception of a few oil reservoirs that have produced oil from fractures, the Mancos has historically been a minor contributor to production in the basin and has been viewed primarily as the major source rock in the basin as well as a seal for underlying and intertonguing sandstone reservoirs.

The Mancos Shale in the San Juan Basin is subdivided formally into two separate formations, the Lower Mancos Shale and the Upper Mancos Shale (Dane, 1960; Lamb, 1968; O'Sullivan et al., 1972; Molenaar, 1977a; Figures 4 and 5). The Upper and the Lower Mancos shales are thought by most geologists to be separated by a regional unconformity, known as the basal Niobrara unconformity (Dane 1960; Pentilla, 1964; McPeek, 1965; Molenaar, 1973, 1977a; Molenaar and Baird, 1992; Ridgely et al, 2013). Both units exhibit intertonguing of more proximal sandy sedimentary deposits in the southwest with more distal, marine mudstone deposits in the northeast.

Lower Mancos Shale

The Lower Mancos Shale consists of five members (Lamb, 1968, 1973; O'Sullivan et al., 1972; ascending): Graneros Shale Member, Greenhorn Limestone Member, Lower Carlile Shale Member, Juana Lopez Member, and Upper Carlile Shale Member. All were deposited in marine environments. The Upper and Lower Carlile Shale members are informal designations. Other workers (e.g., Molenaar and Baird, 1992; Ridgley et al., 2013) leave the strata between the Greenhorn and the Juana Lopez (the Lower Carlile Shale Member) and the strata between the

Juana Lopez and the top of the Lower Mancos Shale (the Upper Carlile Shale Member) unnamed. The terms “Upper and Lower Carlile Shale members” of Lamb (1968) are used in this paper because this usage allows convenient and exact reference to these strata for purposes of lithologic, stratigraphic, source rock, and production description.

Graneros Shale Member

The basal Graneros Shale Member consists of marine shale. The lower part of the Graneros intertongues with the underlying Dakota Sandstone. The kerogen-rich, dark gray shales in the lower part of the Graneros grade upward into lighter-gray calcareous shales which, in turn, grade upward into the overlying Greenhorn Limestone (Lamb, 1968, 1973).

Greenhorn Limestone Member

The Greenhorn Limestone Member is not a true limestone in most of the San Juan Basin. Rather, it consists of calcareous shale and thin beds of argillaceous limestone (Lamb, 1968; Molenaar, 1977a). To the northeast where the Greenhorn crops out on the basin flank near Pagosa Springs, Colorado, it consists of 14 ft of thickly bedded limestone and minor shale (Lamb, 1973). The Greenhorn is easily recognized and correlated in the subsurface by the high resistivity and low gamma-ray signature on well logs. In general, it is 40 to 60 ft thick in the San Juan Basin. To the far southwest, the Greenhorn is 20 to 24 ft. The Greenhorn is locally as thick as 7 ft. It is likely that the limestone facies identified by Lamb (1968) in the Pagosa Springs outcrops represents only a part of the Greenhorn as recognized by well logs throughout the subsurface of the basin. The Greenhorn marks the maximum transgression of the Late Cretaceous interior sea (Eicher, 1969; Blakey, 2014). Molenaar and Baird (1992) refer to the Greenhorn as the Bridge Creek Limestone Member.

Lower Carlile Shale Member

The Lower Carlile Shale Member conformably overlies the Greenhorn Limestone. Calcareous in its lower part, it grades upward into a dark gray, kerogen-rich marine shale, and from there grades upward into the overlying Juana Lopez Member of the Lower Mancos Shale. In places, the Lower Carlile Shale contains marine siltstone and fine-grained sandstone beds in its upper part. The Lower Carlile Shale is 100 to 250 ft thick in the San Juan Basin. In general the Lower Carlile Shale appears to thin to less than 200 ft to the east and northeast.

Juana Lopez Member

The Juana Lopez Member of the Lower Mancos Shale gradationally overlies the Lower Carlile Shale Member. It is composed of thinly bedded calcarenite, dark gray marine shale, and minor very fine-grained marine sandstone (Dane et al., 1966). The Juana Lopez is conformably overlain by the Upper Carlile Shale Member. The Juana Lopez has also been referred to as the Sanostee (or Sanastee) Member by numerous workers, but the term “Juana Lopez” has priority of usage (Bozanic, 1955).

The Juana Lopez is 100 to 150 ft thick throughout most of the San Juan Basin. It is less than 100 ft thick in places where the overlying Upper Carlile Shale was removed by erosion that accompanied formation of the basal Niobrara unconformity.

Upper Carlile Shale Member

The Upper Carlile Shale Member is composed of very dark gray, silty, marine shale. Where the Gallup Sandstone (see discussion in next paragraph) is present in the southern part of the basin, it gradationally overlies the Upper Carlile and also laterally interfingers with it. Farther north, the Gallup Sandstone and temporally equivalent marine-ward strata have been removed by erosion associated with the basal Niobrara unconformity. In these areas, the Upper Carlile is unconformably overlain by the Upper Mancos Shale (see Figure 6; Dane, 1960; Molenaar, 1973). As a consequence of the significant erosion that occurred in some places during formation of the unconformity, the Upper Carlile has been incised in places and completely removed in other places so that the Upper Mancos Shale rests on the Juana Lopez Member. Therefore, the Upper Carlile exhibits the largest thickness variations of any of the five members of the Lower Mancos Shale. It is typically 100 to 250 ft thick and thins to the northeast. In the southeastern part of the basin, the Upper Carlile attains thicknesses of 300 to 350. Where its uppermost part has been preserved, it contains thin sandstone beds interbedded with the dark gray shales (see Lamb, 1968).

Gallup Sandstone

The Gallup Sandstone consists of a pair of regressive fluvial to shoreface sandstone wedges in the southwestern part of the basin that intertongue to the northeast with the Lower Carlile Shale, the Juana Lopez Member, and the Upper Carlile Shale (see Molenaar, 1973, 1977a, b). The upper wedge gradationally and conformably overlaps the Upper Carlile Shale. The Gallup Sandstone is present only in the southwestern part of the basin (Figure 6; [Figure 7 for location]), having been removed in the northeastern part of the basin by erosion associated with formation of the basal Niobrara unconformity. In the southwestern part of the basin, the Gallup attains a maximum thickness of approximately 300 ft. Where present, it is a major fresh-water aquifer but only a minor oil reservoir.

Upper Mancos Shale

The Upper Mancos Shale unconformably overlies the Lower Mancos Shale throughout the San Juan Basin, except for areas where the Gallup Sandstone is present. It consists predominantly of dark gray, kerogen-rich marine shale with interbedded marine siltstones and fine-grained sandstones. The Upper Mancos Shale is 900 to 1550 ft thick in the San Juan Basin. It is thinnest in the southwest and thickens gradually to the northeast toward the basin depocenter.

The sandstones are concentrated in the lower parts of the Niobrara Shale of the Upper Mancos Shale. Along the southwest flank of the basin, the sandstones are present in lentils generally 10 to 20 ft thick that are elongated northwest-southeast. These are referred to as Tocito sandstones or as lower Niobrara sandstones. The Tocito sandstones were formed by offshore marine-bar complexes elongate parallel to the paleoshoreline as well as barrier islands. These sandstone lentils have historically provided most of the oil produced from the San Juan Basin.

Terminology employed for the lower part of the Upper Mancos Shale (also known as the Niobrara Shale) and the marine sandstones is contradictory. In many cases, the prevailing usage is stratigraphically incorrect. Before Dane (1960) documented the regional basal Niobrara unconformity between the Lower Mancos Shale and the Upper Mancos Shale, it was thought that the Carlile to Niobrara sequence was conformable and that the marine bar reservoirs in the lower part of the Upper Mancos were distal stratigraphic equivalents of the Gallup

Sandstone. They were therefore assigned the name of Gallup, and the names of oil reservoirs were assigned the name of Gallup (e.g., Budd, 1957; Silver, 1957). The term "Gallup" became embedded in the geologic and regulatory literature for the offshore marine bar reservoirs which are clearly post-Gallup in age and are separated from the "true" Gallup Sandstone by the basal Niobrara unconformity. However, after publication of Dane's (1960) work, it quickly became recognized that the term "Gallup" is incorrect for these reservoirs. The offshore bar reservoirs are more correctly referred to as "lower Niobrara sandstones" or "Tocito Sandstone lentils" (Lamb, 1973; Molenaar, 1973). Fassett and Jentgen (1978) recommended that these sandstone bodies be named "beds of the Tocito". This confusion rendered by incorrect use of Gallup terminology continues to this day with much of the current exploratory targets referred to as Gallup rather than the correct term of Upper Mancos.

For this project, the Upper Mancos Shale has been subdivided into three stratal units informally designated as Mancos A, Mancos B and C (descending; Figures 6 and 8 [Figure 7 for location]). The subdivisions are defined on the basis of prominent, laterally continuous markers on gamma-ray and resistivity logs. These markers relate primarily to sand and silt content in the shale section but also possibly to carbonate content. The Mancos C unit is 75 to 470 ft thick. It is thinnest in the southeast and thickens to the northwest. The overlying Mancos B unit is 120 to 570 ft thick. It is thinnest in the southwest and generally thickens to the east and north. The Mancos A unit is 324 to 1022 ft thick. The Mancos A is thinnest in the southwestern part of the basin and thickens to the northeast toward the basin depositional axis.

Along the southwest flank of the basin, the Mancos C contains the historically productive Tocito Sandstone reservoirs as well as stratigraphically equivalent shales and thinner sandstones that historically have yielded no production or only subeconomic production. These Tocito Sandstone reservoirs occur within lower part of the Mancos C unit. Detailed examination of the Mancos C reveals numerous internal pinchouts, especially as related to onlapping on the irregular surface formed by the basal Niobrara unconformity. It should be noted that the tops of both the Mancos B and the Mancos C have been referred to as the top of the "Gallup" on scout cards and completion reports of wells drilled in the San Juan Basin. Other sandstone markers in the Mancos B and C units have also been referred to as the top of the "Gallup". These disparate "Gallup" tops appear on scout cards (see Molenaar, 1974, for further discussion). Thus correlation of the top of this "false Gallup" varies considerably from worker to worker although the prominent resistivity-log marker that is the top of the Mancos C appears to form the most common pick for the top of the false Gallup. Isopach and structure contour maps, as well as cross sections, made on the basis of scout card tops of the "Gallup," will incorporate correlations of different stratal surfaces and therefore result in contour maps that have no connection to any geological reality.

El Vado Sandstone Member

The El Vado Sandstone Member of the Mancos Shale (Landis and Dane, 1967; Fassett and Jentgen, 1978; Figure 5) lies higher in the stratigraphic section than the lower Niobrara sandstones. The El Vado consists of thinly interbedded, very fine-grained sandstones, siltstones and medium-gray, organic-rich marine shales. It was deposited in storm-influenced shelf and lower-shoreface environments (Wood and Hedayati, 2012). The El Vado, as defined by Fassett and Jentgen (1978), constitutes the lower part of the Mancos B and upper and middle parts of the Mancos C units, as defined in this paper (Figure 5). The El Vado, as recognized by Fassett and Jentgen, encompasses a greater part of the stratigraphic section than the El Vado, recognized by Landis and Dane (1967), Wood and Hedayati (2012), and Ridgley and others (2013), all of whom use different definitions for the El Vado.

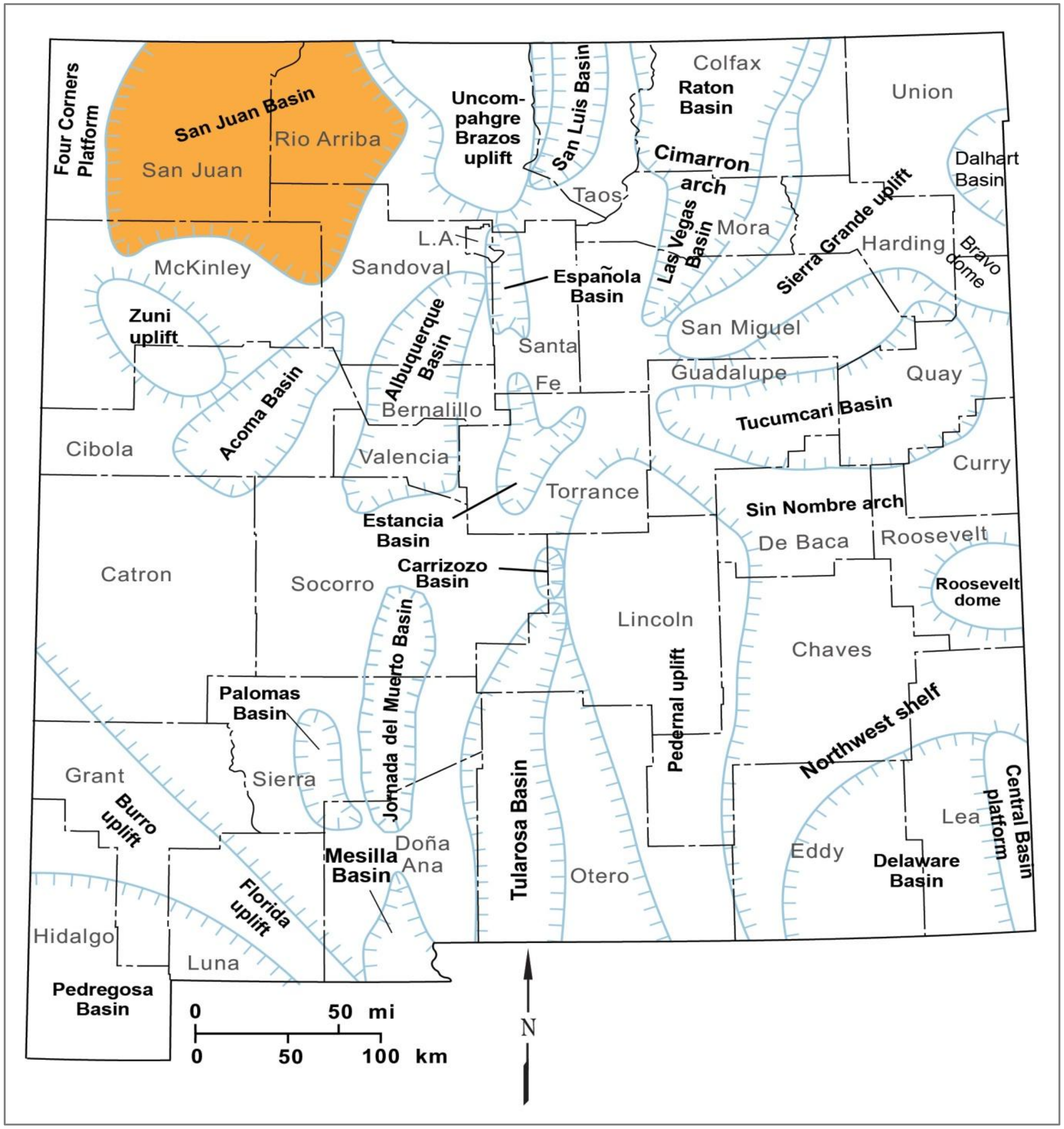

Figure 1. Location of San Juan Basin in New Mexico.

