# Geology and Oil and Gas Assessment of the Todilto Total Petroleum System, San Juan Basin Province, New Mexico and Colorado

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By J.L. Ridgley and J.R Hatch

Chapter 3 of 7

**Total Petroleum Systems and Geologic Assessment of Undiscovered Oil and Gas Resources in the San Juan Basin Province, Exclusive of Paleozoic Rocks, New Mexico and Colorado**

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# Geology and Oil and Gas Assessment of the Todilto Total Petroleum System, San Juan Basin Province, New Mexico and Colorado

By J.L. Ridgley and J.R Hatch

## Abstract

Organic-rich, shaly limestone beds, which contain hydrocarbon source beds in the lower part of the Jurassic Todilto Limestone Member of the Wanakah Formation, and sandstone reservoirs in the overlying Jurassic Entrada Sandstone, compose the Todilto Total Petroleum System (TPS). Source rock facies of the Todilto Limestone were deposited in a combined marine-lacustrine depositional setting. Sandstone reservoirs in the Entrada Sandstone were deposited in eolian depositional environments. Oil in Todilto source beds was generated beginning in the middle Paleocene, about 63 million years ago, and maximum generation of oil occurred in the middle Eocene. In the northern part of the San Juan Basin, possible gas and condensate were generated in Todilto Limestone Member source beds until the middle Miocene. The migration distance of oil from the Todilto source beds into the underlying Entrada Sandstone reservoirs was short, probably within the dimensions of a single dune crest. Traps in the Entrada are mainly stratigraphic and diagenetic. Regional tilt of the strata to the northeast has influenced structural trapping of oil, but also allowed for later introduction of water. Subsequent hydrodynamic forces have influenced the repositioning of the oil in some reservoirs and flushing in others. Seals are mostly the anhydrite and limestone facies of the Todilto, which thin to as little as 10 ft over the crests of the dunes.

The TPS contains only one assessment unit, the Entrada Sandstone Conventional Oil Assessment Unit (AU) (50220401). Only four of the eight oil fields producing from the Entrada met the 0.5 million barrels of oil minimum size used for this assessment. The AU was estimated at the mean to have potential additions to reserves of 2.32 million barrels of oil (MMBO), 5.56 billion cubic feet of natural gas (BCFG), and 0.22 million barrels of natural gas liquids (MMBNGL).

## Introduction

The boundary of the Middle Jurassic Todilto Total Petroleum System (TPS) was drawn to coincide with the boundary of the San Juan Basin Province except along the northwest and southwest margins (fig. 1). In these areas, the TPS boundary was drawn basinward from Todilto outcrops because analysis of facies in the Todilto Limestone Member of the Wanakah Formation and the underlying Entrada Sandstone in these areas suggested a lack of source rock potential, insufficient thermal maturity, and unfavorable reservoir geometry. The Todilto TPS is the stratigraphically oldest TPS evaluated in the 2002 National Oil and Gas Assessment of the San Juan Basin Province. The TPS contains only one assessment unit, the Entrada Sandstone Conventional Oil Assessment Unit (AU) (50220401) (fig. 2).

The Todilto TPS comprises two Middle Jurassic rock units:

1. Entrada Sandstone, the reservoir, and
2. the overlying Todilto Limestone Member of the Wanakah Formation, the source and seal (fig. 2).

The Todilto Limestone Member is the source of the oil and small quantities of associated gas found in the Entrada; it is also the seal to migrating hydrocarbons. The Entrada Sandstone is mostly of eolian origin, including large ergs with individual dune thickness ranging from 60 to 330 ft. The ergs are extensive throughout the San Juan Basin and continue into surrounding areas of Utah, Arizona, and Colorado. There is little evidence of basin subsidence on deposition of the upper part of the Entrada Sandstone except near the end of its time of deposition.

Near the close of deposition of the Entrada, an area extending south from central Colorado well into New Mexico subsided. Marine waters from the north flowed south across a sill, located in south-central Colorado, and formed a large bay in the subsided area (Ridgley, 1989) (fig. 3). Rapid flooding in this embayment by marine waters from the north modified the topographic expression of the Entrada dunes, resulting in relict dune topography of variable height. A large inland sea formed within the embayment (Tanner, 1970; Kirkland and others, 1995). This inland sea is characterized by a basal limestone facies, which contains interbedded organic-rich shale, and an overlying anhydrite facies, which alters to gypsum at the surface. These chemical facies make up the Todilto Limestone Member of the Wanakah Formation. Preservation of individual sand dunes overlain by a carbonate unit that serves as both source rock and seal make the Todilto a locally sourced TPS.

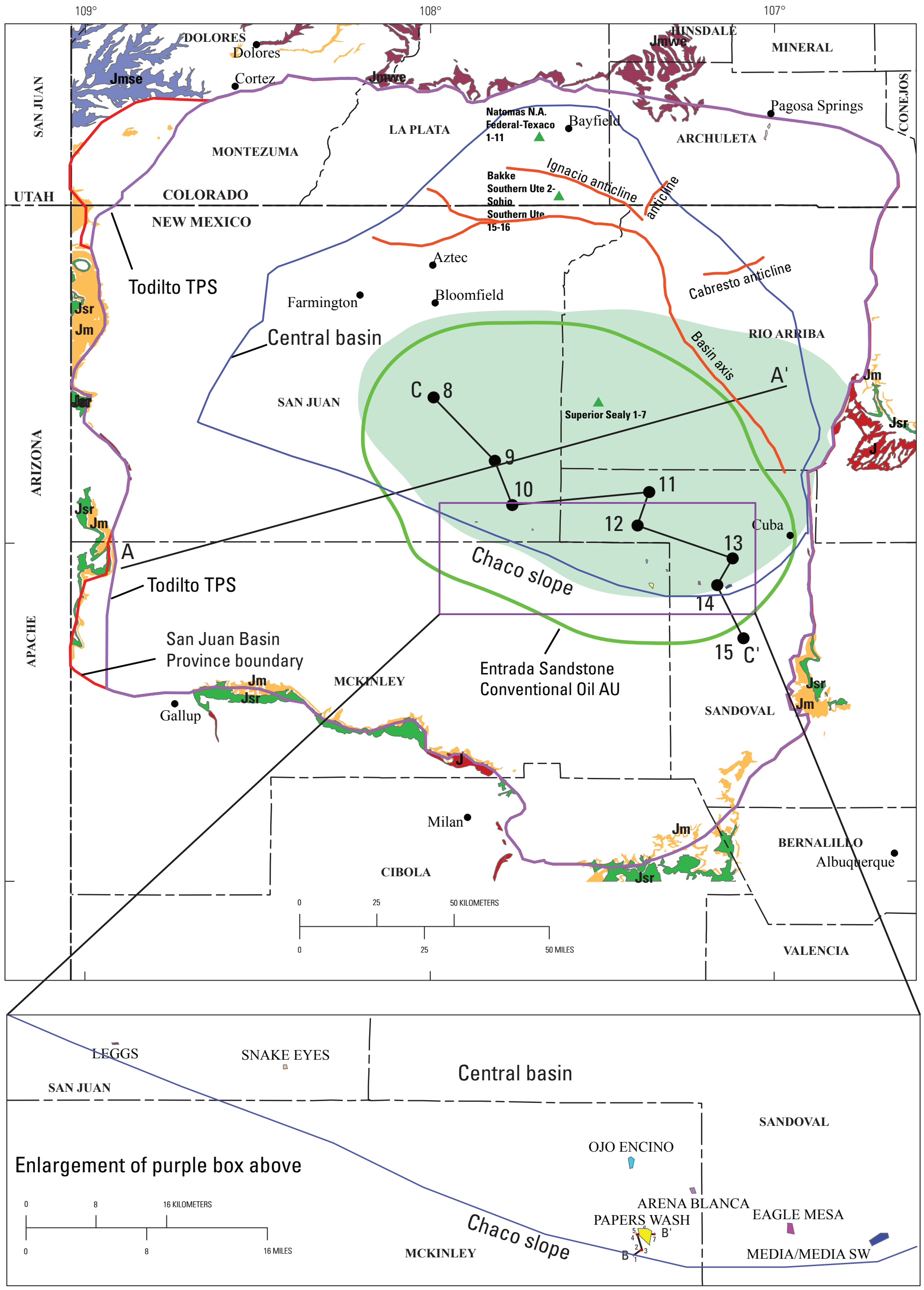



**Figure 1.** Map showing boundary of the San Juan Basin Province (5022) (red line), Todilto Total Petroleum System (TPS) (purple line), Entrada Sandstone Conventional Oil Assessment Unit (AU) (green line), and location of Entrada Sandstone Conventional Oil AU oil fields (see inset for enlargement and oil field locations). Geologic map from Green (1992) and Green and Jones (1997): J, Jurassic rocks, undivided; Jm, Morrison Formation; Jmse, Morrison and Summerville Formations and Entrada Sandstone; Jmwe, Morrison and Wanakah Formations and Entrada Sandstone; Jsr, San Rafael Group, undivided. Pod of mature oil source rock (solid light-green area) modified from Vincelette and Chittum (1981). Location of cross sections *A–A′* (fig. 7), *B–B′* (fig. 9*A*; see inset) and *C–C′* (fig. 9*B*). Also shown are the outline of the central basin area (blue line), location of the Chaco slope, and the location of the three wells (green triangles) for the burial history curves used in this report (figs. 8*A–C*). Area of the central basin and location of the Chaco slope taken from Fassett (1991).