Figure 2. Location of Cretaceous Western Interior Seaway (from Cobban and McKinney, U.S. Geological Survey).

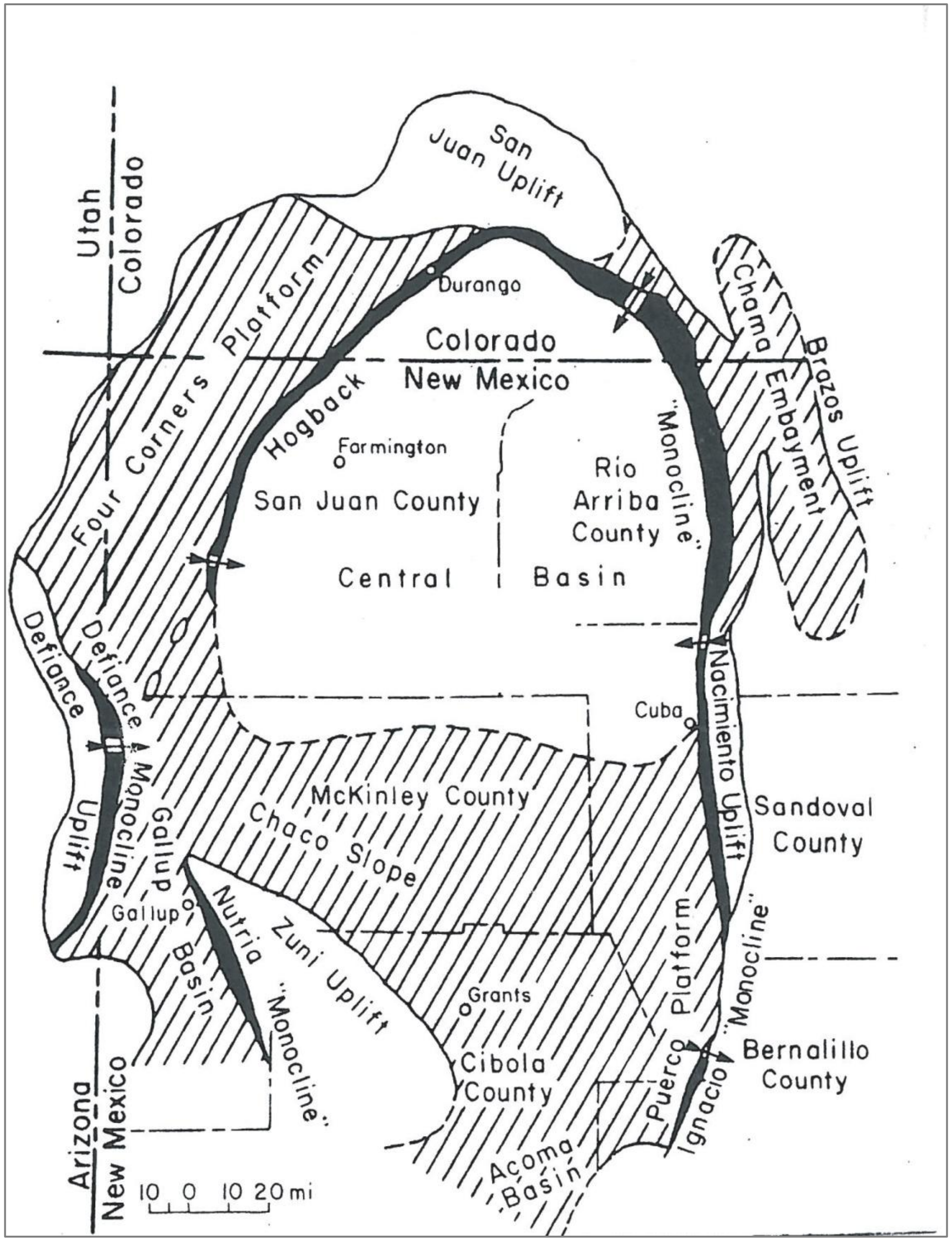

Figure 3. Tectonic map of San Juan Basin (from Stone et al. 1983).

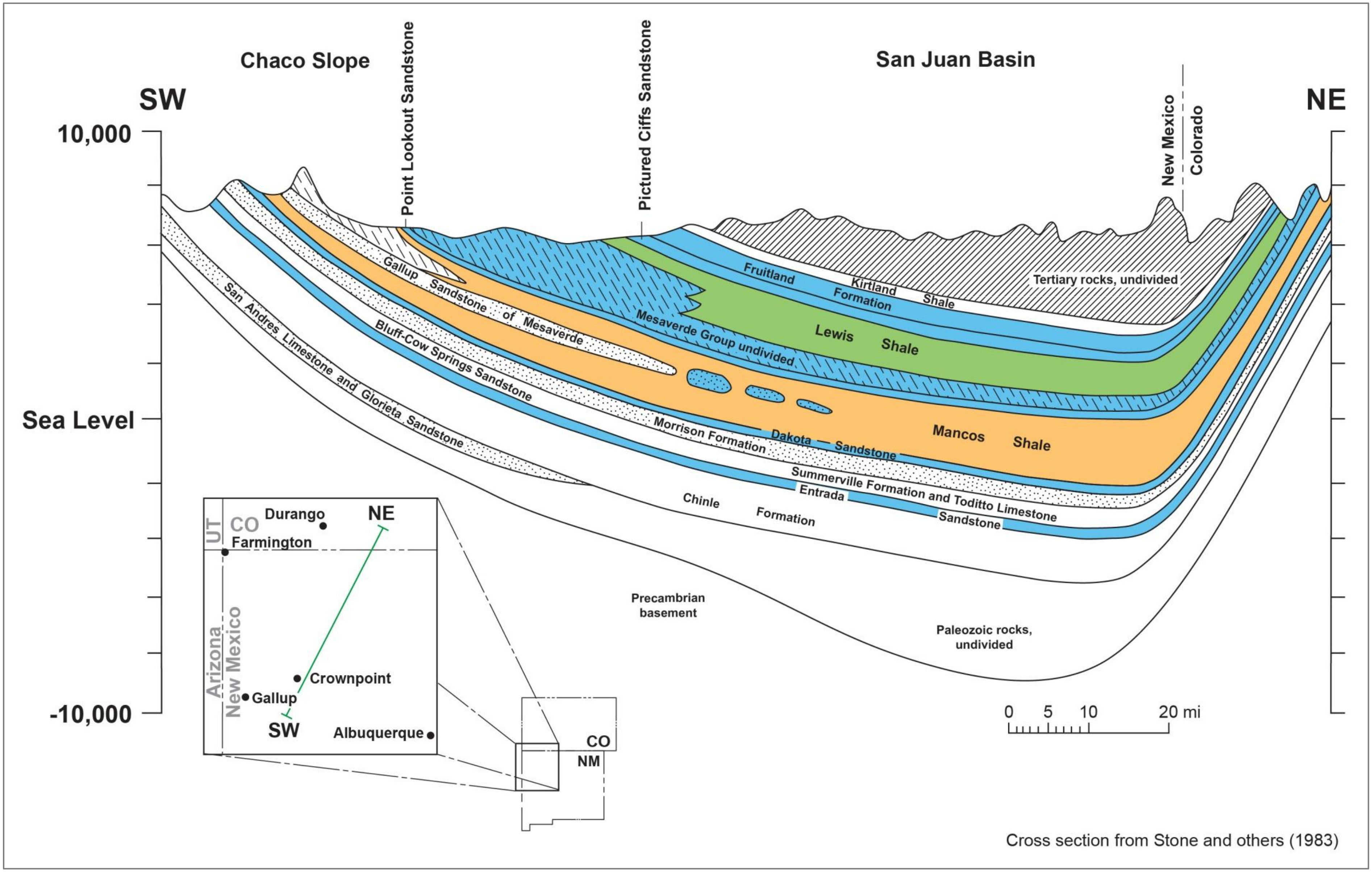

Figure 4. Southwest-northeast structural cross section through San Juan Basin. Mancos Shale is shown in orange. Major productive non-Mancos strata are blue. Modified from Stone et al. (1983).

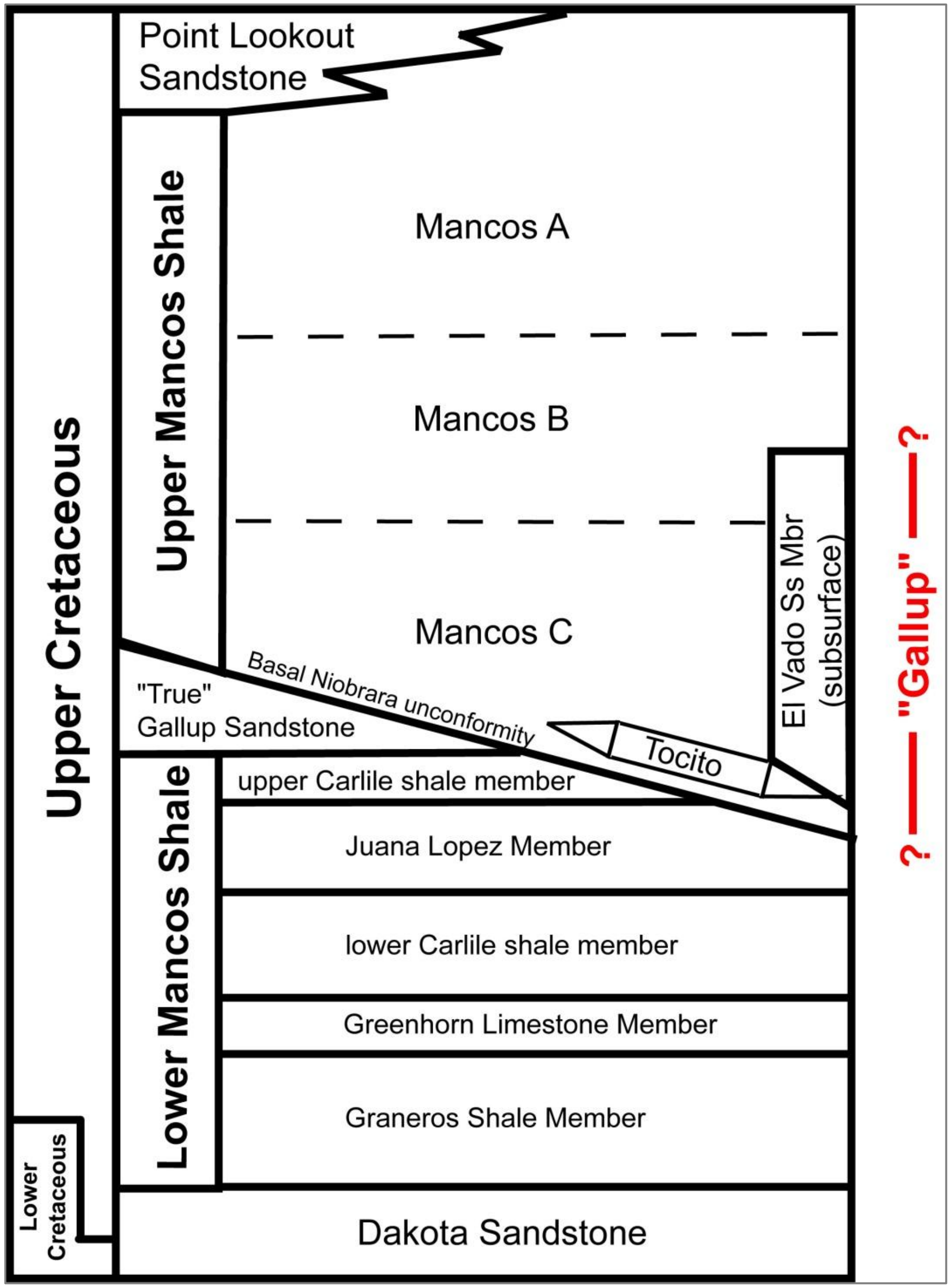

Figure 5. Stratigraphic column of Mancos Shale in San Juan Basin.

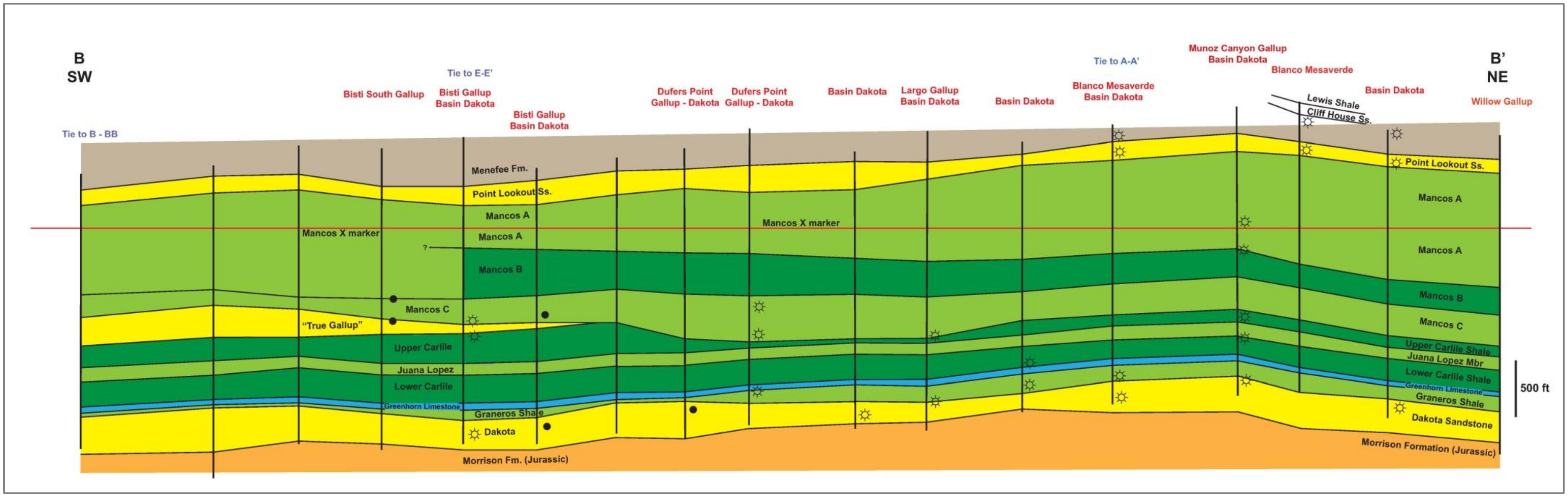

Figure 6. Stratigraphic cross section B-B'. Datum is a prominent log marker (Mancos X marker) in the Mancos A unit. Many of the wells are productive from conventional oil and gas pools, the names of which are shown in red above the wells. See Figure 7 for location.

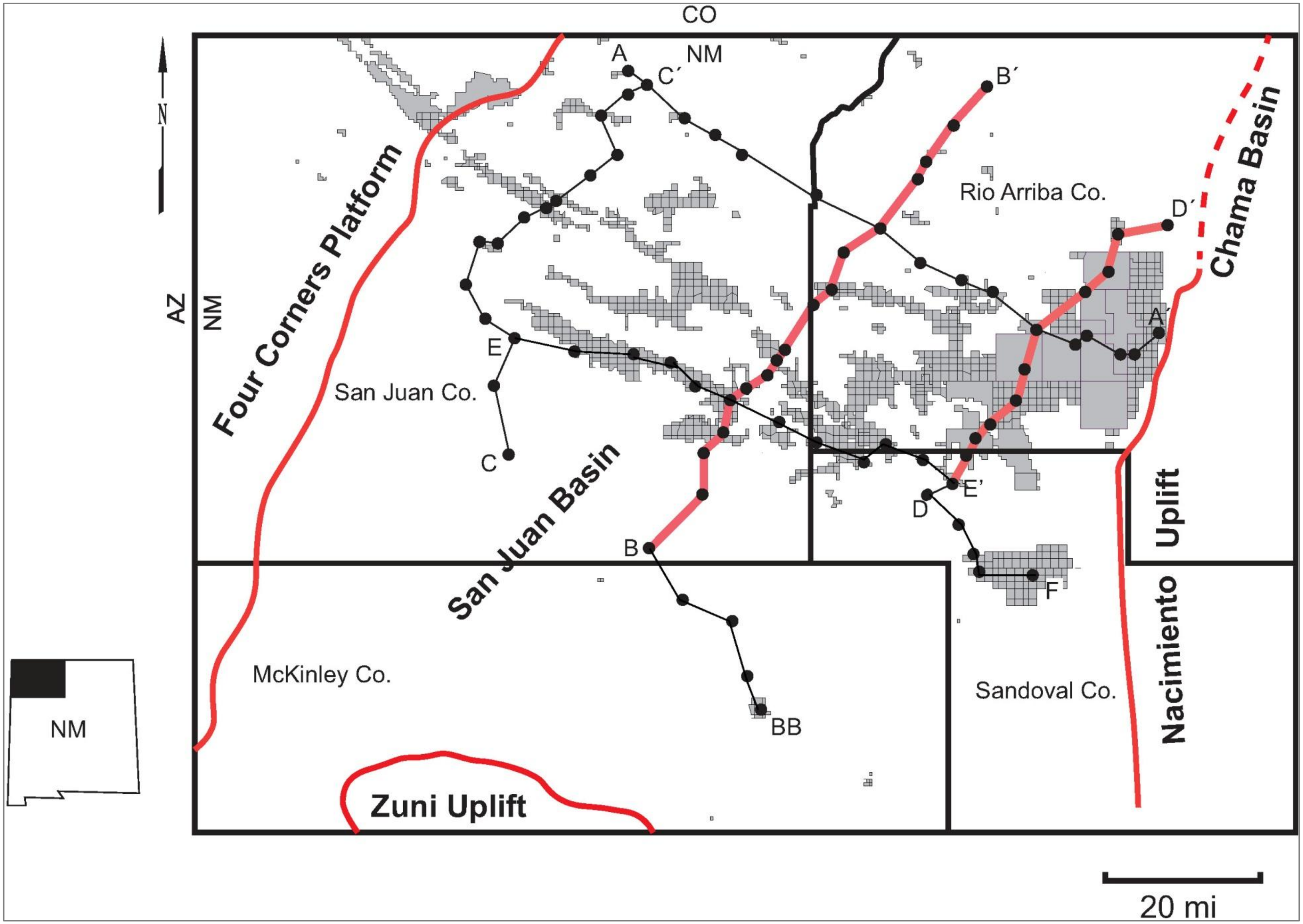

Figure 7. Reservoirs productive from the Upper Mancos Shale and Tocito sandstones and locations of cross sections B-B' (Figure 6) and D-D' (Figure 8).

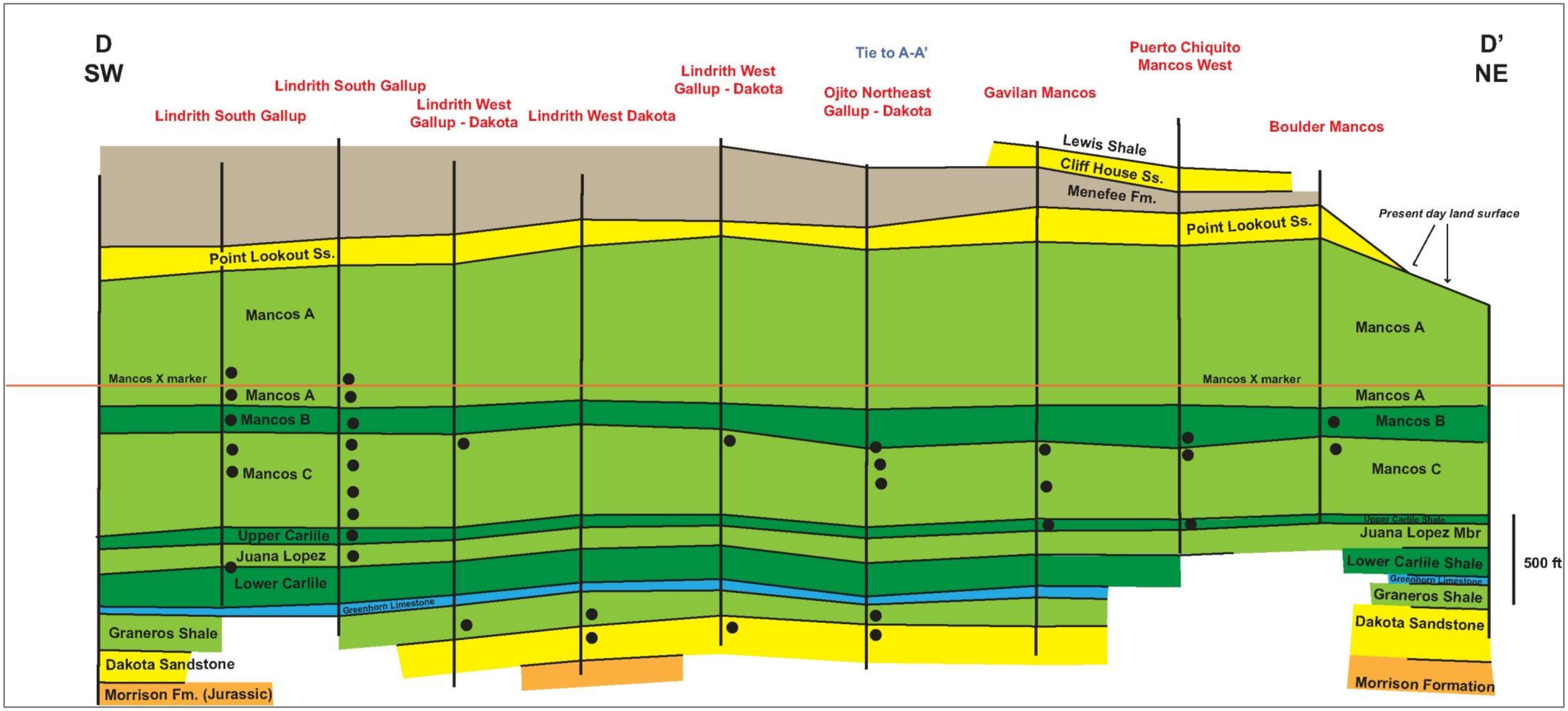

Figure 8. Stratigraphic cross section D-D'. Datum is a prominent log marker (Mancos X marker) in the Mancos A unit. Many of the wells are productive from conventional oil and gas pools, the names of which are shown in red above the wells. See Figure 7 for location.

Mancos Shale Plays

Productive reservoirs in the Upper Mancos Shale can be grouped into three plays (Figure 9) on the basis of reservoir lithology, internal Mancos stratigraphy, and the extent of natural fracturing of the reservoir. The first play, the *Tocito marine bar play*, consists of Tocito ("false Gallup") sandstones that form northwest-southeast-trending shoestring-shaped reservoirs along the south flank of the basin. The second play, the *Naturally fractured Mancos Shale play*, consists of naturally fractured Mancos shales along the southeast and northwest flanks of the basin. The third play, the *Offshore Mancos Shale play*, consists of marine Mancos shales and thinly interbedded and interlaminated fine-grained sandstones deposited farther offshore (northeast) of the barrier bar sandstones of the first play. The first and second plays are mature and have provided almost all of the historical production from the Mancos Shale. They are conventional oil plays. The third play has historically provided generally marginal and subeconomic production. It is an unconventional oil play that has recently emerged as the target of intensive exploration and drilling, primarily by both extended-reach horizontal exploration wells and by vertical exploration wells that are completed in multiple pay zones within the Upper Mancos Shale and the Lower Mancos Shale. The geology of the first two, conventional plays is summarized below. The geology of the *Offshore Mancos Shale play* is discussed in somewhat more detail because of the recent and ongoing exploratory interest and because it holds promise for significant future oil and natural gas production in the San Juan Basin. To some extent, the three plays form a continuum and merge into each other with some productive areas having characteristics of two or even all three plays.

Although outside the main emphasis of this paper, it should be mentioned that the Lower Mancos Shale has been productive of natural gas and oil in the San Juan Basin. Perforated intervals in Dakota natural gas wells in the Basin Dakota field commonly extend upward into the Graneros Shale and the Greenhorn Limestone. Production from the Greenhorn and Graneros is commingled in these wells, with production from the Dakota predominating in most wells. The Lower Carlile Shale, Juana Lopez Member, and Upper Carlile Shale are calcareous and are fractured on structures; oil accumulations are thought to have formed in the fractured areas (Emmendorfer, 1997).

Tocito Marine Bar Play

The *Tocito marine bar play* consists of northwest-southeast-trending shoestring sandstone reservoirs in the lower part of the Mancos C unit (Figures 9 and 10; Molenaar, 1973). The elongate linear nature of these sandstone bodies are mimicked by the shape of the oil pools that they form. Some of the pools in this play are formed by multiple shoestring sandstone bodies that are parallel to each other and overlap each other (e.g., Sabins, 1963). The marine bars were deposited offshore of and parallel to the Late Cretaceous shoreline.

Most of the reservoirs in this play were discovered in the 1950's. They have produced oil and associated gas. Peak production has long-since passed. Some of the sandstones rest on the basal Niobrara unconformity (McCubbin, 1969; Sabins, 1972; Pentilla, 1964; Molenaar, 1973). However, several reservoirs such as Bisti (Sabins, 1963, 1972) occur higher in the section and do not rest directly on the basal Niobrara unconformity. Kerogen-rich Mancos shales encase and seal the sandstone reservoirs and are also the source rocks for the oil and gas found in these reservoirs. Although most of the Mancos shales appear to have been deposited in an open-marine environment, the shales to the landward (northwest) side of some of the sandstones contain a restricted marine fauna and were deposited in a restricted marine, lagoonal environment (Sabins, 1972). These sandstones may have been deposited as emergent bars or barrier islands. Other sandstones have stratigraphically equivalent shales with open-marine fauna to the landward (southwest) side and were, therefore, deposited as submerged offshore sand buildups.

Exact depositional mechanisms are poorly understood, but sand distribution may have involved hyperpycnal turbidites. Most of the reservoirs are 10 to 20 ft thick and are readily detected on gamma-ray, S.P., and resistivity logs (Figure 10 [Figure 11 for location]).

Naturally Fractured Mancos Shale Play

The *Naturally fractured Mancos Shale play* is present along the southeastern and northwestern flanks of the San Juan Basin (Figure 9). In these areas, Laramide tectonic uplift that helped form the present-day basin outline steeply turned Cretaceous strata upward on the basin-bounding monoclines and acted to initiate fracturing of the more brittle lithologies within the Upper Mancos Shale. The more brittle strata contain dolomitic siltstones and very fine-grained sandstones interbedded with laminated marine shales (London, 1972; Greer and Ellis, 1991). These sediments were deposited farther offshore (northeast) than the sandstone reservoirs of the *Tocito marine bar play*. The interbedded shales are largely siltstone and sandstone free, contain less carbonate than the fractured siltstones and sandstones, and remain unfractured, thereby providing the seals for the fractured shales.

The two types of strata, fractured shales and unfractured shales, can be distinguished on well logs. The fractured carbonate-rich shales with sandstone and siltstone laminae have lower gamma-ray responses and higher resistivity responses than the interlayered carbonate-poor shales with relatively sparse laminae of siltstone and very fine-grained sandstone (Greer and Ellis, 1991). The major reservoirs along the eastern margin of the basin (Figure 9) are the East and West Puerto Chiquito Mancos pools (discovered in 1960 and 1962, respectively; Mallory, 1977; Greer 1978 a, b; Greer and Ellis, 1991), the Boulder Mancos pool (discovered in 1961; Needham, 1978; Carlstrom, 1997), and the Rio Puerco Mancos pool (discovered in 1981 as the San Ysidro Mancos pool; Chittum, 1983, 1985). The Verde (discovered in 1955; Speer, 1957; Mallory, 1977; Riggs, 1978) and La Plata (discovered in 1959; Greer, 1978c) pools are the major reservoirs along the western margin of the basin. At Puerto Chiquito, the production mechanism is primarily gravity drainage with a solution-gas drive assist. In the interior of the basin, the Mancos is locally fractured from drape of Mancos strata over basement faults, as at the Rio Puerco reservoir, but these reservoirs are included in the *Offshore Mancos Shale play*, as the production volumes are significantly less than in the *Naturally fractured Mancos Shale play* (Chittum, 1985)There is a continuum between the *Naturally fractured Mancos Shale play* and the *Offshore Mancos Shale play* with the natural fractures becoming less pervasive as one moves farther into the basin interior from the basin boundaries.