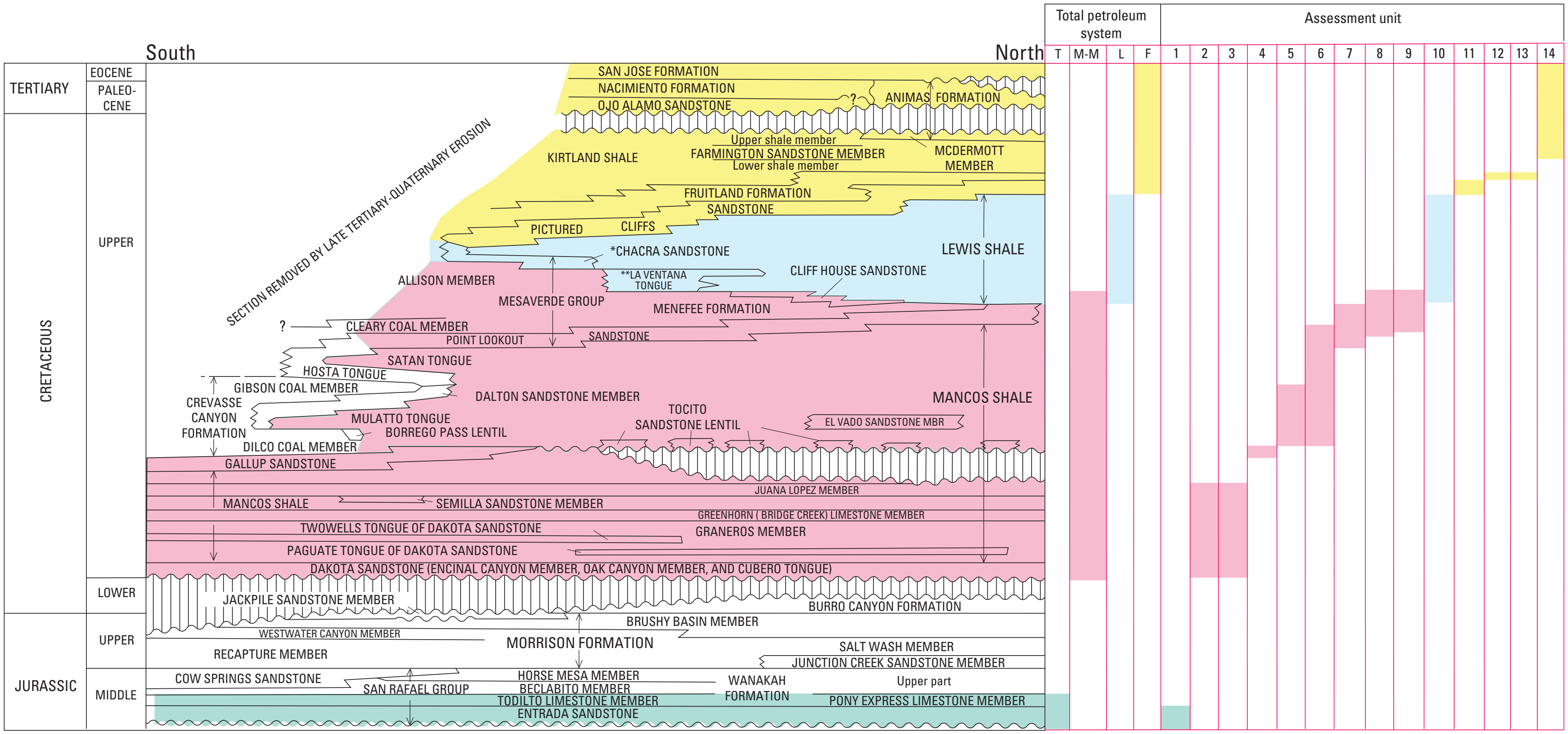



**Figure 2.** Chart showing regional chronostratigraphic correlations in the San Juan Basin (modified from Molenaar, 1977) to the base of the Jurassic, and the extent of the total petroleum systems and assessment units defined in this 2002 National Oil and Gas Assessment of the San Juan Basin Province (5022), New Mexico and Colorado. Total petroleum systems: F, Fruitland; L, Lewis Shale; M–M, Mancos-Menefee Composite; and T, Todilto. Assessment units: 1, Entrada Sandstone Conventional Oil; 2, Dakota-Greenhorn Conventional Oil and Gas; 3, Dakota-Greenhorn Continuous Gas; 4, Gallup Sandstone Conventional Oil and Gas; 5, Mancos Sandstone Conventional Oil and Gas; 6, Mancos Sandstone Continuous Gas; 7, Mesaverde Updip Conventional Oil; 8, Mesaverde Central-Basin Continuous Gas; 9, Menefee Coalbed Gas; 10, Lewis Continuous Gas; 11, Pictured Cliffs Continuous Gas; 12, Basin Fruitland Coalbed Gas; 13, Fruitland Fairway Coalbed Gas; and 14, Tertiary Conventional Gas. *Chacra sandstone is an informal term used by drillers and geologists in the basin; **La Ventana Tongue of the Cliff House Sandstone. Vertical lines indicate unconformities.

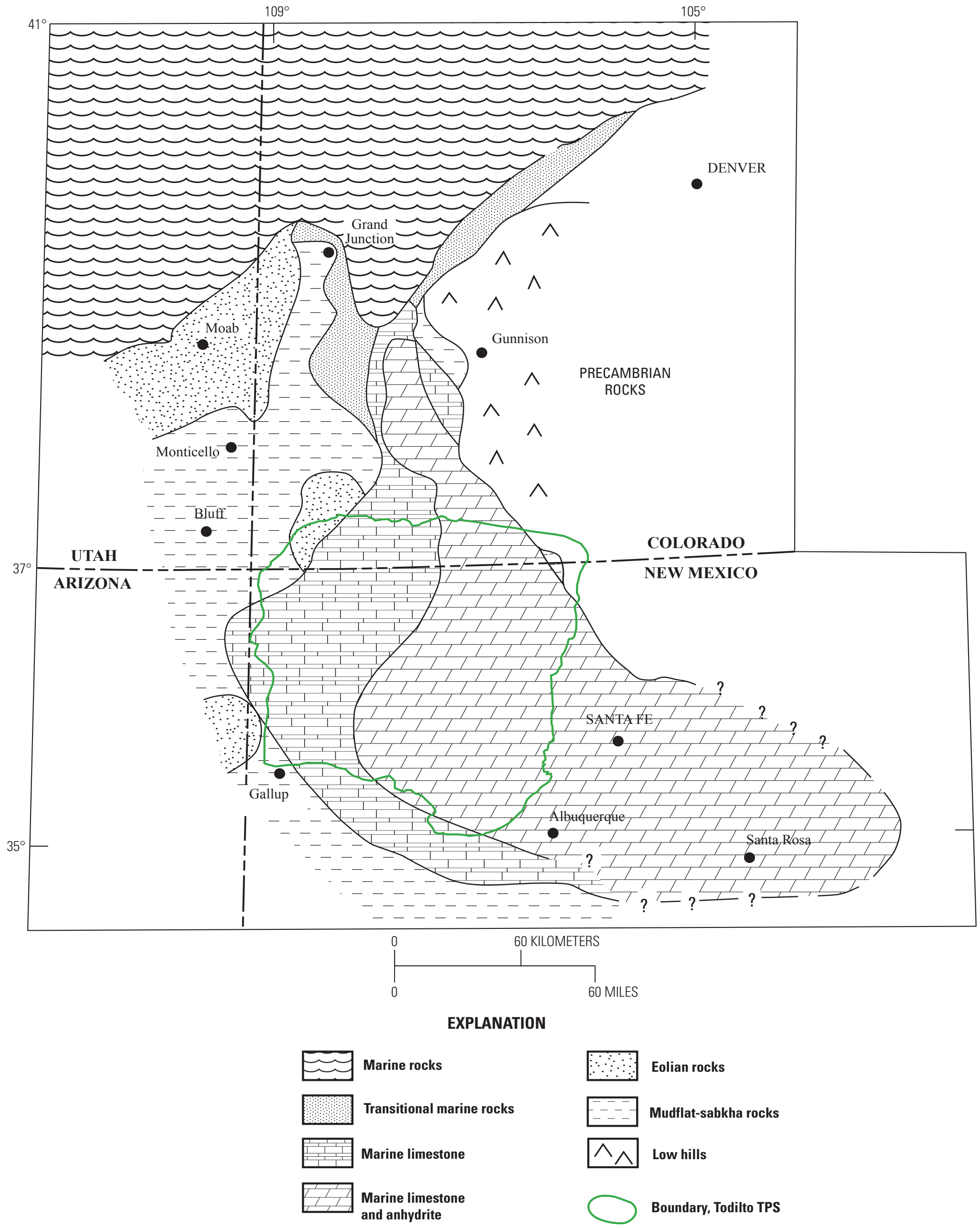



**Figure 3.** Paleogeographic reconstruction showing distribution of rock types and environments of deposition related to Middle Jurassic Todilto Limestone Member of the Wanakah Formation deposition (from Ridgley, 1989). TPS, Total Petroleum System.