Offshore Mancos Shale Play

The *Offshore Mancos Shale play* is located northeast of the *Tocito marine bar play*. The Mancos in this area was deposited basinward (“farther offshore”) than the Tocito marine bars. Reservoir lithology is generally similar to what is found in the *Naturally fractured Mancos Shale play*, except that natural fractures, if present, are more widely disseminated and perhaps are not open, although they may provide preferential conduits of travel for fluids used to create artificial fractures. The *Offshore Mancos Shale play* is present across the Chaco Slope and extends northward into the gently dipping south flank of the basin. Along the Chaco slope, sandstones are finer grained and more thinly bedded than they are in the *Tocito marine bar play*. There appears to be a lateral gradation from the Tocito marine bars into the shales of the *Offshore Mancos Shale play*. In general, the percentage and thickness of sandstone beds decrease to the northeast with increasing distance from the paleoshoreline and with increasing water depth on the Mancos shelf. Most production in the *Offshore Mancos Shale play* is from the Mancos C, but a minor amount of production has been obtained from the Mancos B. Some production is obtained from strata that are laterally equivalent to the Tocito marine bars, but production also has been obtained from strata that are equivalent to shales above and below the Tocito marine bars. Therefore, there is a continuum between the *Tocito marine bar play* and the *Offshore Mancos Shale play*.

The El Vado Sandstone Member, as defined by Fassett and Jentgen (1978,) is productive in the eastern part of the San Juan Basin. The El Vado is the reservoir at the Puerto Chiquito Mancos pools on the eastern flank of the basin (Figure 9) and also contributes to production in several pools to the west of Puerto Chiquito in east-central San Juan County (Fassett and Boyce, 2005), where it is productive in the Offshore Mancos play. The El Vado Sandstone is present in the eastern part of the area that encompasses the *Tocito marine bar play*. Most of the production in the *Tocito marine bar play* has been obtained from distinct offshore marine bars within the lower part of the Mancos C beneath the El Vado but the El Vado provides some production that is in most wells commingled with the marine-bar production. The El Vado, therefore, acts as a reservoir in both the *Offshore Mancos Shale play* and the *Naturally fractured Mancos Shale play*. There is a continuum between these two plays. The El Vado Sandstone intertongues laterally with Mancos shales to the west and north of where it has been defined in the subsurface.

As previously discussed, the Mancos reservoirs in the *Offshore Mancos Shale play* have subeconomic to marginally economic volumes of oil and natural gas from most vertical wells. The productive vertical oil wells have targeted the sandier intervals within the Upper Mancos Shale. In most wells productive from this play, production from the Mancos has been commingled with production from the Dakota Sandstone, which has been prolifically productive from the giant Basin Dakota pool. In the commingled wells, it is not possible to know the percentage of production that is contributed by the Upper Mancos Shale, but it is almost certain to be less than the production from the Dakota. In the northern part of the basin, where the Mancos Shale is in the thermogenic gas window, commingled production in vertical wells over several hundred feet of shale can exceed initial production (IP) volumes of 1 million ft^3 gas per day (MMCFD) and IP volumes from horizontal wells can exceed 10 MMCFD as discussed later. Figure 12 shows a well log and core photographs from a productive zone in the *Offshore Mancos Shale play*. Cores indicate general decreasing sand content (and therefore increasing shale content) of the Mancos to the northeast as one moves from the more proximal part of the *Offshore Mancos play* to the more distal part of the play. The S.P., gamma-ray and resistivity logs indicate the presence of upward-coarsening cycles within the Upper Mancos. Interpretation of lithology from logs without accompanying cores would result in the conclusion that discrete coarsening upward sandstone beds form the leftward deflections on the S.P and gamma-ray logs. However, in the *Offshore Mancos play* upward-coarsening cycles seen on the S.P, and gamma-ray logs are formed by interlaminated very fine sandstones and shales. At the top of the upward coarsening cycles, the sandstones contain substantial amounts of shale laminations and therefore have low vertical permeability (Figure 12) [Figure 11 for location]).

Mancos Petroleum Source Rocks

Mancos Organic Content

The following section summarizes the total organic carbon (TOC) content and types of kerogens present in each stratigraphic unit of the Mancos Shale. Lower Mancos Shale source rocks are summarized because many of the productive vertical wells in the Mancos have commingled production from the Upper Mancos Shale (including the Tocito sandstones) and the Lower Mancos Shale.

Lower Mancos Shale

Each of the subdivisions of the Lower Mancos Shale is a generative petroleum source rock in the San Juan Basin. Somewhat sparse source rock analyses indicate that the Upper Carlile Shale and Juana Lopez Member are the richest source units in terms of organic carbon. The Lower Carlile Shale, although not as kerogen rich, has also probably generated appreciable volumes of petroleum.

Greenhorn Limestone and Graneros Shale

Only three source rock analyses were available for the Greenhorn Limestone. Two of the three analyses were from cuttings in which the sampled interval contained the Lower Carlile Shale (one analysis) and the Graneros Shale (one analysis) in addition to the Greenhorn. The one sample that included only the Greenhorn sample has 1.0% TOC, adequate kerogen for petroleum generation. The sample that included the Lower Carlile as well as the Greenhorn has 1.2% TOC and the sample that included the Graneros as well as the Greenhorn has 1.2% TOC. These sparse data suggest that the calcareous Greenhorn interval may have less organic carbon than overlying and underlying shales, but this may be a function of limited sampling. Very limited Rock-Eval and petrographic data indicates the Greenhorn has a mixture of oil-prone and gas-prone types with appreciable amounts of inertinite.

The two Graneros samples have 1.2 and 3.7% TOC, rendering it a good source rock in terms of organic carbon content. Available source rock data contain no information as to kerogen type, but a partial marine kerogen population can be expected because of the marine origin of the Graneros with perhaps a terrestrial kerogen population supplied by temporally equivalent Dakota deltas.

Lower Carlile Shale Member

TOC of Lower Carlile shales is more than 1% in most samples and exceeds 2% in two of the 22 samples, ample for petroleum generation even if somewhat less than in other stratigraphic subdivisions of the Mancos Shale. The average TOC content per well is 1.4%. The presence of a mixed kerogen population with substantial amounts of oil-prone types is indicated by limited petrographic and Rock-Eval data.

Juana Lopez Member

TOC content of Juana Lopez shales ranges from 0.9 to 2.6% and is more than 1% in most samples, ample for petroleum generation. The average TOC per well is 2.0%. Limited petrographic and Rock-Eval data indicate a mixture of oil-prone, woody and intertinitic types with a significant population of oil-prone types.

Upper Carlile Shale Member

TOC of Upper Carlile shales ranges from 0.6 to 6.0% and is more than 1% in most of the available samples. The average TOC content per well is 2.0%. Limited petrographic and Rock-Eval indicate mixed oil-prone, gas-prone, and inertinitic kerogen types with woody gas-prone types dominant in most samples.

Upper Mancos Shale

Mancos C Unit

Most kerogen analyses available for this study are from samples in the Mancos C unit. Therefore, the Mancos C unit has the best source-rock characterization of any of the subdivisions of the Mancos Shale. As discussed in the section on recent exploratory drilling in the Mancos, most of the recent drilling has focused on the Mancos C. Therefore, source rock parameters in the Mancos C receive the most detailed discussion in the paper.

The Mancos C unit is rich in organic carbon. TOC ranges from 0.5 to 3.2%. Ninety-nine of the 122 available samples (81%) have more than 1% TOC. Fifty-four samples (44%) have TOC more than 2%. In general TOC content increases in a basinward direction (northeast). TOC is less than 1% southwest of the Tocito marine bar sandstone trend and increases to more than 2% northeast of the Tocito trend. The average TOC content of the Mancos C is 1.6% per well. Wells to the northeast of the Mancos C marine bar trend have an average TOC of 1.7%, ranging from 1.0% to 2.2%.

In general, petrographic analyses of kerogen types and the pseudo-Van Krevelen diagram derived from Rock-Eval data (Figure 13) indicate that the Mancos C shales contain mixtures of oil-prone, gas-prone, and inertinitic kerogens. Oil-prone kerogens are dominant in the majority of samples. The samples that sit astride and to the left of the Type I/IIS line of the pseudo-Van Krevelen diagram probably contain Type IIS rather than Type I kerogens because the Mancos C was deposited in a marine rather than a lacustrine setting and Type I kerogens are typically deposited in lacustrine settings. See Dembicki (2009) for a discussion of this topic.

Mancos B Unit

The Mancos B unit contains sufficient TOC for petroleum generation. Most of the available samples contain more than 1% TOC. TOC exceeds 2% in approximately 1/3 of the 29 Mancos B samples. Although data are sparse it appears that the lower part of the Mancos B unit contains higher levels of TOC than the upper part of the Mancos B unit. Limited petrographic and Rock-Eval data indicate that most Mancos B Shale samples have a mixture of oil-generative, gas-generative, and inertinitic kerogens. A small percentage of Mancos B shales are dominated by oil-prone Type II and Type IIS kerogens.

Mancos A Unit

The Mancos A unit contains sufficient organic matter for petroleum generation. Source rock analyses are available for only 14 Mancos A samples. The Mancos A shales are somewhat leaner on the southern flank of the basin. Throughout most of the San Juan Basin Mancos A shales contain between 1% and 2% TOC. TOC exceeds 5% in one location, the Shell No. 113 Carson Unit well in Sec. 17 T25N R11W. On the southern flank of the basin in McKinley County, TOC levels are less than 1%. Limited petrographic data indicate that Mancos A kerogens are dominated by woody gas-prone types, but that some parts of the Mancos A may contain mixtures of gas-prone (Type III) and oil-prone (Type

II) kerogens. Some areas may be dominated by oil-prone kerogen types. More source rock analyses and further study are needed to map distribution of oil-prone kerogens within the Mancos A. For now it appears that the Mancos A is mostly a gas-generative unit because the kerogens are dominantly gas- prone.

Thermal Maturity of the Mancos Shale

Thermal maturity of the Upper Mancos Shale increases to the north/northeast as the Mancos descends into the deep axial part of the San Juan Basin from the shallow Chaco Slope to the south/southwest. On the southern/southwestern flank of the basin (Chaco Slope), the entire thickness of the Upper Mancos Shale is immature and within the biogenic gas window (Figure 14) [Figure 15 for location]). To the north/northeast as burial depths become greater, the Upper Mancos Shale is increasingly mature, first entering the upper part of the oil window in the vicinity of the Tocito marine bar play (Figure 16 [Figure 15 for location]). Farther to the north/northeast the Upper Mancos is within the lower part of the oil window and therefore has attained peak petroleum generation. Yet farther north and deeper in the basin, the Mancos enters the thermogenic gas window (Figure 17 [Figure 15 for location]). At any single place in the basin, the Mancos A is less mature than the Mancos B which is, in turn, less mature than the underlying Mancos C. The Lower Mancos shales are somewhat more mature than the Upper Mancos shales.

Contours of vitrinite reflectance (Figure 15) indicate that the Mancos C is thermally mature throughout most of the San Juan Basin. On the very southern flank of the basin where burial depths on the Mancos C are shallow (less than 1500 ft), the Mancos C shales are thermally immature. Thermal maturity increases to the northeast with increasing burial depth and the Mancos C passes through the early oil window, into the peak oil window and, with increasing depth, passes into the thermogenic gas window. The region of peak oil generation fortuitously coincides approximately with the northeastern limit of the Tocito marine-bar reservoirs that occur in the central part of the basin and the naturally fractured Mancos Shale reservoirs along the eastern flank of the basin. The available data indicate that the 1.0 R_o contour which marks the transition to late oil and wet gas, occurs 8 to 10 miles to the northeast of the marine bar reservoirs. The northward transition from oil-productive Mancos C reservoirs and from oil-productive Mancos C exploratory wells to gas-productive Mancos C wells (Figure 18) indicates the transition from the oil window to the wet-gas window occurs at R_o values of just over 1.0.

Maximum thermal maturity in the basin is only partially influenced by burial depth. The other major factor influencing thermal maturity is the presence of Oligocene (Middle Tertiary) batholiths beneath the San Juan Mountains which are present just north of the basin in Colorado. This results in offset of maximum thermal maturity to the north of the basin axis. Maximum maturity in coals of the Fruitland Formation (Upper Cretaceous) and in the Dakota Sandstone (Lower to Upper Cretaceous) occurs on the northern flank of the basin in Colorado (Rice, 1983). This depth-independent pattern of thermal maturation coincides with higher heat flows and paleotemperatures in the northern part of the basin as determined by Reiter and Clarkson (1983). Rice (1983) hypothesized that the offset of maximum thermal maturity was caused by heat omitted from Tertiary batholiths emplaced beneath the San Juan Mountains. Reiter and Clarkson (1983) concluded that hydrothermal activity associated with the batholiths, rather than simple heat emanation, is responsible for the offset in maximum thermal maturity.