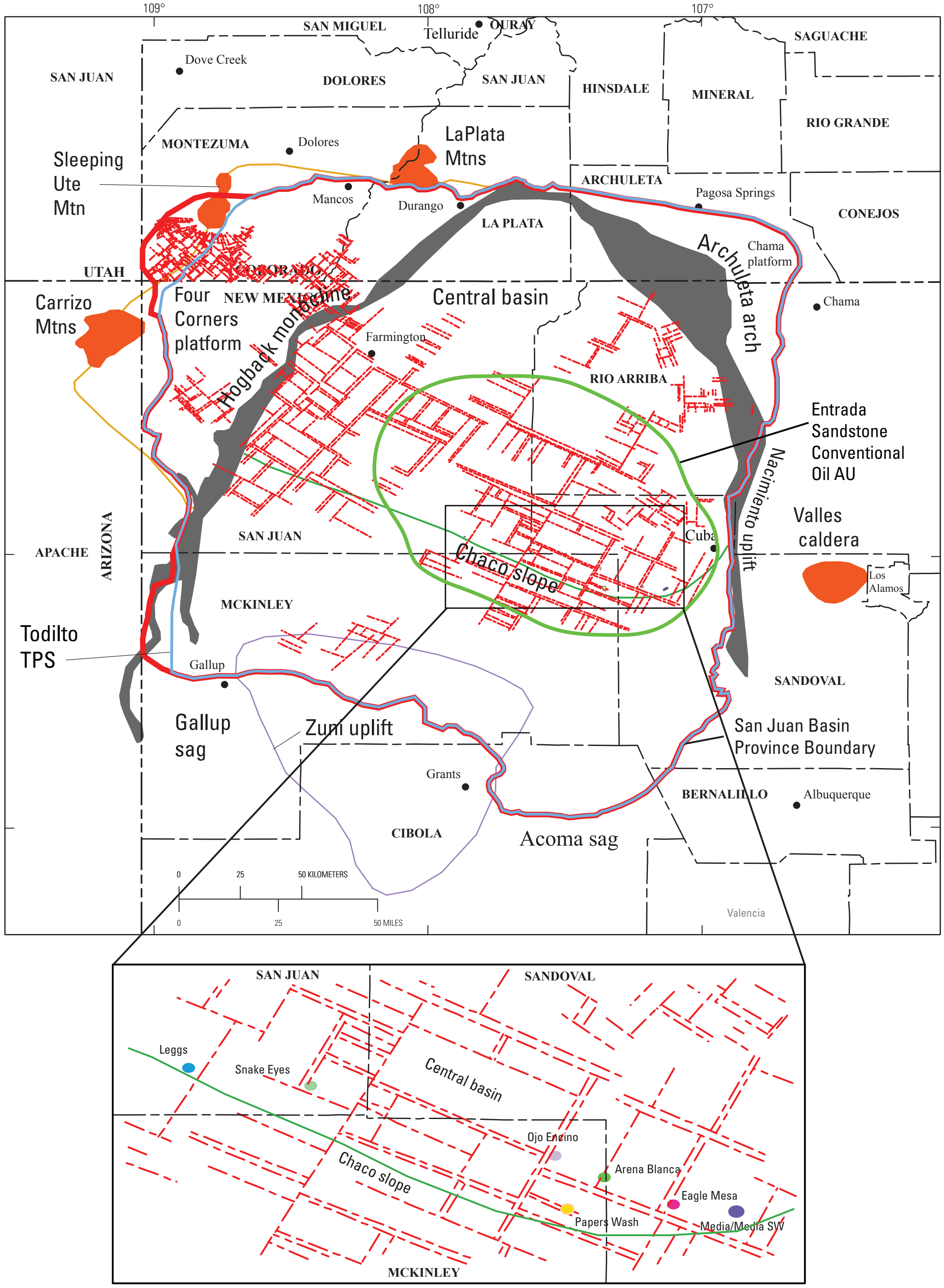



**Figure 4.** Map showing the boundary of the San Juan Basin Province (5022) (heavy red line), Todilto Total Petroleum System (TPS) (light blue line), Entrada Sandstone Conventional Oil Assessment Unit (AU) (heavy green line), and location of Entrada Sandstone oil fields (inset map). Also shown are the locations of inferred basement structural blocks (dashed red lines) modified from Taylor and Huffman (1998, 2001), and Huffman and Taylor (2002). Names and areal distribution of structural elements modified from Fassett (1991). Orange polygons are Late Cretaceous and Tertiary intrusive and extrusive igneous centers; gray polygons are areas of steep dip along monoclines. Inset map (enlargement) shows the relation of Entrada Sandstone oil fields to inferred basement structural blocks and boundary between the central basin and Chaco slope (light-weight green line).

There are eight oil fields in the Entrada reservoirs:

1. Arena Blanca,
2. Eagle Mesa,
3. Leggs,
4. Media,
5. Media Southwest,
6. Ojo Encino,
7. Papers Wash, and
8. Snakes Eyes (fig. 1),

and several isolated undesignated fields consisting of single wells (see field descriptions in Fassett, 1978a,b, 1983). Approximately 6 MMBO and 124 BCFG have been produced from 44 wells in the Entrada (IHS Energy Group, 2003). Media field, the first Entrada discovery, was found in 1953 (Vincelette and Chittum, 1981) and produced only small quantities of oil until 1969. At that time new exploration concepts were developed, and the field was recognized as primarily a stratigraphic trap and not a structural trap. Once this control on oil accumulation was recognized, subsequent production was increased through the drilling of new wells. After 1969, new drilling for Entrada oil elsewhere in the basin was more successful. Most of the Entrada oil fields were discovered in the early to mid 1970s. The Arena Blanca field was discovered in 1985. Most of the post-1970s discoveries were wildcat wells drilled in the Entrada, and all but the Arena Blanca field consist of single-well production (IHS Energy Group, 2002). Seismic studies have always been an integral part of exploration because the Entrada target (dune crests) is too small to determine from conventional well-log correlation. In the San Juan Basin, fewer than 910 wells penetrate the Entrada.

In the San Juan Basin, a slight break in the regional tilt occurs between the Chaco slope to the south and the central basin to the north (fig. 4). It is near this break in slope in the southern part of the central basin that all the oil fields are found. In fact, the oil fields, although isolated, are aligned northwest–southeast subparallel to the regional structural grain. When these fields are superimposed on the basement blocks (fig. 4), each field occurs within a block near the southern terminus where two blocks intersect. The blocks probably did not control migration of the oil, but rather may have controlled original depositional thickness and preservation of the Entrada. There has been some re-migration of oil out of traps; these sandstone traps are now water wet and some contain residual oil (Vincelette and Chittum, 1981). Flushing of traps probably occurred after the northeast regional tilt was developed, and erosion of rocks along the southern and eastern margin of the basin allowed inclusion of younger meteoric water.

# Todilto Total Petroleum System

The Todilto TPS is in many ways similar to the Minnelusa and Leo Total Petroleum Systems in the Powder River Basin (Ahlbrandt and others, 2003). The main difference is that the Entrada is a much more massive sand sea, or erg, with much less source rock potential, and the hydrocarbon accumulations are trapped along the buried topography of the final Entrada dunes that are at the top of the extensive erg system. Key elements that define the Todilto TPS in the San Juan Basin are source rocks of sufficient thermal maturity to generate hydrocarbons, migration pathways that permit the hydrocarbons to move into reservoirs, structural or stratigraphic traps that serve as areas where hydrocarbons accumulate, seals to contain the accumulations, and reservoir rocks to host the accumulations. These key elements are described more fully below.

## Structural Configuration

Although there was differential tectonic activity during the Paleozoic and Mesozoic, the principal time of formation of the San Juan Basin occurred during the Laramide orogeny, which began in the Paleocene and extended into the Eocene. Structure contours drawn on top of the Todilto Limestone Member (fig. 5) are similar to those drawn on top of the Dakota Sandstone (Thaden and Zech, 1984; plate 1), and both show the present-day configuration of the basin. The basin deepens from south to north (fig. 5); the deepest part of the basin is asymmetrically centered near the Colorado-New Mexico State line. The dip of the structure contours on top of the Todilto rises along the western and northern margins of the basin, coincident with the Hogback monocline, and along the eastern margin, coincident with the Archuleta arch (figs. 4 and 5). Overburden thickness above the Todilto ranges from 0 ft at the outcrop, along the eastern, southern, and western margins of the basin, to more than 9,500 ft in the deeper part of the basin.

## Hydrocarbon Source Rock

### Todilto Limestone Member of the Wanakah Formation

The Todilto Limestone Member of the Wanakah Formation comprises a basal limestone facies, which contains interbedded organic-rich shale, and an overlying anhydrite facies, which diagenetically alters to gypsum at or near the surface.