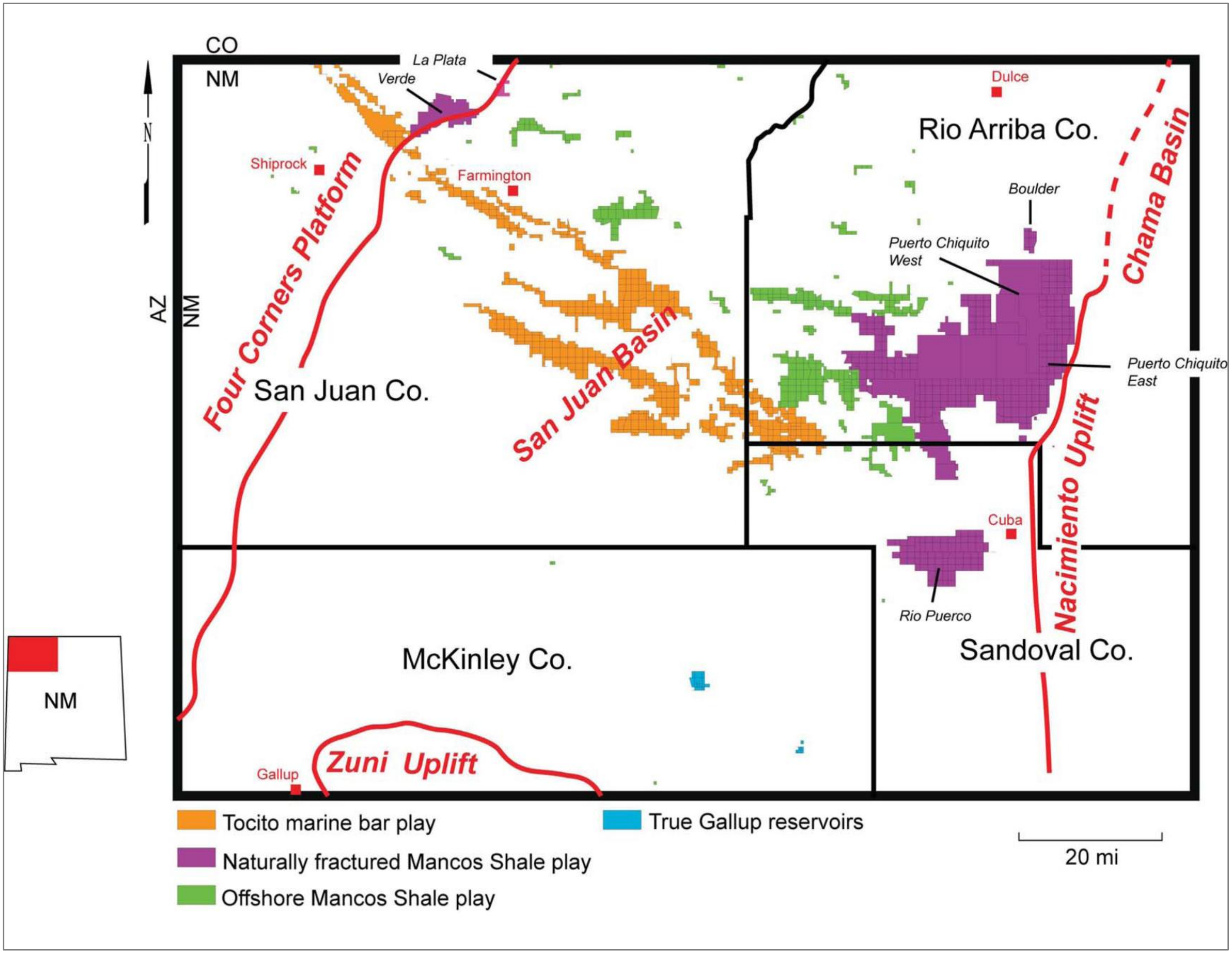

Figure 9. Subdivision of Mancos reservoirs into three plays: the *Tocito marine bar play*, the *Naturally fractured Mancos Shale play*, and the and the *Offshore Mancos Shale play*. Also shown are reservoirs that are productive from the “true” Gallup Sandstone (in blue).

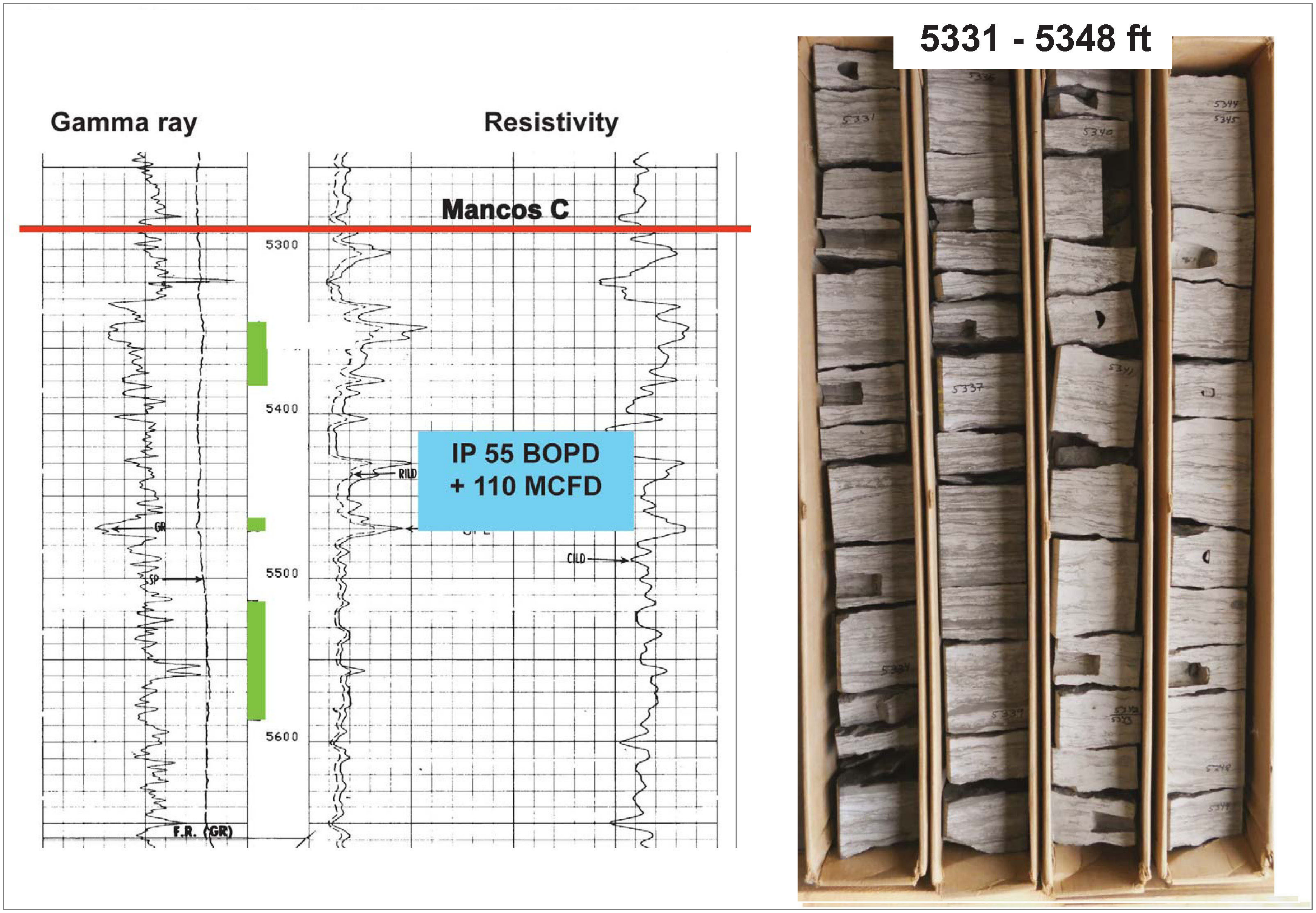

Figure 10. Core and well log from a reservoir in the *Tocito marine bar play*. Well is the Mesa Petroleum No. 5 South Blanco, which is located in the Lybrook "Gallup" pool. See Figure 11 for well location.

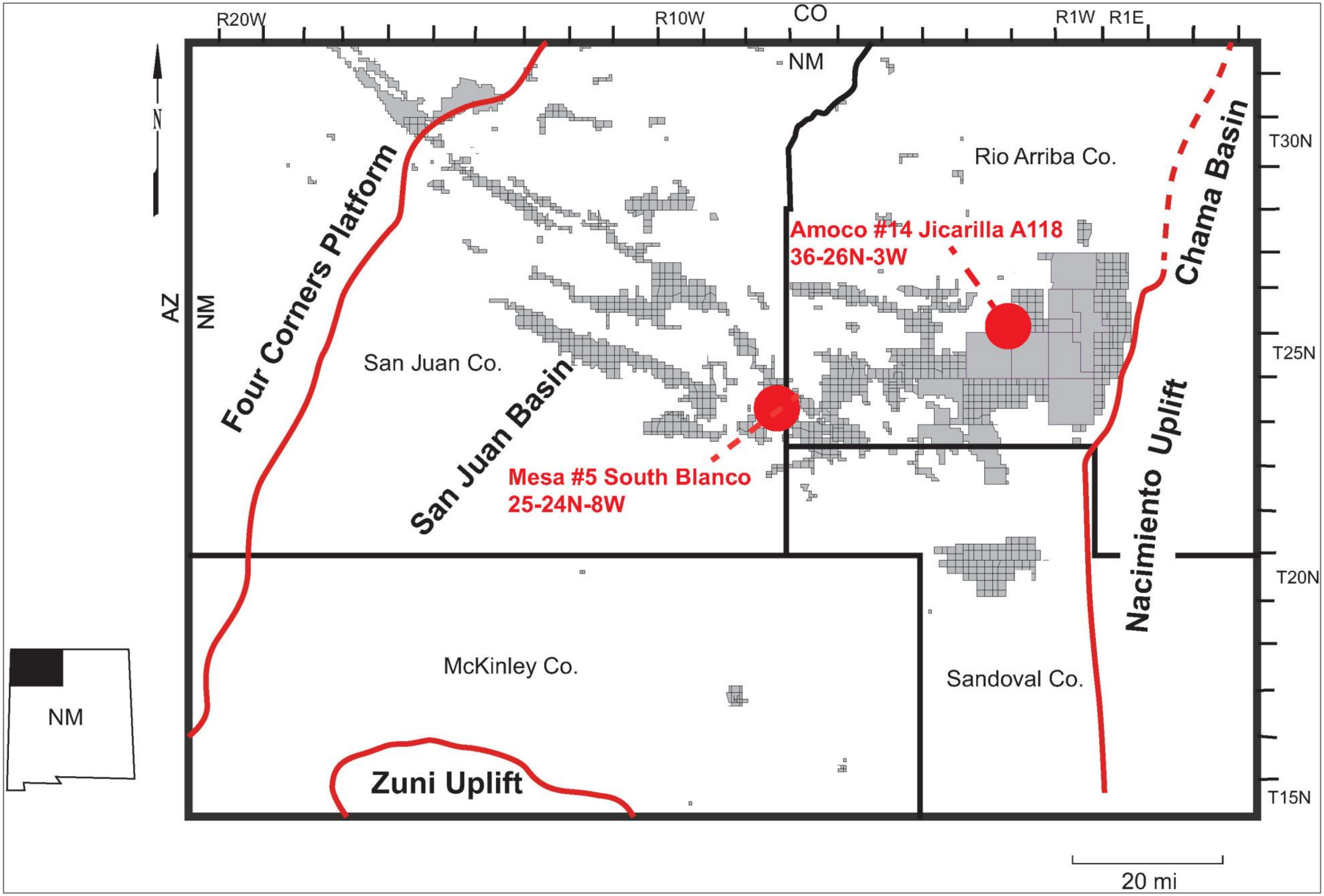

Figure 11. Locations of cores from Figures 10 and 12.

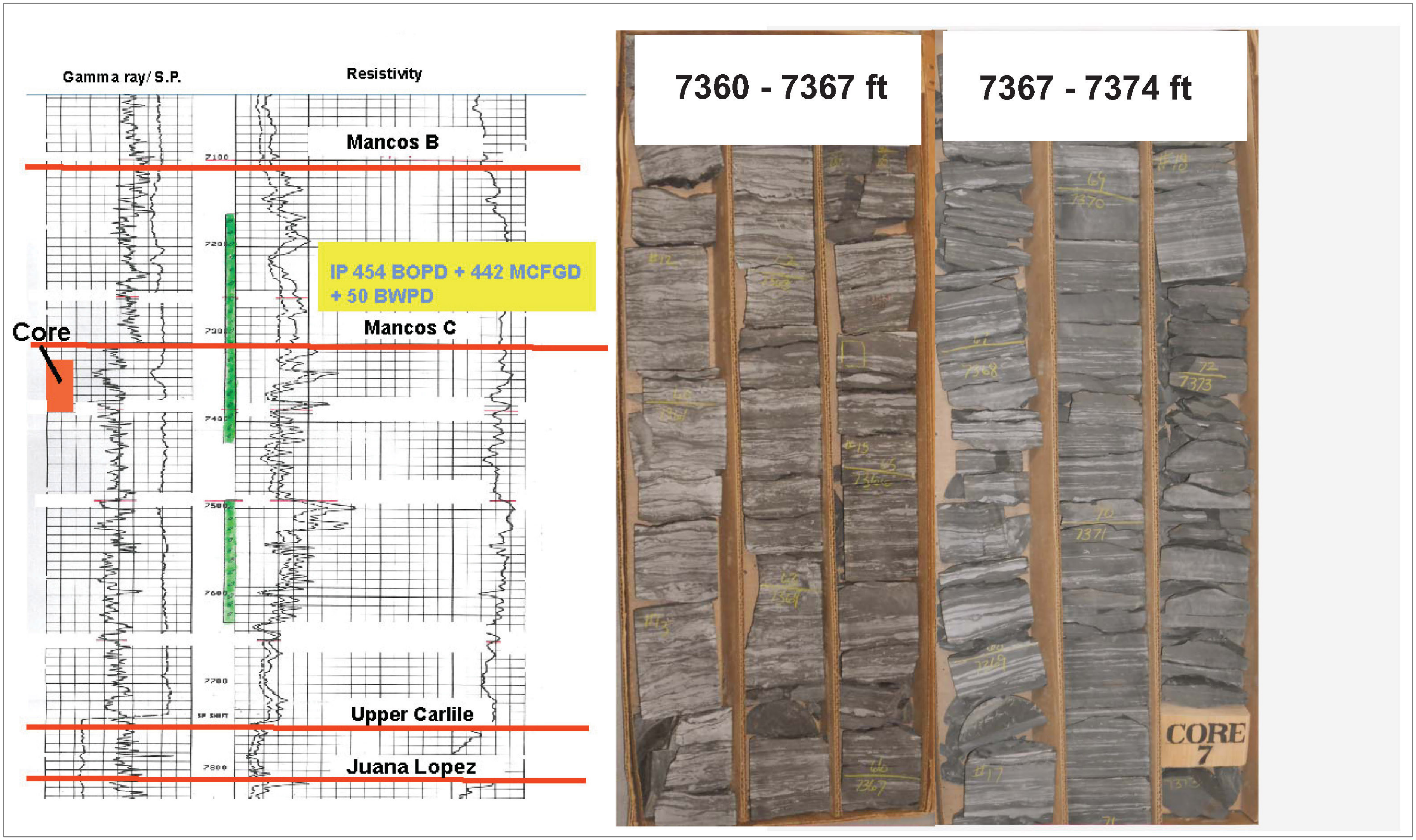

Figure 12. Core and well log from a reservoir in the *Offshore Mancos Shale play*. Well is the Amoco No. 14 Jicarilla A118, which is located in the Ojito Northeast Gallup-Dakota pool. Vertical wells in this pool are productive from the Mancos Shale and the Dakota Sandstone. See Figure 11 for well location.