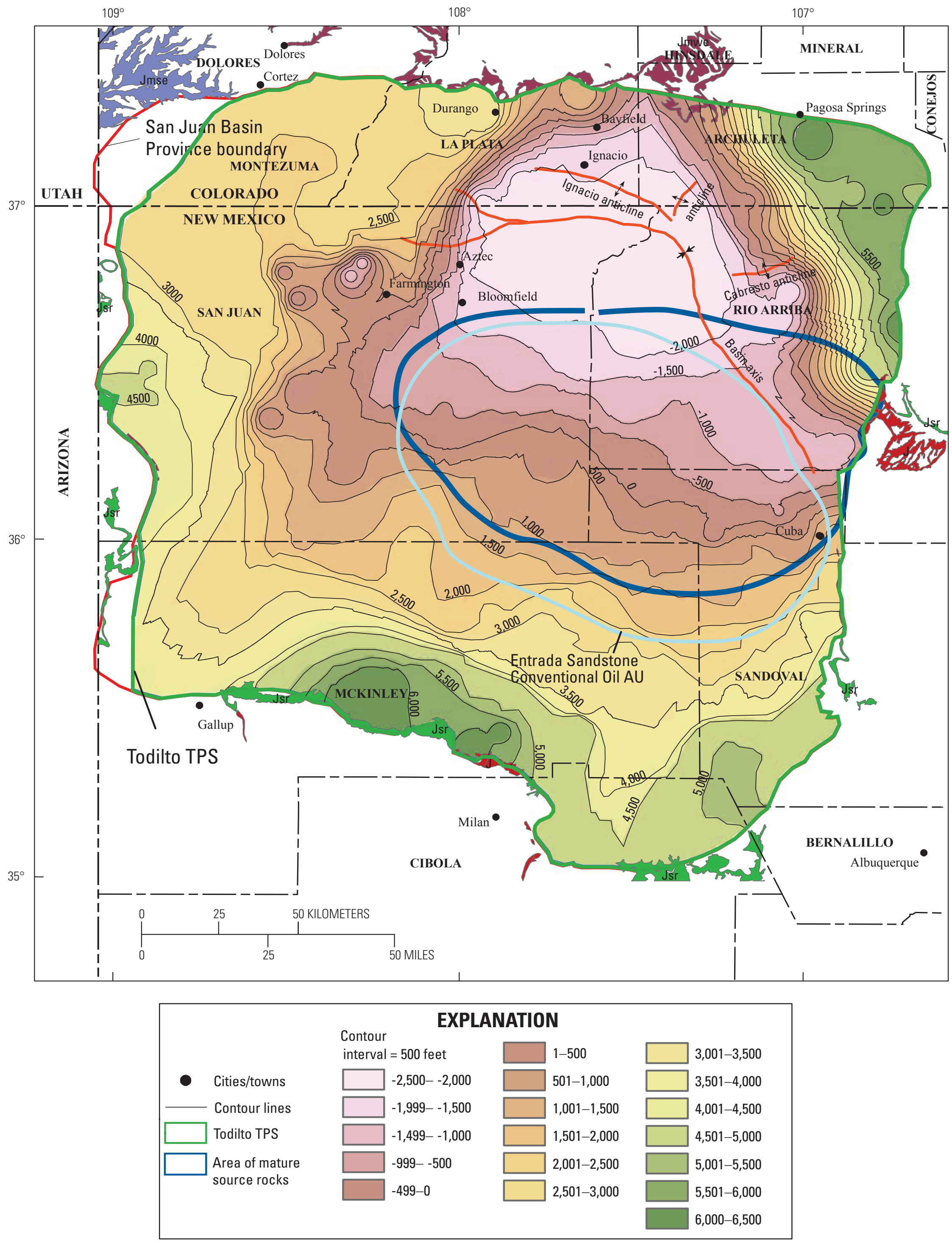



**Figure 5.** Structure contour map, with color shading for depths, drawn on top of the Todilto Limestone Member of the Wanakah Formation (produced from data from IHS Energy Group, 2002); contour interval 500 ft. Geologic map from Green (1992) and Green and Jones (1997). Datum is mean sea level. Pod of mature oil source rock (dark blue line). Also shown is the boundary of the San Juan Basin Province (5022) (red line), Todilto Total Petroleum System (TPS) (dark green line), and Entrada Sandstone Conventional Oil Assessment Unit (AU) (light blue line). See figure 1 for explanations of map symbols.

Throughout most of its areal extent (fig. 3), the limestone facies is laminated, consisting of alternating layers of calcium carbonate and shaly layers rich in organic matter, mostly sapropel (Anderson and Kirkland, 1960). This facies is commonly less than 20 ft thick throughout the depositional extent of the Todilto. The organic matter in the limestone facies appears to be best preserved in the area of the San Juan Basin where the limestone is overlain by anhydrite (Vincelette and Chittum, 1981, their fig. 3). However, preservation of organic matter could extend beyond the anhydrite. The anhydrite facies contains few organic source beds. Along the western and southwestern outcrop of the Todilto, the limestone is light gray, contains algal remains, and appears to have been deposited in more oxygenated depositional environments (Tanner, 1970) where organic matter is less well preserved.

Thickness of the Todilto ranges from less than 10 ft along the western margin to over 100 ft in the eastern part of the TPS (fig. 6). The thickness variation directly reflects the amount of topographic relief on the underlying Entrada dunes because the Todilto fills in the topographic relief on top of the dunes as well as covers the crests of the dunes, thus forming potential source rock and seal for underlying Entrada hydrocarbon accumulations. In the central and eastern part of the TPS where there is variable relief on the dunes, the Todilto is thickest, up to 130 ft. Where relief on the Entrada dunes is the greatest and where Todilto overlies the crest of the dunes, it is thinnest, down to 10 ft or less. The area of overall maximum total thickness of the Todilto (fig. 6) also coincides with the areal extent of the anhydrite beds (fig. 3). In the western part of the TPS, the total thickness of the Todilto is generally less than 20 ft and reflects the absence of the anhydrite facies. Isopach thicknesses of the Todilto are only an approximation of the true thickness because there are only about 900 wells drilled into the Entrada and most of these are in the areas of known oil fields.

Depths to the top of the Todilto and Entrada are variable, ranging from 120 to more than 10,000 ft (n = 417) and from 30 to more than 10,100 ft (n = 904), respectively. In the main producing fairway, depths to the top of the producing zone in the Entrada range from 4,600 to 6,000 ft. A structure contour map on top of the Todilto Member shows that the unit is less deeply buried along the western and southern margin of the TPS (fig. 5). If source rocks were at one time present in these areas of the TPS, they may have been oxidized by incursion of post-deposition meteoric groundwater. Indeed, there is evidence from the outcrop along the southern margin of the San Juan Basin that anhydrite once had a greater distribution in the area (Rawson, 1980). Post-depositional groundwater movement has altered the anhydrite to calcium carbonate. Evidence for organic matter once present in the limestone facies along the southern margin of the basin (where the anhydrite has possibly been altered) is inferred from the distribution of uranium deposits—which are associated with isolated organic matter—along the southern margin of the basin at the outcrop or in the near subsurface (Rawson, 1980).

The Todilto Limestone Member can be subdivided sedimentologically into two distinct facies, an outer margin facies (5 to 40 ft thick) and a central basin facies (2 to 120 ft thick) (figs. 1 and 7). The changes in style of deposition and vertical succession of the limestone help to determine the relative position of any location to the original depositional basin geometry and to potential source rocks. Figure 7 shows the interpretation of facies distribution in a schematic cross section through the basin. The outer margin facies can be subdivided into three limestone lithofacies, from base to top:

1. thick, parallel-bedded limestone, where the thickness of individual beds is related to the depth of water in which the calcium carbonate was precipitated;
2. sedimentary boudinage; and
3. massive crossbedded limestone.

Limestones in the thick, parallel-bedded lithofacies are similar in geometry to those considered to represent deposition in “deeper water” (Carrasco-V, 1977; Garrison and Fischer, 1969; Wilson, 1969; Yurewicz, 1977). Overall, this lithofacies consists of couplets of parallel-bedded micritic limestone (2 to 6 in. thick) separated by thin (commonly less than 0.5 in. thick) shaly limestone. The shaly layers are much darker gray than the encasing limestone beds and are probably more organic rich than the thicker limestone beds. The thick, parallel-bedded limestone lithofacies is distributed along the western margin of the central basin facies. It grades laterally landward into and is overlain by the sedimentary boudinage lithofacies (fig. 7). This lithofacies may contain a few potential source beds in the organic-rich shale layers.

The sedimentary boudinage lithofacies is characterized by wavy bedding surfaces, which impart a characteristic sedimentary boudinage or pinch-and-swell appearance (fig. 7). Limestone of this interval is thinner bedded, more micritic, and less sandy than in the overlying massive crossbedded lithofacies. The limestone is darker gray than limestone of the massive crossbedded lithofacies, indicating greater reducing conditions in the depositional environment. Thin silty or sandy, clayey or possibly gypsiferous lenses are commonly intercalated with limestone. The boudinage texture is a result of differential compaction of the limestone lenses into underlying silt, clay, or gypsum lenses while both were still plastic. Similar sedimentary boudinage have been reported from the lower part of the Cambrian and Ordovician Whipple Cave Formation, Nevada (Cook and Taylor, 1977). Wilson (1969, p. 17) and Cook and Taylor (1977, p. 55) suggested that sedimentary boudinage formed in shallow subtidal shelf waters, below wave base but within oxygenated water. Cook and Taylor (1977) also noted that the rocks in the sedimentary boudinage zone of the Whipple Cave Formation were gradational into overlying rocks characteristic of shoaling depositional environments and differed from rocks deposited in deeper water. Potential hydrocarbon source beds probably do not occur in this lithofacies.