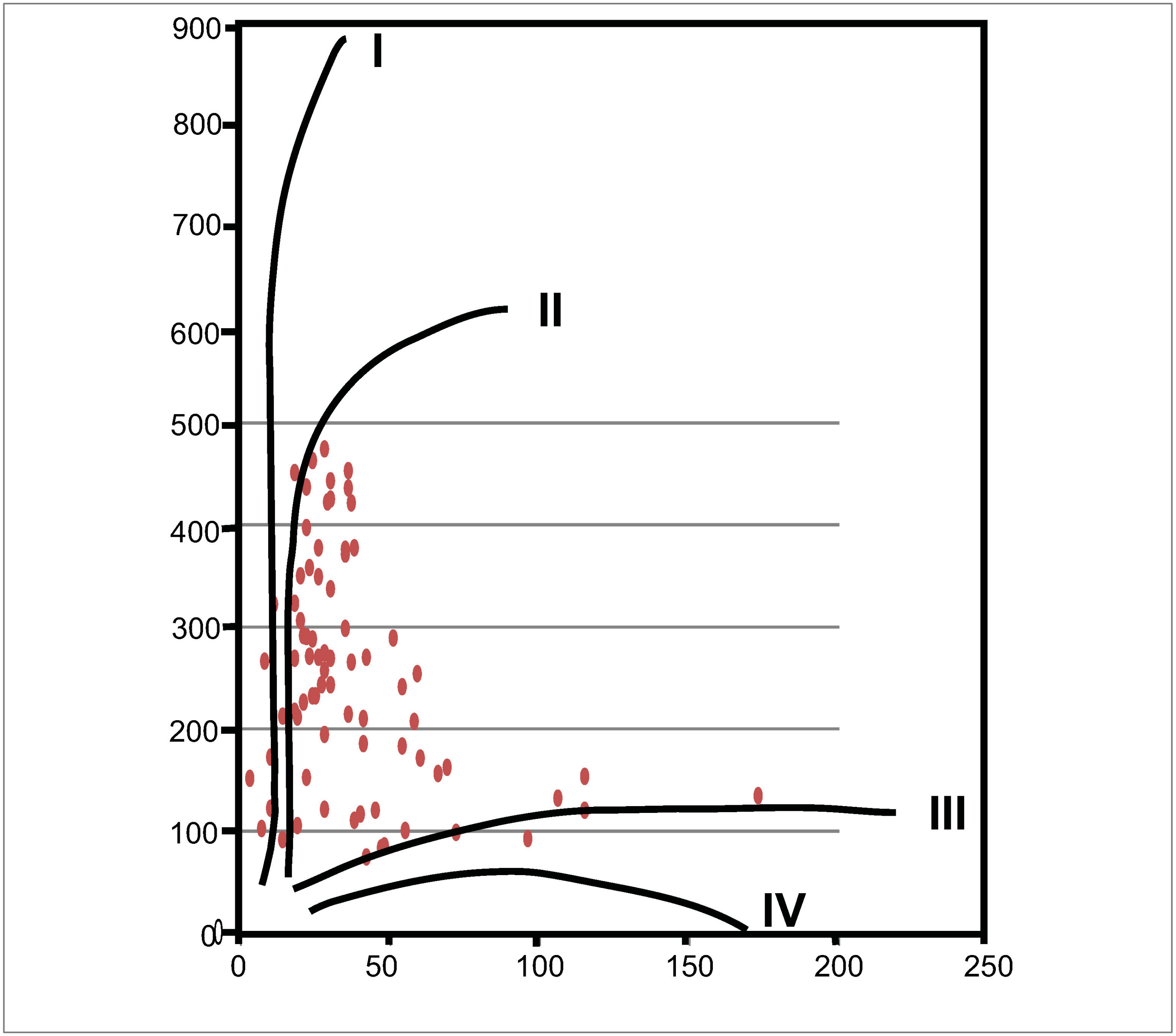

Figure 13. Pseudo-Van Krevelen diagram derived from Rock-Eval data for Mancos C shales in the San Juan Basin.

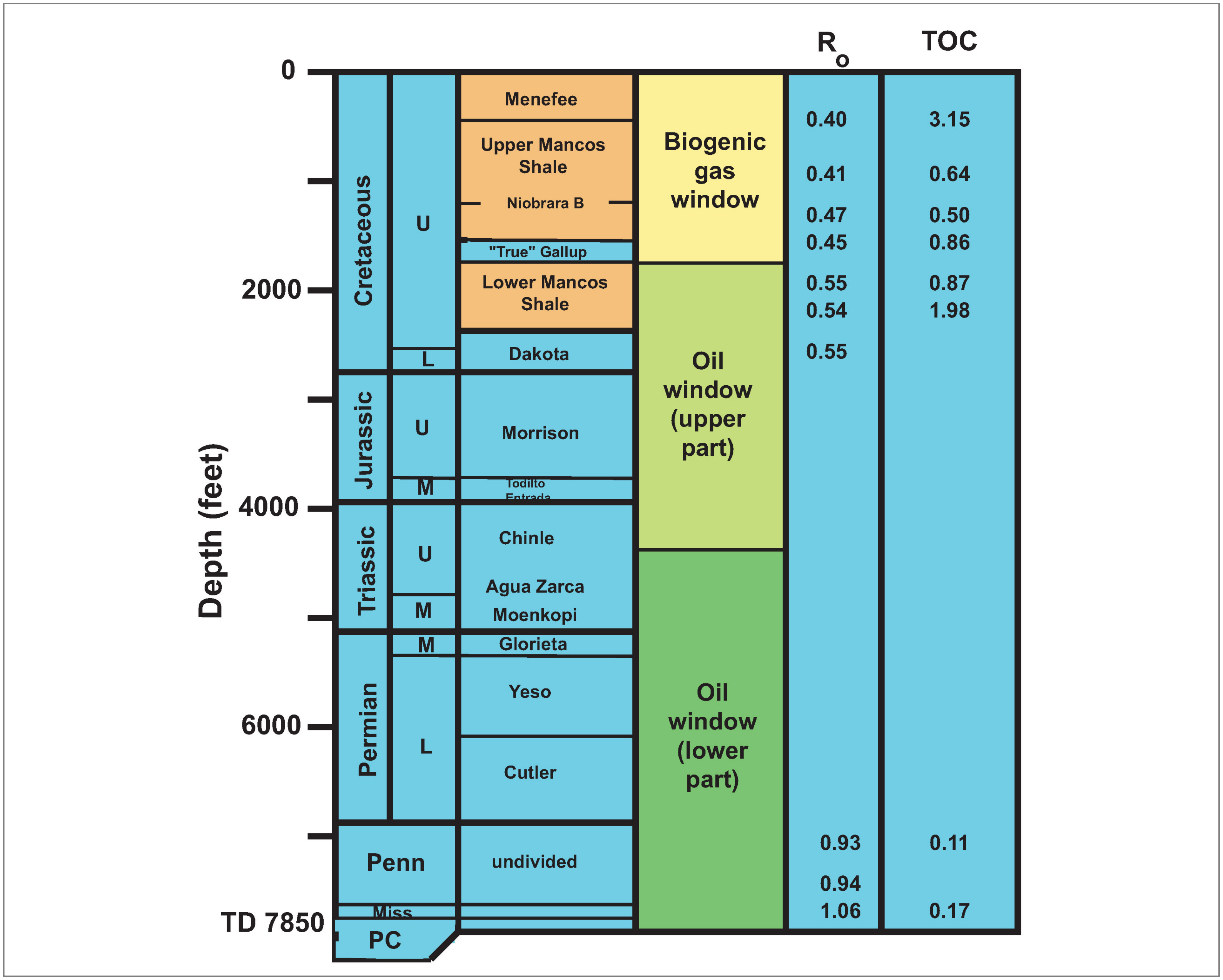

Figure 14. Petroleum source rock profile for the Great Western No. 1 Hospah well,located on the southwestern flank of the San Juan Basin. Source rock data obtained from Russell (1979) and Keal (1982). See Figure 15 for well location.

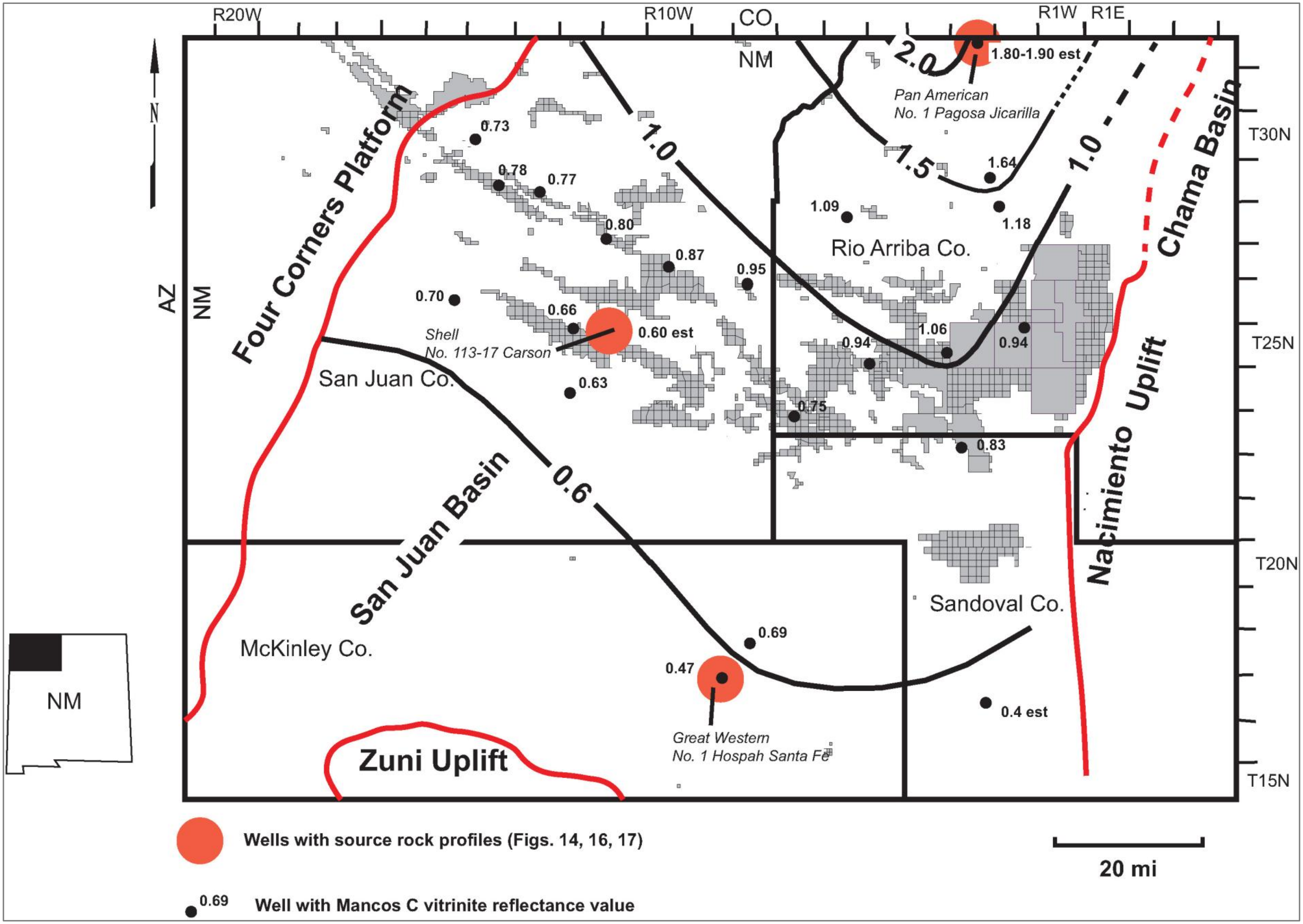

Figure 15. Vitrinite reflectance values of Mancos C shales and locations of source rock profiles of Figures 14, 16, and 17.

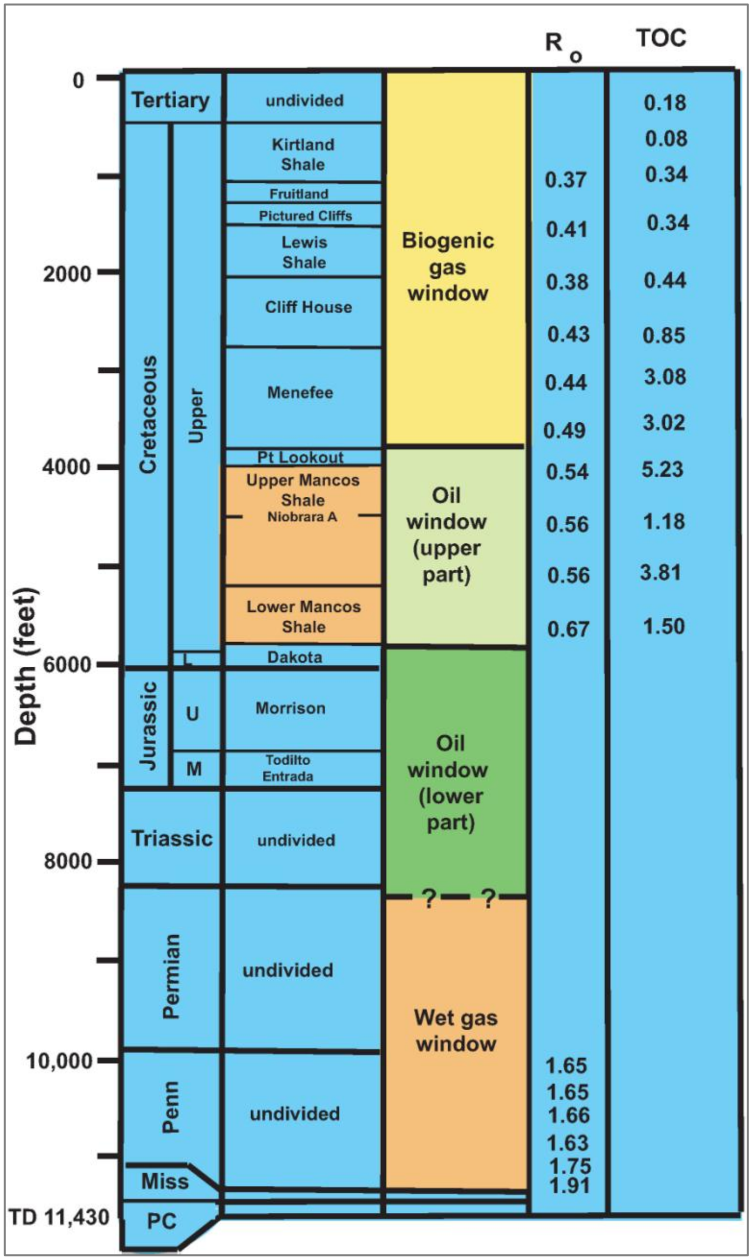

Figure 16. Petroleum source rock profile for the Shell No. 113-17 Carson well, located along the main trend of the Tocito marine bar reservoirs. Source rock data obtained from Keal (1982). See Figure 15 for well location.