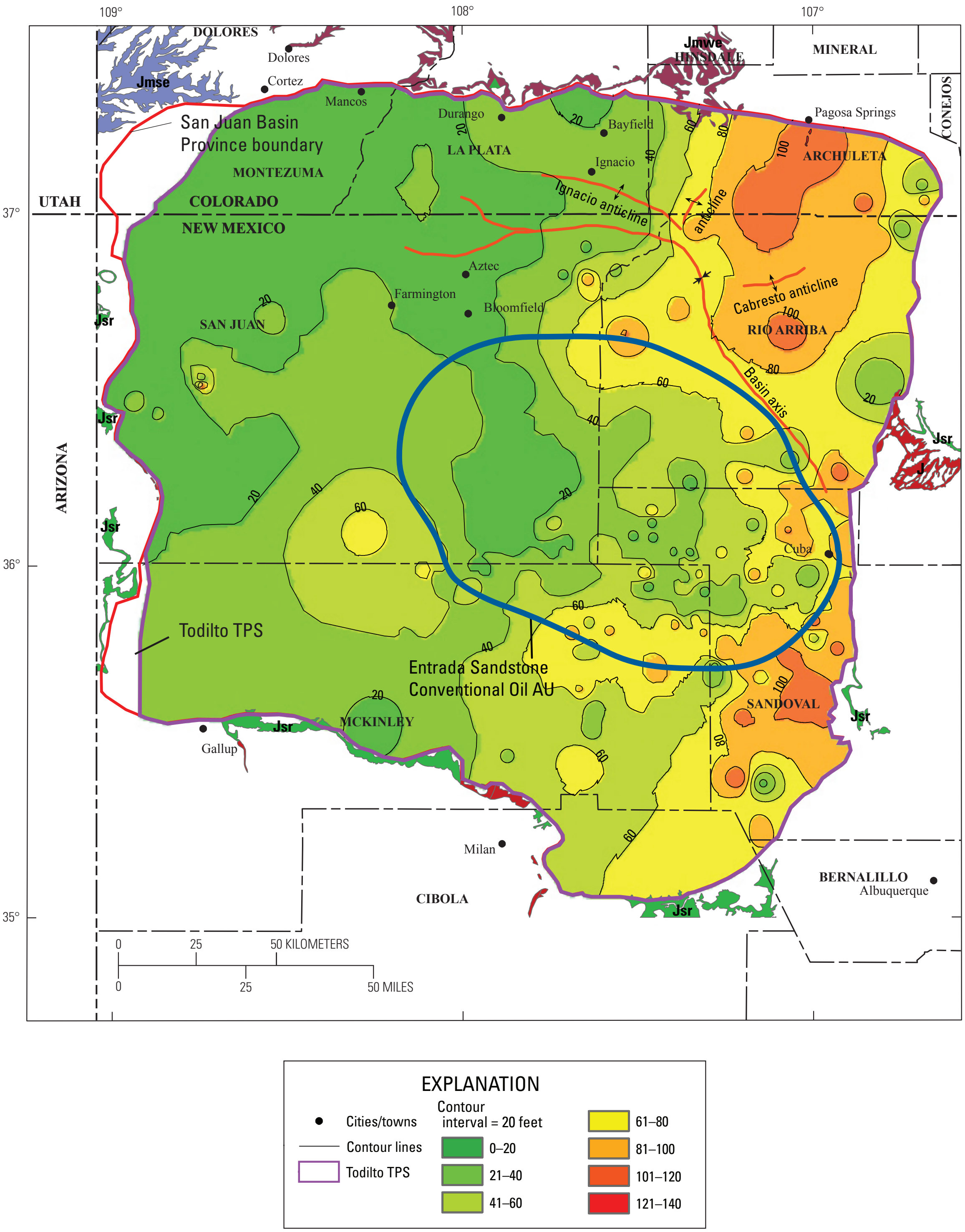



**Figure 6.** Isopach map of Todilto Limestone Member of the Wanakah Formation (produced from data from IHS Energy Group, 2002); contour interval 20 ft. Geologic map from Green (1992) and Green and Jones (1997). Also shown is the boundary of the San Juan Basin Province (5022) (red line), Todilto Total Petroleum System (TPS) (magenta line), and Entrada Sandstone Conventional Oil Assessment Unit (AU) (blue line). See figure 1 for explanation of geologic symbols.

The sedimentary boudinage lithofacies is overlain by and grades laterally landward into light-gray to light-purple-brown thick-bedded limestone of the massive crossbedded lithofacies (fig. 7). This limestone is commonly crossbedded and sandy, and locally contains either algal stromatolites or chert pebbles at the top. Crossbedding in the limestone indicates deposition in shallow water depths affected by water currents. The sandier component of the limestone indicates close proximity to the coast where marginal sand could be reworked, during storms or higher water level, into the precipitating limestone. The light-gray color of the rocks and presence of algal stromatolites indicate that the water was well oxygenated, and thus these rocks are poor candidates for preserving high total organic carbon (TOC). These limestones locally contain spherical to irregular masses of sparry calcite that possibly represent replacement of evaporite minerals. Potential hydrocarbon source beds are absent in this lithofacies due to shallow water depositional conditions and presence of oxygenated environments.

The central basin facies occupied the eastern part of the depositional basin, extending from near Gunnison, Colo. to east of Santa Rosa, N. Mex. (fig. 3). It can be divided into two subfacies, A and B, both of which are found throughout this part of the depositional basin and reflect different depositional conditions with respect to buried Entrada Sandstone dune topography (fig. 7). Subfacies A contains only limestone and is confined to the crests of the Entrada dunes. Subfacies B contains limestone overlain by gypsum (anhydrite in the subsurface) and is confined to the flanks and areas where a relict Entrada dune is least thick (fig. 7). Subfacies A can be subdivided into three distinct lithofacies (fig. 7), in ascending order:

1. platy limestone,
2. crinkly limestone, and
3. breccia limestone.

Thin parallel-bedded limestone consisting of thin laminated (only a few millimeters thick) dark-gray, fetid, micrite makes up the platy limestone lithofacies. The limestone has an appearance of papery-thin shale and consists of alternating laminae of micrite and organic matter (sapropel). The best hydrocarbon source beds are found in this lithofacies. At a few locations, thin sandstone beds are intercalated with the basal limestone. The sandstone has limited lateral extent at the outcrop. This platy lithofacies is found in both subfacies A and B (fig. 7) and may serve, in part, as a seal to upward and lateral hydrocarbon migration.

Overlying the basal platy limestone lithofacies is the slightly thicker crinkly lithofacies (fig. 7). This limestone is medium to dark gray and consists of alternating thin laminae of micritic limestone and organic matter that commonly contains clastic grains (Anderson and Kirkland, 1960). The micritic laminae are thicker (up to 10 mm thick) than in the underlying platy limestone lithofacies. Some laminae are light gray or white and represent calcite replacement of bedded gypsum. The clastic-grain laminae are commonly only one grain thick and consist of quartz and lesser amounts of feldspar, clays, and iron minerals. The rhythmic vertical succession of micrite laminae, organic laminae, and clastic laminae in the platy and the crinkly lithofacies imparts the varved appearance so often referred to in the literature. The varved appearance is confined to the central basin facies; individual laminae are believed to be seasonally deposited (Anderson and

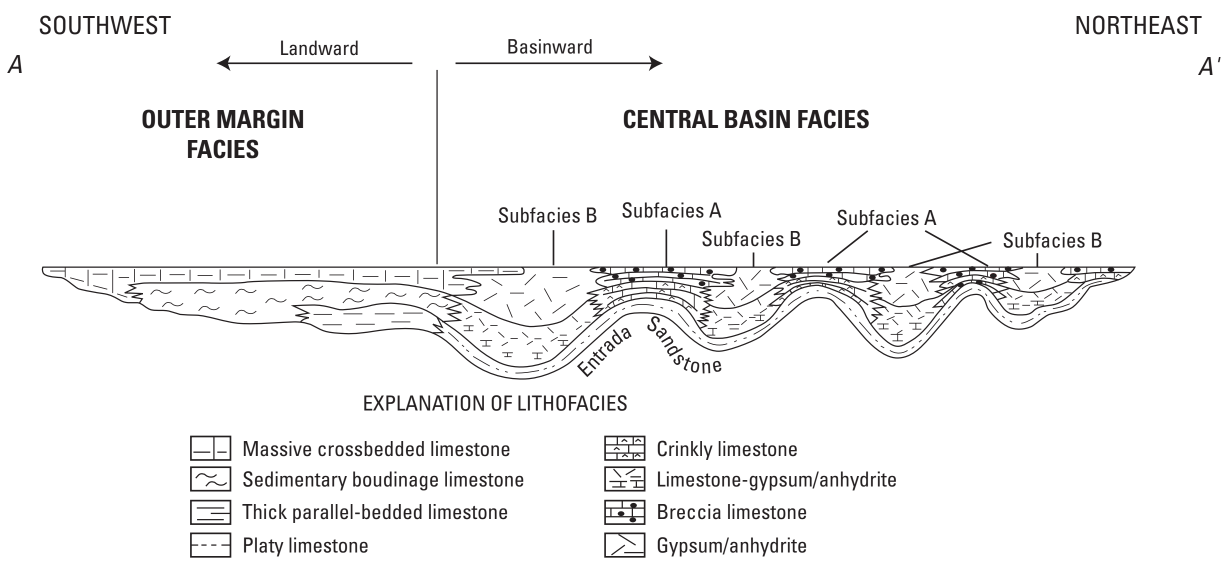



**Figure 7.** Schematic southwest–northeast cross section (*A–A′*) through the Todilto Limestone Member of the Wanakah Formation in the San Juan Basin, showing interpreted facies distribution between outer margin and central basin. (Approximate location on figure 1.) In the central basin facies, subfacies A, vertical lithofacies distribution over the crest of an Entrada dune; subfacies B, vertical lithofacies distribution between the crests of Entrada dunes.

Kirkland, 1960). Potential hydrocarbon source beds (aggregate up to about 5 ft) are also found in this lithofacies. This lithofacies (5 to 10 ft thick) may also serve, in part, as a seal to upward hydrocarbon migration.

The upper breccia-limestone lithofacies comprises thick, laminated to "brecciated" limestone (fig. 7). This lithofacies (10–30 ft thick) consists dominantly of microcrystalline calcite; however, more sparry calcite is present than in the crinkly lithofacies. This lithofacies is thicker than either of the two underlying lithofacies and commonly has a mound-like shape. The breccia-limestone lithofacies may occur as a single mass or as several laterally continuous masses separated by a bounding surface that represents a paraconformity. The lithofacies is made up of three distinct types of limestone. The first type of limestone consists of sparry calcite that contains fragments of dense micritic limestone similar to that observed in the lower two lithofacies. The sparry calcite is a secondary replacement of authigenic gypsum, and the micrite fragments are not true breccia clasts (Ridgley, 1986). The brecciated fabric is diagenetic and resulted from interstitial growth of gypsum, which ultimately consumed parts of the micrite, leaving remnant patches of micrite that look like breccia clasts. A second type of limestone is similar to the first except that clasts of limestone, similar to that in the lower two lithofacies, are actually clast-supported or are surrounded by calcite. Calcite in this type of breccia is both a true cement and a replacement of authigenic gypsum. This type of limestone may actually represent a true solution breccia. The third type of limestone is wavy-laminated to weakly crossbedded limestone. The limestone is micritic with thin laminae of clastic grains, one grain thick, and is similar to the texture observed in the platy and crinkly subfacies. The clastic grains are quartz, clay minerals, and feldspar. Patches of sparry calcite occur in the micrite. This calcite either replaced individual anhydrite or gypsum grains or clusters of these minerals, or filled in the voids when the evaporite minerals dissolved (Ridgley, 1986). Texturally, the three types of limestone of the breccia-limestone lithofacies indicate the former presence of gypsum. This lithofacies does not contain potential hydrocarbon source beds, nor is it a potential reservoir. However, because of their well-cemented nature, rocks in this lithofacies form a good seal to upward hydrocarbon migration.