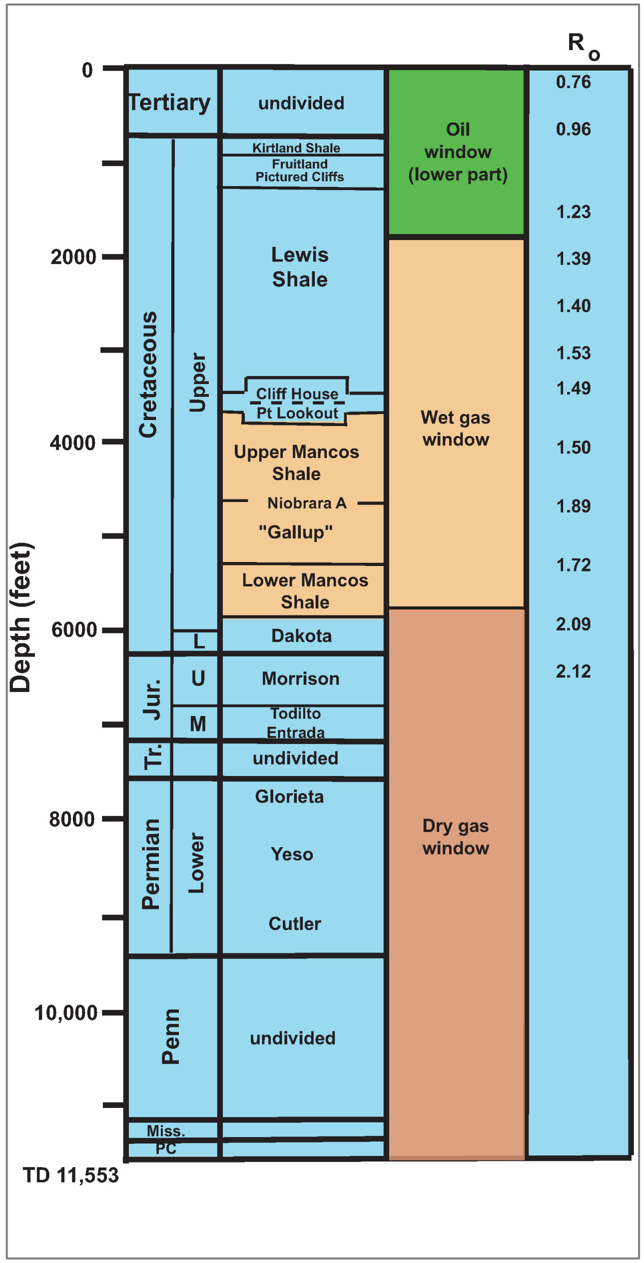

Figure 17. Petroleum source rock profile for the Pan American No. 1 Pagosa Jicarilla well, located in the northern deep part of the San Juan Basin. Source rock data obtained from Russell (1979). See Figure 15 for well location.

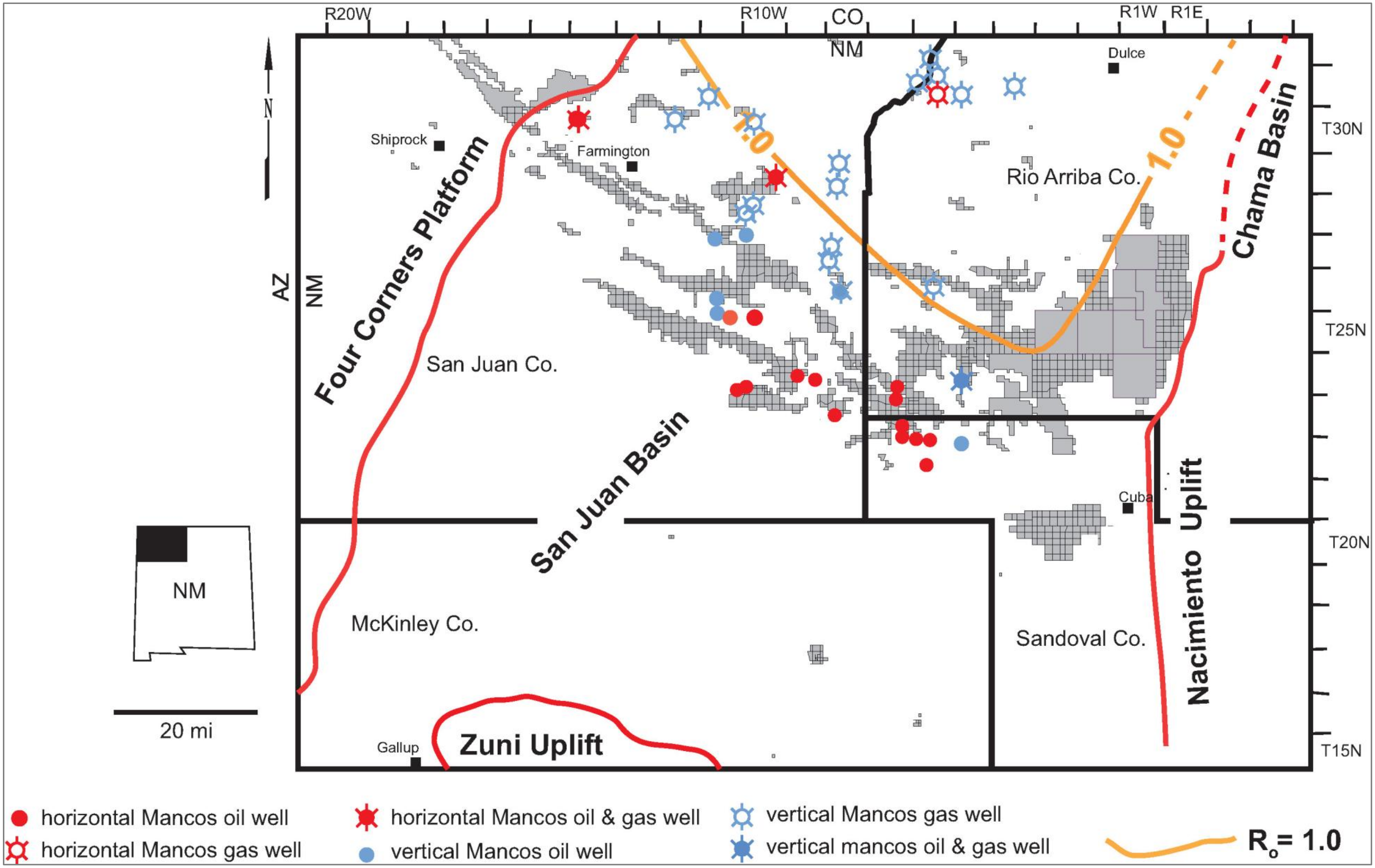

Figure 18. Selected recent exploratory wells in the Mancos Shale. See Tables 1 and 2 for well data and Mancos C 1.0 vitrinite reflectance contour.

Recent Exploratory Activity

Approximately 90 exploratory wells have been drilled in recent years to evaluate the Mancos Shale in the San Juan Basin. Both vertical and horizontal wells have been drilled. Selected vertical wells (Table 1) and horizontal wells (Table 2) are shown in Figure 18. In general, the horizontal wells obtained significantly higher production rates than vertical wells. Both the vertical and horizontal wells have been hydraulically fractured. Several of the vertical wells have been completed in multiple stratigraphic units within the Mancos and have obtained respectable initial production rates as well as cumulative production. Of course, in these wells it is not possible to ascertain which of the stratigraphic units may be providing most of the production.

For this project, a network of cross sections were constructed (Figure 7) that indicate the top and base of each stratigraphic unit discussed in the stratigraphy section of this paper. The productive wells listed in Tables 1 and 2 were correlated into the cross sections to determine which stratigraphic units are productive in each well. If no appropriate well log was available for correlation, then the stratigraphic unit given on the well completion records was used in Tables 1 and 2. In most records, this unit is listed as “Gallup” but in two wells the productive interval is listed as “Mancos”.

In most of the vertical wells (Table 1), the Mancos C has been perforated and artificially fractured; other Mancos units, including the Mancos A, Mancos B, and units in the Lower Mancos Shale have also been perforated and presumably contribute to production. However, in some of the vertical wells only members of the Lower Mancos Shale were perforated, but listed in the completion records as “Gallup”. Ironically because wells completed in the Upper Carlile Shale Member and the Juana Lopez Member are productive from strata equivalent to the Gallup Sandstone, the term “Gallup” may be applicable. In most of the wells, however, the term “Gallup” refers to Upper Mancos strata in addition to subdivisions of the Lower Mancos Shale, including pre-Juana Lopez strata, which are pre-Gallup in age. The lack of correct stratigraphic terminology renders it impossible to fully evaluate the petroleum potential of the Mancos Shale utilizing the stratigraphic nomenclature presented in completion reports.

The Mancos C is the exploratory target for horizontal wells (Table 2). Nine wells in Table 2 are listed on completion reports as having been completed in the “Gallup”. For these wells, there was no suitable log available for definitive correlation of the pay zone, but true vertical depth (TVD) and comparison to nearby wells indicates that the horizontal part of the wells is within the Mancos C.

The data in Tables 1 and 2 was used to determine the transition from Mancos oil wells to Mancos gas wells (Figure 18). In the eastern part of the basin, this occurs at approximately the Mancos C vitrinite reflectance contour of 1.0, but the oil-to-gas transition deviates from the contour in the western part of the basin. The dry gas window is present in the more northerly, deeper parts of the basin.

Summary

The marine Mancos Shale (Upper Cretaceous) in the San Juan Basin is subdivided into two formations, the Lower Mancos Shale and the Upper Mancos Shale. The Mancos crops out around the perimeter of the basin. Depth to the top of the Mancos exceeds 6500 ft along the basin axis in the northern part of the basin, which is asymmetrical.

Most production has been obtained from the Upper Mancos Shale. There are three plays in the Upper Mancos Shale: the *Tocito marine bar play*, the *Naturally fractured Mancos Shale play*, and *the Offshore Mancos Shale play*. Most reservoirs occur within the lower 400 ft of the Upper Mancos Shale, which is 900 to 1600 ft thick in the San Juan Basin. The Tocito marine bar play is a mature conventional play productive from northwest-southeast-trending shoestring sandstones on the southwestern flank of the basin. The reservoirs in this play are most often classified as being productive from the Gallup Sandstone (Upper Cretaceous) but are separated from the Gallup by a regional unconformity at the base of the Upper Mancos Shale. The *Naturally fractured Mancos Shale play* is a mature conventional play productive from brittle Mancos shales that have been upturned by Laramide deformation along the northwestern and southeastern flanks of the basin. The *Offshore Mancos Shale play* is an unconventional play productive from marine Mancos shales that contain laminations and thin interbeds of fine-grained marine sandstones. Most reservoir strata are located basinward of the Tocito marine bars but are also stratigraphically positioned above and below productive Tocito sandstones. Similar strata are productive in the *Naturally fractured Mancos Shale play*. A continuum exists among all three plays and reservoirs that have historically produced from the *Offshore Mancos play* appear to be naturally fractured, but less pervasively than the reservoirs in the *Naturally fractured Mancos play*.

Upper Mancos Shale source rocks contain 0.5 to 3.2% TOC. Most contain more than 1% TOC and almost ½ of the shales in the lower 400 ft of the Upper Mancos (Mancos C zone of this report) contain more than 2% TOC, more than adequate for petroleum generation. Kerogens in the Mancos C are dominantly oil-prone. Sparse data indicate that kerogens in Upper Mancos strata above the Mancos C may be dominantly gas-prone. Most shales in the Lower Mancos contain 0.9 to 2% TOC, although some Lower Mancos shales contain as much as 6% TOC. Sparse data indicate a mixed population of oil-prone, gas-prone and inertinitic kerogens are present. The Mancos Shale is thermally immature on the southwestern flank of the basin. Maturity increases to the northeast with increasing depth. Peak oil generation coincides approximately with the northeastern limit of the Tocito marine bar trend. Farther to the northeast, the Mancos passes into the thermogenic gas window.

The Offshore Mancos Shale play has been the target of significant recent exploration. Both vertical and horizontal wells have been drilled. Vertical wells have principally targeted the Mancos C, but most have commingled production from shallower parts of the Upper Mancos as well as from the Lower Mancos Shale. Horizontal wells have been completed in the Mancos C. Wells have been drilled in both the oil window in the southern part of the basin and the gas window in the northern part of the basin, with most exploratory drilling concentrated in the southern oil-bearing area.

Operator, well number, well name	API number	Location (quarter section, section- township-ragne, county)	True vertical depth (feet)	Wellbore orientation	Reservoir unit(s)	Initial production	Cumulative production (from Mancos only as of 5/2015)	Completion date (mo/yr)
Logos Capital Management No. 1 Logos (now WPX No. 1 Logos)	30-043-21119	NW 5-22N-5W, Sandoval	6,630	vertical	Mesaverde, Mancos B, Mancos C, Dakota (commingled)	53 BOPD + 36 BWPD allocated to Upper Mancos	10,040 BO + 10,92 MCFG + 8,857 BW	9/2012
Logos Operating No. 2 Logos (now WPX No. 2 Logos)	30-043-21120	SE 6-22N-5W, Sandoval	6,639	vertical	Mancos A, Mancos B, Mancos C, Upper Carlile, Juana Lopez, Lower Carlile, Greenhorn, Dakota (commingled)	4 BOPD + 30 BWPD allocated to Upper and Lower Mancos	9,121 BO + 18,612 MCFG + 10,350 BW	11/2012
Logos Operating No. 3 Logos (now WPX No. 3 Logos)	30-043-21135	SE 5-22N-6W, Sandoval	6,695	vertical	Mancos B, Mancos C, Upper Carlile, Juana Lopez, Lower Carlile, Greenhorn	120 BOPD + 741 BWPD	11,935 BO + 39,768 MCFG + 13,425 BW	2/2013
Logos Operating No. 5 Logos	30-045-35423	SE 4-23N-8W, San Juan	6,443	vertical	Mancos C, Juana Lopez	0 BOPD + 0 MCFD + 524 BWPD	14,328 BO + 64,363 MCFG + 32,674 BW	3/2013
XTO Energy No. 10 Apache Federal	30-039-05477	SE 18-24N-5W, Rio Arriba	6,794	vertical	Mancos C	8 BOPD + 1480 MCFD + 72 BWPD	10,287 BO + 78,395 MCFG + 2,492 BW	11/2016
Logos Operatong No. 7A NCRA State	30-039-31181	NE 16-24N-6W, Rio Arriba	6,310	vertical	Mancos B, Mancos C, Upper Carlile	153 BOPD + 90 BWPD	11,837 BO +50,480 MCFG + 3,487 BW	6/2013
XTO Energy No. 5 Canyon	30-045-21315	SE 3-25N-11W, San Juan	5,490	vertical	Mancos C	820 MCFD + 22 BOPD + 262 BWPD	18,598 BO + 147,401 MCFG + 2,236 BW	10/2010
XTO Energy No. 136G Breech A	30-039-30705	NE 10-26N-6W, Rio Arriba	7,765	vertical	Mancos C	190 MCFD	2,248 BO + 164,268 MCFG + 749 BW	11/2011
ConocoPhillips No. 14E Hodges	30-045-35261	NE 21-26N-8W, San Juan	6,843	vertical	"Gallup"	1303 MCFD + 18 BOPD + 18 BWPD	2,183 BO + 49,246 MCFG + 1,003 BW	7/2012
XTO Energy No. 1 Caldwell A	30-045-05674	SE 27-26N-11W, San Juan	6,200	vertical	Mancos C	4 BOPD + 69 MCFD + 15 BWPD	5,869 BO + 85,225 MCFG + 1,623 BW	5/2006
XTO Energy No. 6 Bolack B	30-045-32559	NE 30-27N-8W, San Juan	7,028	vertical	Mancos C	1596 MCFD + 4 BOPD allocated to Mancos C	596 BO + 47,552 MCFG + 1,592 BW	7/2005
XTO Energy No. 19 Bolack C	30-045-31911	SE 31-27N-8W, San Juan	6,794	vertical	Mancos C	458 MCFD + 0 BOPD + 0 BWPD allocated to Mancos C	6,877 BO + 75,607 MCFG + 2,146 BW	3/2004
XTO Energy No. 1G Pipkin Gas A	30-045-33445	NW 7-27N-10W	6,755	vertical	Mancos C	48 BOPD + 144 MCFD + 16 BWPD	2,280 BO + 39,795 MCFG + 2,794 BW	11/2006
XTO Energy No. 2E Bolack 15	30-045-32225	NW 15-27N-11W, San Juan	7,080	vertical	Mancos C	6 BOPD + 318 MCFD + 66 BWPD allocated to Mancos	2,609 BO + 205,593 MCFG + 27 BW	11/2006
XTO Energy No. 12E Kutz Federal	30-045-29779	NW 21-28N-10W, San Juan	6,799	vertical	Mancos C, Dakota (commingled)	80 MCFD + 0.5 BOPD + 2 BWPD (average rate based on 77 days production)	258 BO + 33,022 MCFG + 426 BW	12/2012
XTO Energy No. 1F Hubbell Gas Com B	30-045-34490	SE 30-28N-10W, San Juan	6,770	vertical	Mancos C, Upper Carlile, Juana Lopez, Dakota (commingled)	156 MCFD + 0 BOPD + 15 BWPD allocated to Upper and Lower Mancos	2,068 BO + 104,483 MCFG + 2,470 BW	3/2009
BP America No. 245 Gallegos Canyon Unit	30-045-11689	NW 36-28N-12W, San Juan	6,475	vertical	Mancos C	58 MCFD	1,070 BO + 63,087 MCFG + 517 BW	6/2013
Burlington Resources No. 2C Day	30-045-35221	SW 9-29N-8W, San Juan	7090*	deviated vertical	Mesaverde, Mancos (commingled)	111 MCFD allocated to Mancos	121 BO + 40,219 MCFG + 164 BW	5/2013
Conoco Phillips No. 6N Hughes A	30-045-35360	NW 33-29N-8W, San Juan	7389*	deviated vertical	"Gallup"	80 MCFD + 0 BOPD + 0 BWPD allocated to Mancos	146 BO + 34,203 MCFG + 827 BW	2/2013
Burlington Resources No. 1N Sullivan	30-045-35177	NE 7-30N-10W, San Juan	7,333	vertical	Mesaverde, " Mancos", Dakota (commingled)	110 MCFD allocated to Mancos	46 BO + 28,021 MCFG + 2,805 BW	5/2013
XTO Energy No. 2F Schumacher	30-045-33176	SW 8-30N-12W, San Juan	7,042	vertical	Lower Carlile	50 MCFD	37 BO + 1,578 MCFG + 380 BW	10/2013
XTO Energy No. 2F Federal N	30-045-33243	NE 17-30N-12W, San Juan	7,000	vertical	Juana Lopez, Lower Carlile	50 MCFD + 0 BOPD + 0 BWPD	233 BO + 4,392 MCFG + 376 BW	5/2006
Williams Production No. 602 Rosa Unit	30-039-30914	NW 27-31N-4W, Rio Arriba	8.885	vertical	Mesaverde, Juana Lopez	750 MCFD	0 BO + 120,754 MCFG + 3,700 BW	10/2010
Williams Production No. 17C Rosa Unit	30-039-30381	20-31N-5W, Rio Arriba	7990*	deviated vertical	Mesaverde, Mancos C, Dakota (commingled)	446 MCFD allocated to Mancos C	0 BO + 162,316 MCFG + 53 BW	8/2009
Williams Production No. 167 D Rosa Unit	30-045-34985	SE 8-31N-6W, San Juan	7903*	deviated vertical	Mancos B, Mancos C	53 MCFD allocated to Mancos B and Mancos C	0 BO + 133,033 MCFG + 1,890 BW	10/2009
Williams Production No. 75D Rosa Unit	30-045-34964	NW 10-31N-6W, San Juan	7,949	vertical	Mesaverde, Mancos B, Mancos C, Dakota (Commingled)	31 MCFD allocated to Mancos B and Mancos C	0 BO + 117,080 MCFG + 113 BW	9/2009
Williams Production No. 9C Rosa Unit	30-039-30179	SW 11-31N-6W, Rio Arriba	8,138	vertical	Mesaverde, Mancos B, Mancos C, Dakota (commingled)	47 MCFD allocated to Mancos B and Mancos C	0 BO + 103,462 MCFG + 641 BW	10/2009
Conoco Phillips No. 2N Heaton B	30-045-35326	SE 30-31N-11W, San Juan	6974*	deviated vertical	Mesaverde,Mancos C, Dakota (commingled)	418 MCFD allocated to Mancos C	300 BO + 43,114 MCFG + 4,744 BW	9/2012
Williams Production No. 9C Rosa Unit	NE 30-045-34278	33-32N-6W, San Juan	8012*	deviated vertical	Mesaverde, Mancos B, Mancos C, Dakota (commingled)	47 MCFD allocated to Mancos	0 BO + 89,715 MCFG + 53 BW	11/2009

Table 1. Selected recent vertical exploratory wells drilled to test the Mancos Shale. BOPD, bbls oil per day; MCFD, thousand cubic ft gas per day; BWPD, bbls water per day; BO bbls oil; MCFG, thousand cubic ft gas; BW, bbls water.

Operator,well number,well name	API number	Bottom Hole Location (quarter section, section-township-range, county)	Measured depth (feet)	True vertical depth (feet)	Reservoir unit	Initial production	Cumulative production (as of 5/2015)	Completion date (mo/yr)
WPX Energy No. 225H Chaco 2206-02H	30-043-21149	NW 2-22N-6W, Sandoval	10,219	5,344	"Gallup"	406 BOPD + 88 BWPD	77,263 BO + 153,031 MCFG + 15,857 BW	8/2013
Encana No. 1H Lybrook A03-2206	30-043-21130	NW 3-22N-6W, Sandoval	9565	5,335	Mancos C	692 BOPD + 1523 MCFD + 160 BWPD (GOR test 6/214/13)	122,543 BO + 467,153 MCFG + 9,952 BW	11/2012
Encana No. 1H Lybrook H03-21123	30-043-21123	NW 3-22N-6W, Sandoval	9,870	5,397	Mancos C	362 BOPD + 311 MCFD + 7 BWPD (GOR test 8/1/13)	93,668 BO + 442,676 MCFG + 9,537 BW	5/2013
Encana No. 1H Lybrook D22-2206	30-043-21131	NW 21-22N-6W, Sandoval	10,350	5,311	Mancos C	32 BOPD + 161 MCFD + 384 BWPD (GOR test 6/18/13)	40,190 BO + 279,821 MCFG + 31,459 BW	12/2012
Encana No. 1H Lybrook H32-2306	30-043-21126	NE 31-23N-6W. Sandoval	12,575	5,552	Mancos C	442 BOPD + 2896 MCFD + 3 BWPD (GOR test 9/6/13)	139,506 BO + 831,063 MCFG + 19,708 BW	6/2013
Encana No. 1H Lybrook I32-2306	30-043-21129	SW 32-23N-6W, Sandoval	10,060		"Gallup"	439 BOPD + 1198 MCFD + 128 BWPD (GOR test 10/5/13)	74,096 BO + 405,999 MCFG + 15,816 BW	6/2013
Encana No. 2H Lybrook I32-2306	30-043-21125	SW 32-23N-6W, Sandoval	10,204		"Gallup"	320 BOPD + 787 MCFD + 58 BWPD (GOT test 10/5/13)	88,408 BO + 388,764 MCFG + 19,860 BW	6/2013
WPX Energy No. 168H Chaco 2307-12E	30-039-31173	NW 12-23N-7W, Rio Arriba	10,444	5,532	Mancos C	308 BOPD + 39 BWPD	9,087 BO + 80,175 MCFG + 24,267 BW	7/2013
WPX Energy No. 191 H Chaco 2306-19M	30-043-21139	SW 24-23N-7W, Sandoval	10,367	5,430	Mancos C	593 BOPD + 8500 BWPD	76,718 BO + 103,803 MCFG + 16,246 BW	6/2013
Encana No. 1H Lybrook H26-2307	30-043-21118	NE 26-23N-7W, Sandoval	9,900	5,615	Mancos C	364 BOPD + 997 MCFD + 160 BWPD (GOR test 6/18/13)	87,378 BO + 320,284 MCFG + 16,934 BW	2/2013
Encana No. 2H Lybrook H26-2307	30-043-21133	NW 26-23N-7W, Sandoval	9,640	5,255	Mancos C	0 BOPD + 516 MCFD + 320 BWPD (GOR test 7/1/13)	53,265 BO + 252,531 MCFG + 43,463 BW	2/2013
Encana No. 1H Lybrook H36-2307	30-043-21117	NW 36-23N-7W, Sandoval	9,985	5,607	Mancos C	182 BOPD + 420 MCFD + 40 BWPD (GOR test 5/4/12)	78,653 BO + 426,818 MCFG + 19,876 BW	3/2012
WPX Energy No. 147H Chaco 2308-161	30-045-35439	SW 16-23N-8W, San Juan	9.751	4,992	Mancos C	267 BOPD + 102 BWPD	60,851 BO + 75,634 MCFG + 14,750 BW	5/2013
Encana No. 1H Good Times A06-2310	30-045-35319	NW 6-23N-10W, San Juan	8,950	4,552	Mancos C	106 BOPD + 392 MCFD + 964 BWPD	13,263 BO + 45,663 MCFG + 69,907 BW	9/2012
Encana No. 1H Escrito A36-2407	30-039-31134	NW 36-24N-7W, Rio Arriba	9,745	5,420	"Gallup"	105 BOPD + 1060 MCFD + 0 BWPD (GOR test 7/3/13)	20,544 BO + 270,994 MCFG + 6612 BW	12/2012
WPX Energy No. 114H Chaco 2408-32P	30-045-35441	SW 32-24N-8W, Sandoval	10,349	5,440	"Gallup"	361 BOPD + 1236 MCFD + 134 BWPD	59,597 BO + 253,319 MCFG + 29,612 BW	4/2013
Encana No. 1H Escrito P16-2409	30-045-35313	SW 16-24N-9W, San Juan	9,585	5,306	Mancos C	98 BOPD + 871 MCFD + 10 BWPD (GOR test 7/21/12)	30,687 BO + 327,998 MCFG + 7,646 BW	5/2012
Encana No. 1H Escrito I24-2409	30-045-35322	SW 24-24N-9W, San Juan	10,020	5,446	"Gallup"	119 BOPD + 735 MCFD + 0 BWPD (GOR test 12/27/12)	95,720 BO + 478,636 MCFG + 13,496 BW	10/2012
Encana No. 1H Good Times P32-2410	30-045-35315	SW 32-24N-10W, San Juan	8,800	4,503	"Gallup"	119 BOPD + 107 MCFD + 60 BWPD (GOR test 6/25/12)	52,272 BO + 68,121 MCFG + 35,668 BW	4/2012
Encana No. 1H Bisti H09-2510	30-045-35341	NW 9-25N-10W, San Juan	9,760	5,585	Mancos C	207 BOPD + 193 MCFD + 78 BWPD (GOR test 10/9/12)	16,489 BO + 91,560 MCFG + 5,790 BO	7/2012
XTO Energy No 19H Canyon	30-045-35387	SE 2-25N-11W, San Juan	11,415	5,068	"Gallup"	50 BOPD + 100 MCFD + 0 BWPD	17,635 BO + 66,361 MCFG + 7,689 BW	5/2013
XTO Energy No. 1H Martin	30-045-35452	NW 14-27N-10W, San Juan	11,950	6,009	"Gallup"	31 BOPD + 1300 MCFD + 94 BWPD	4,737 BO + 306,264 MCFG + 912 BW	5/2013
Encana No. 1H Meadows I08-3014	30-045-35320	SW 8-30N-14W, San Juan	9,467	5,114	Mancos C	11 BOPD + 658 MCFD + 8 BWPD (GOR test 9/3/12)	9,986 BO + 222,309 MCFG + 1,878 BW	6/2012
WPX Energy No. 634B Rosa Unit	30-039-30937	NE 23-31N-6W, Rio Arriba	12,913	6,925	Mancos C	11.0 MMCFD	0 BO + 2,597,111 MCFG + 10,357 BW	11/2010
WPX Energy No. 634A Rosa Unit	30-039-30970	NE 23-31N-6W, Rio Arriba	13,130	7,150	Mancos C	8.3 MMCFD	0 BO + 2,293,665 MCFG + 9,628 BW	11/2010

Table 2. Selected recent horizontal exploratory wells drilled to test the Mancos Shale. BOPD, bbls oil per day; MCFD, thousand cubic ft gas per day; BWPD, bbls water per day; BO bbls oil; MCFG, thousand cubic ft gas; BW, bbls water.

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