Subfacies B can be subdivided into three lithofacies that are lateral equivalents of the three lithofacies of subfacies A (fig. 7). These lithofacies, from base to top, are

1. platy limestone (<5 ft thick),
2. limestone-gypsum/anhydrite (5–20 ft thick), and
3. gypsum/anhydrite (20–100 ft thick).

The platy limestone lithofacies, previously described, is depositionally continuous with the platy limestone lithofacies of limestone subfacies A. Source beds with the best hydrocarbon potential are found in this lithofacies. This lithofacies may also serve as a partial seal to vertical and lateral migration of hydrocarbons.

The platy limestone lithofacies is overlain by the limestone-gypsum/anhydrite lithofacies (fig. 7) consisting of thinly laminated limestone that is interbedded with bedded gypsum. The limestone is laminated like that of the underlying platy limestone lithofacies. Generally, within a few feet of the base of this interval, gypsum laminae occur. Initially the gypsum laminae may occur several inches apart. Vertically, more gypsum laminae occur, and they become closer-spaced until proportionally they dominate over limestone laminae. Source bed potential of this lithofacies is minimal because of the amount of gypsum interbeds; the best petroleum source beds are near the base of the lithofacies where the thin laminated limestone beds are most prominent. The upper part of this lithofacies serves as a seal to lateral hydrocarbon migration, focusing the hydrocarbons into the upper part of the Entrada dunes.

Thick beds of gypsum/anhydrite compose the gypsum/anhydrite lithofacies (fig. 7). The gypsum also has a coalescing nodular texture, commonly called "chicken wire," due to the concentration of insoluble residue along the margins of the gypsum nodules as the nodules grew. The nodular aspect of the gypsum represents diagenetic alteration of originally bedded gypsum. The nodules are not formed by coalescence of large gypsum crystals, such as those described by Warren and Kendall (1985) from coastal salinas of Australia. At many locations the upper massive gypsum also appears to be interbedded with thin discontinuous limestone laminae, especially near the top. This lithofacies does not contain any potential hydrocarbon source beds or reservoirs but does form a seal to lateral migration of hydrocarbons into and out of the upper part of the Entrada dunes.

## Oil Geochemistry

There are eight oil fields with Entrada reservoirs:

1. Arena Blanca,
2. Eagle Mesa,
3. Leggs,
4. Media,
5. Media Southwest,
6. Ojo Encino,
7. Papers Wash, and
8. Snakes Eyes (fig. 1),

and several isolated undesignated fields consisting of single wells (see field descriptions in Fassett, 1978a,b, 1983). The Todilto Limestone Member is considered to be the source of oil in the Entrada Sandstone reservoirs (Vincelette and Chittum, 1981). This determination was based on a comparison of oil samples from the Eagle Mesa, Media, and Papers Wash Entrada fields with known Cretaceous and Pennsylvanian oils from the San Juan Basin (Ross, 1980; Vincelette and Chittum, 1981). The Entrada oil sample had a higher boiling point (205°F, 96°C), higher pour point (50° to 90°F, 10° to 32°C), and higher paraffin content compared to Cretaceous or Pennsylvanian oils (Ross, 1980; Vincelette and Chittum, 1981). Entrada oil is characterized by a low pristane/phytane ratio (0.86) and even-carbon predominance index of 0.91, suggesting generation from a carbonate source. API gravities are similar for all fields, ranging from 29.3° at Snake Eyes to 35.5° at Ojo Encino (table 1). These API gravities, which cover a narrow range, are among the heaviest in the basin. Sulfur content is low, ranging from 0.3 to 0.6 percent (Richard Vincelette, written commun., 2003; NRG, 2001).

There is little publicly available organic geochemical data for the Todilto. The range of total organic carbon is unknown; however, one sample from the basal part of the Todilto from the area of the Nacimiento Mountains on the east side of the basin yielded a TOC of 1.24 (Richard Vincelette, written commun., 2003). This sample had a hydrogen index (HI) of 717, which is indicative of type-I organic carbon. Rock-Eval analysis of the sample provided the following information: $T_{max}$ = 424°C, $S_1$ = 0.32, $S_2$ = 8.89, and PI = 0.02, where $S_1$ = integral of first peak (existing hydrocarbons volatized at 250°C for 5 minutes) (in milligrams/gram rock); $S_2$ = integral of second peak (hydrocarbons produced by pyrolysis of solid organic matter (kerogen) between 250°C and 550°C (in milligrams/gram rock); and PI, production index ($S_1/(S_1+S_2)$). Although the data indicate that the Todilto in this area is immature, the $S_1$ and $S_2$ values indicate sufficient hydrocarbon generative capability under the right thermal maturation conditions.

The most comprehensive published data on the organic geochemistry of the Todilto is on 28 samples from drill cuttings (Vincelette and Chittum, 1981). Although no Rock-Eval analyses were performed on the samples, the samples were analyzed for kerogen color (for thermal maturation) and subjected to pyrolysis to determine the potential hydrocarbon yield. The high HI value of the single outcrop sample may be indicative of algal organic matter. Unpublished laboratory data for the samples used in the study by Vincelette and Chittum (1981) also support a partly algal source for some of the Todilto source rock samples (Richard Vincelette, written commun., 2003). Residue of some samples had a distinct cellular-type pattern, which might be indicative of colonial-type algae, such as *Botrycoccus*. Samples T-2, T-7, T-11, T-13, T-17, and T-23a (see Vincelette and Chittum, 1981, their fig. 9 for locations) were reported to contain some algal-like matter, thereby indicating the presence in the Todilto of type-I organic matter. These samples generally lie outside the zone of maximum oil generation as determined by the color of the kerogen. However, all the samples lie within the area of preserved anhydrite facies, as discussed above, and thus some algal matter must have been present throughout the broader Todilto depositional system and not just confined to the shallow water margins (Tanner, 1970). The presence of algal matter may support a lacustrine or partly lacustrine origin for the Todilto.

Although little Rock-Eval data is available, pyrolysis yields were calculated for 5 samples of the Todilto in New Mexico (Vincelette and Chittum, 1981, their fig. 9). Within the area defined by the central basin facies, pyrolysis yields ranged from 0.6 to 2.4 gal/ton; these values may not reflect potential yield, because the samples are from the part of the basin where the Todilto is thermally mature (Vincelette and Chittum, 1981).

**Table 1.** Characteristics of Entrada Sandstone reservoir rocks, including oil API gravities, compiled from Vincelette and Chittum (1981) and from field descriptions in Fassett (1978a,b, 1983).

[N/A, not available].

| Field | Avg. depth (ft) | Porosity (%) | Permeability (millidarcies) | Water saturation (%) | Oil API gravity (degrees) | Net pay (ft) | Type of drive |
|---|---|---|---|---|---|---|---|
| Eagle Mesa | 5,460 | 25 | 430 | 45 | 33 | 23 | Water |
| Leggs | 5,400 | 23.3 | N/A | 55 | 31.5 | 16 | N/A |
| Media | 5,250 | 23 | 290 | 58.4 | 33.5 | 25 | N/A |
| Media, southwest | 5,310 | 24 | 360 | 58.4 | 33.5 | 18 | Water |
| Ojo Encino | 5,890 | 22 | 180 | 50 | 35.5 | 20 | Fluid expansion, water drive |
| Papers Wash | 5,170 | 25 | 290 | 53 | 32.5 | 29 | Fluid expansion, water drive |
| Snake Eyes | 5,600 | 24 | 665 | 50 | 29.3 | 23 | Fluid expansion, water drive |

## Source Rock Maturation

The time of thermal maturity of the source-bed facies in the Todilto can be estimated from three burial history curves (Bond, 1984; Law, 1992) (figs. 1, 8*A*, 8*B*, and 8*C*). These curves, taken from the literature, only cover the Cretaceous and Tertiary part of the stratigraphic column. Thus, the time of oil generation in the Todilto can only be extrapolated from these figures as no detailed modeling has been done for this unit. The burial history curves indicate distinct thermal maturation histories for different parts of the basin. Formation of the basin may have begun as late as 90 million years ago during the Sevier orogeny and continued until about 13 million years ago. Only the northernmost burial profile from the Natomas North America Federal-Texaco 1-11 well shows reconstructed temperature profiles. It is inferred that temperature profiles for the composite burial history for the Bakke Southern Ute 2 and Sohio Southern Ute 15-16 wells should be similar to the profiles in the Natomas well because the well also penetrates the deep part of the San Juan Basin. On the other hand, it is inferred that temperature profiles at the Superior Sealy 1-7 well in the southern part of the central San Juan Basin would show lower maximum burial temperature because this well penetrates strata that were never as deeply buried as strata in the Sohio or Natomas wells.

The southernmost burial history curve for the Superior Sealy 1-7 well in Rio Arriba County, N. Mex. (Law, 1992) (figs. 1 and 8*A*) is located in the northern part of the AU and indicates that this area of the central basin was never as deeply buried as the northern part of the central basin (figs. 4 and 5). Maximum burial for this curve was shown to span a time from 40 to about 12 million years—before uplift and erosion. In contrast, the composite burial curve from the Bakke Southern Ute 2 and Sohio Southern Ute 15-16 wells in the northern part of the central basin in La Plata County, Colo. (Law, 1992) (figs. 1 and 8*B*), documents a younger, present-day configuration. The northern part of the central basin, in which this northern curve is located, was an area of greater subsidence and accumulation of a thicker section of overburden as represented by Tertiary rocks, when compared to the area of the southern part of the central basin. Any liquid hydrocarbons generated earlier would have cracked to gas. Using the Dakota Sandstone thermal history profile (fig. 8*C*), the cracking would have started in the late Eocene and continued into the Oligocene.

Maximum hydrocarbon generation for Cretaceous source rocks probably occurred during the mid- to late-Eocene based on the burial reconstructions (fig. 8*C*) (Bond, 1984; Law, 1992). However, onset of oil generation may have begun as early as mid-Paleocene for source rocks in the Cretaceous Dakota Sandstone–Greenhorn Limestone Member of Mancos Shale interval, which is used here to aid in estimating Todilto maturation throughout the basin (fig. 8*C*). Oil generation may have continued until the middle Eocene, and in the deeper part of the basin, wet gas and condensate may have been generated until middle Miocene (fig. 8*C*). The thickness from the base of the Dakota Sandstone to the top of the Todilto averages about 1,000 ft. This thickness alone would probably not significantly change the overall maturation history of the Todilto source beds, and thus, the maturation history of these Middle Jurassic source beds probably approximates that of the lowest part of the Cretaceous section. Although the onset of hydrocarbon generation may have begun in the late Paleocene, the critical moment for maximum liquid hydrocarbon production was in the Eocene. The critical moment (Magoon and Dow, 1994) that defines the time of maximum hydrocarbon generation, migration, and accumulation will differ throughout the basin. Generation of liquid hydrocarbons ceased in the Pliocene as the basin was uplifted and cooled. Today, bottom-hole temperatures in the producing fields are generally below 60°C.

In their study of source-rock thermal maturity of the Todilto, Vincelette and Chittum (1981) examined the color of the kerogen in 28 samples from outcrop and core. Their results showed the Todilto to be thermally immature along the west, southwest, and extreme northeast parts of the depositional system and to increase in thermal maturity in the central and northern part of the San Juan Basin (Vincelette and Chittum, 1981, their fig. 9). They concluded that potential source beds in the Todilto would be mature enough to produce oil in the central part of the TPS, between the +1,000- and –2,000-ft contour intervals (fig. 5). South and west of this area, the source beds were immature, judged from a few samples. North of the –2,000-ft contour, in the deeper part of the basin, the source beds were considered to be overmature and beyond oil generation. The organic matter from several samples from this part of the basin appeared to be carbonized (overheated), and thus, the expected hydrocarbons would be gas and condensate. The apparent area of maximum oil generation, based on limited data, would be found between 5,000- and 8,000-ft depth, which corresponds to about +1,500- to –2,000-ft structural elevation (Vincelette and Chittum, 1981).

## Hydrocarbon Migration Summary

The period of migration and accumulation of oil in the Entrada may have extended from the Eocene through the end of the Miocene. Basin subsidence continued well into the Miocene, and it is this later subsidence that might have aided migration of oil from source to trap. During this period, strata in the southern part of the San Juan Basin were further tilted to the northeast. A slight break in the regional tilt occurs between the Chaco slope to the south and the central basin to the north (fig. 4). All the oil fields are found just north of the Chaco slope in the southern part of the central basin. The oil fields, although isolated, are aligned northwest–southeast subparallel to the regional structural grain and in proximity to the intersection of basement blocks, which have a predominant northwest to southeast orientation (fig. 4). The blocks probably did not control migration of the oil, but rather may have controlled syndepositional thickness and preservation of thick Entrada Sandstone. The migration distance of oil from Todilto

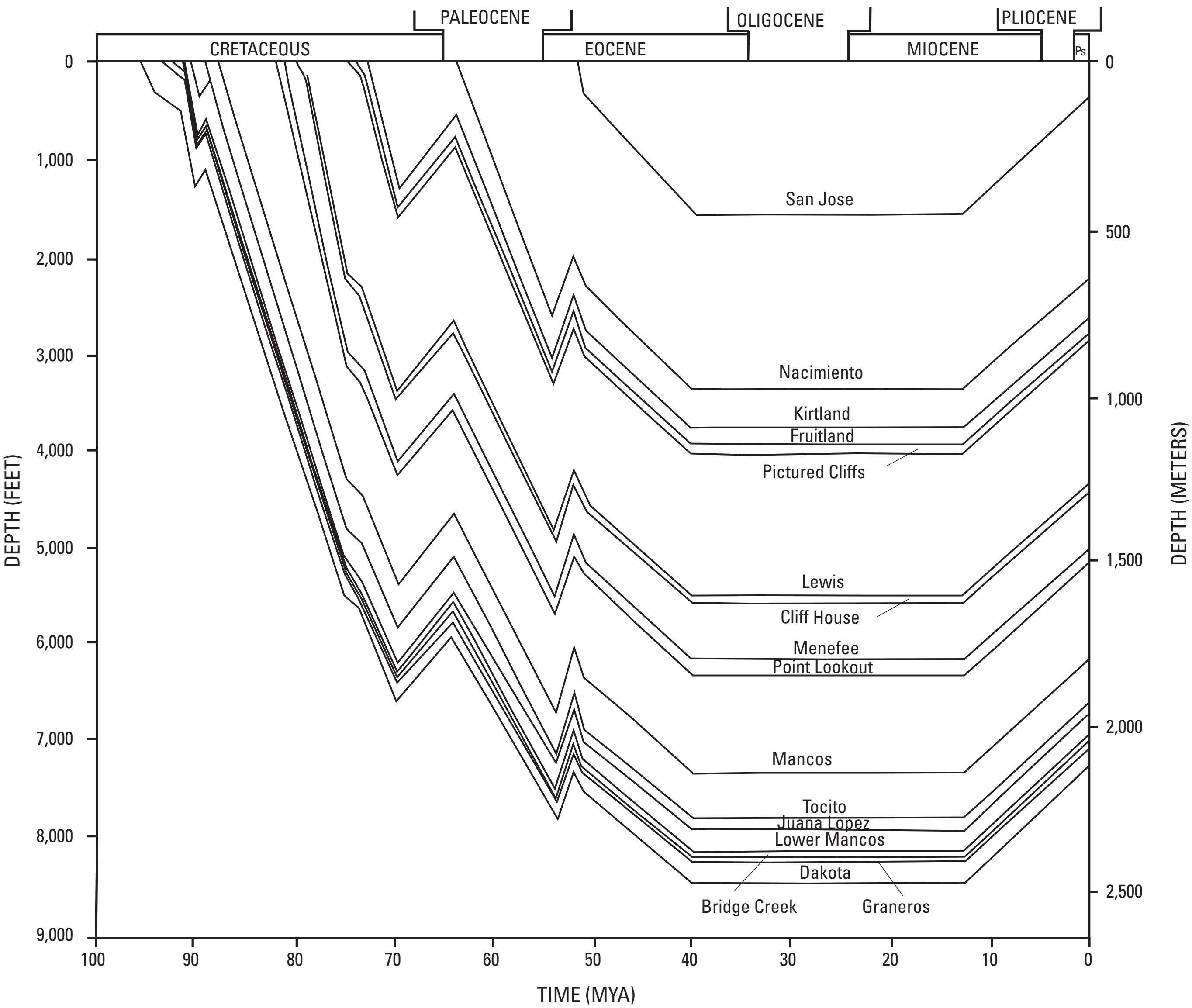



**Figure 8*A*.** Burial history curve for the Superior Sealy 1-7 well in the southern part of the central San Juan Basin (modified from Law, 1992). MYA, million years ago; Ps, Pleistocene.

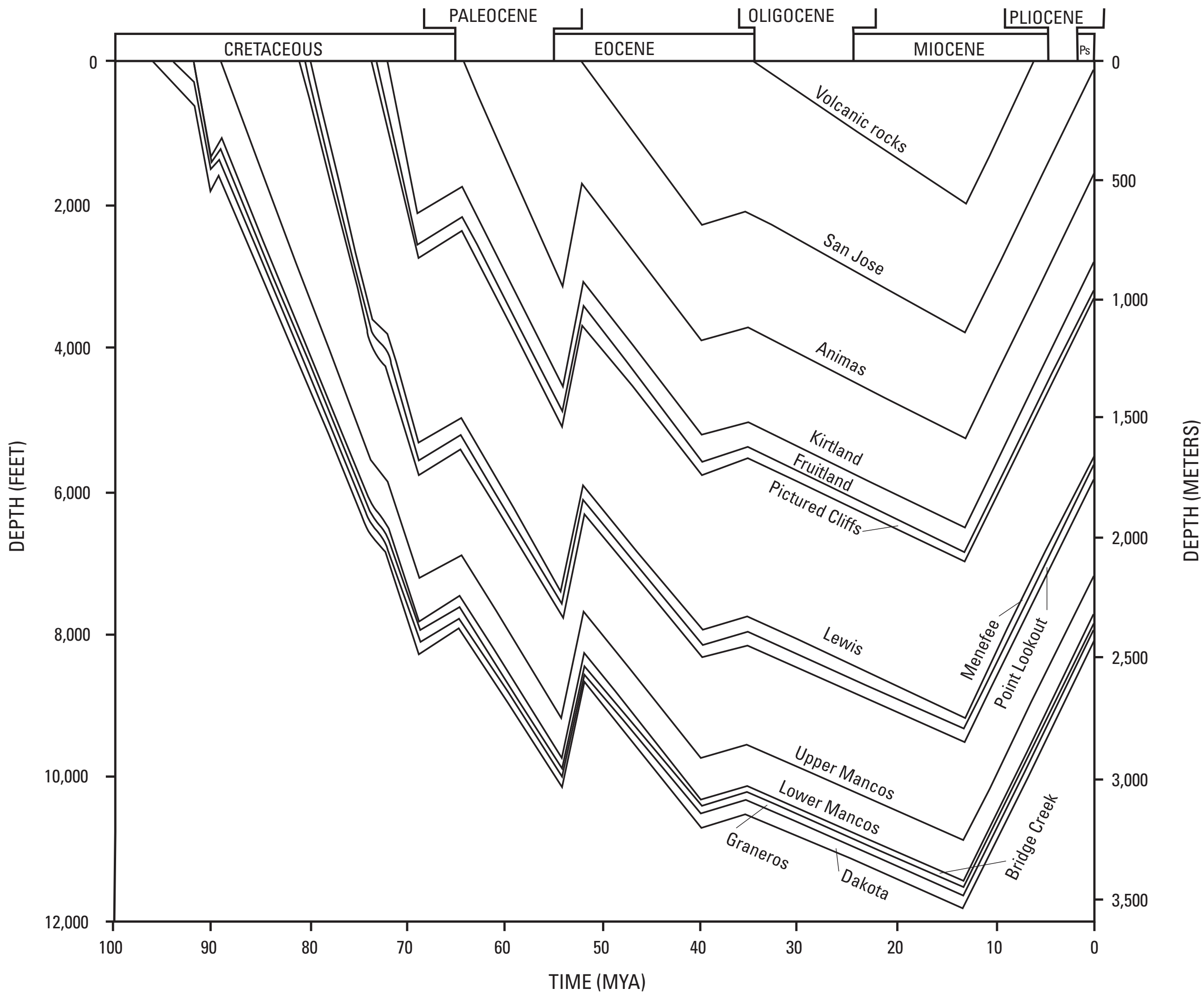



**Figure 8*B*.** Composite burial history curve for the Bakke Southern Ute 2 and Sohio Southern Ute 15-16 wells in the northern part of the central San Juan Basin (modified from Law, 1992). MYA, million years ago; Ps, Pleistocene.

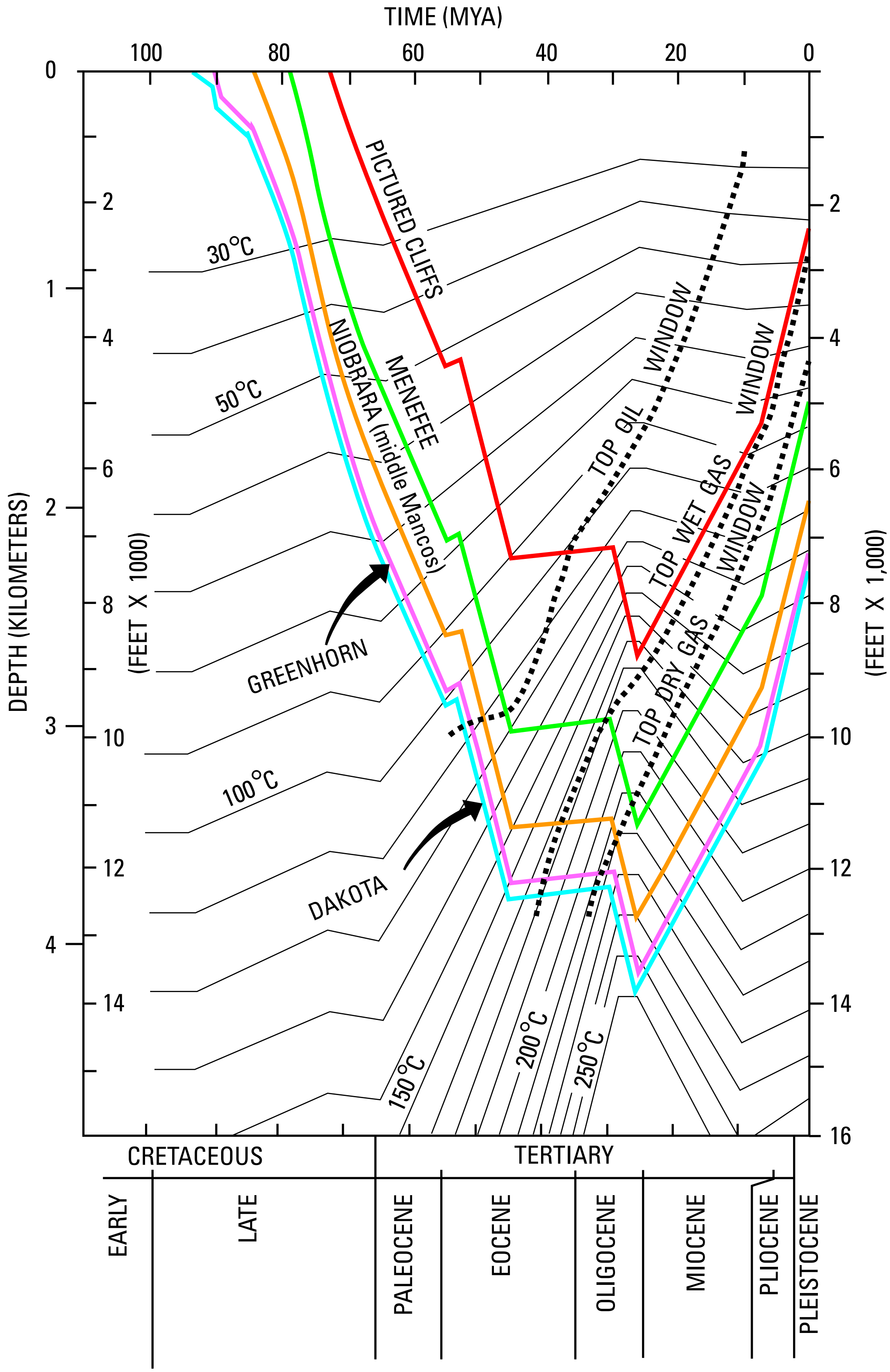



**Figure 8*C*.** Burial history curve for the Natomas North America (N.A.) Federal-Texaco 1-11 well in the northern part of the San Juan Basin (modified from Bond, 1984). Geologic time scale is from the Geological Society of America web page *http://www.geosociety.org/science/timescale/timescl.htm*, last accessed 2/1/2008. MYA, million years ago.

source beds into underlying Entrada Sandstone reservoirs was short (less than a few miles), probably within the dimensions of a single dune crest. However, early longer distance migration from the central basin cannot be ruled out. A stratigraphic cross section through the Papers Wash field (fig. 9*A*) shows the position of the oil. The oil in this field, as well as in others, is confined to the upper part of the dune where the Todilto Limestone Member (both limestone and anhydrite facies) is thinnest and where there is some stratigraphic closure. The oil-water contact (below the oil shown in fig. 9*A*) in this field appears to occur where the flanks of the dune begin to flatten and dune height and stratigraphic closure is diminished. The position of the oil-water contact may also have been influenced by later hydrodynamic factors and faulting.

The influence of hydrodynamics was documented in the Media and Media Southwest fields (Vincelette and Chittum, 1981). In those fields, oil mostly fills the southernmost parts of the stratigraphic closure. Other wells evaluated in the oil-producing area show evidence of flushing of the original oil accumulation by later hydrodynamic forces, indicating that the oil has remigrated to some other site or has otherwise been lost to the system (Vincelette and Chittum, 1981). Flushing of traps probably occurred after the northeast regional tilt was developed and erosion of rocks along the southern and eastern margin of the basin allowed intrusion of younger meteoric water.

Because the dune topography varies dramatically throughout the central part of the TPS, most of the oil would have been generated fairly locally, as it might have been difficult for the oil to migrate regionally through the laterally adjacent thick anhydrite facies that accumulated in the off-flank position of the dune. The various Entrada fields do not appear to be linked along any regional migration pathway that might suggest movement of hydrocarbons from the deeper part of the central basin along regional faults or through the lower sandstone of the Entrada. All the oil fields appear to occur where the Todilto is sufficiently mature to produce oil within the Entrada Sandstone Conventional Oil AU (fig. 1). These observations suggest that potential Entrada reservoirs are under-filled.

## Hydrocarbon Reservoir Rocks

Potential reservoir rocks are confined to the eolian sandstone facies in the Entrada Sandstone. The Entrada Sandstone consists primarily of sandstone deposited in dune and interdune eolian environments. The upper part of the Entrada (generally less than 100 ft thick) shows evidence of having been deposited or reworked in subaqueous conditions related to the incursion of marine waters in which the overlying Todilto Limestone Member was deposited (Reese, 1984; Fryberger, 1986). This water-laid facies is prevalent along the western and southwestern margin of the Todilto depositional system, but also has been reported from outcrops in the Chama Basin to the east (for the location of the Chama Basin, see chap. 2, fig. 1, this CD-ROM) (Tanner, 1970). In the southern part of the basin, the Entrada contains thin beds of reddish-brown siltstone deposited in interdune and inland sabkha environments (Green and Pierson, 1977). Thin coarse-grained sandstone units have also been reported in the Entrada from the southern part of the San Juan Basin and were probably deposited in ephemeral wadis (Green, 1974). Inland sabkha and wadi deposits are absent to the north and are not found along the eastern margin of the San Juan Basin nor in the Chama Basin; they appear to be confined to the margins of the Todilto depositional system.

The thickness of the Entrada in the San Juan Basin ranges from 60 to 330 ft (Green and Pierson, 1977). The variable thickness reflects, in part, the relict dune topography. Sandstone beds of Entrada generally exhibit three styles of crossbedding that have been observed along the east side of the basin and in the neighboring Chama Basin (Ridgley, 1977; Reese, 1984). In these areas, the basal Entrada consists of large-scale, sweeping wedge and trough cross stratification characteristic of eolian deposition. Parallel laminated beds in the lower part of the Entrada probably represent interdune deposits (Reese, 1984). Sandstones in the interdune deposits are commonly finer grained than in the dune sandstones and where present may be locally interbedded with siltstones and mudstones. The middle part of the Entrada consists of mostly medium-angle planar crossbeds and wavy-laminated sandstone. The wavy laminations were produced by adhesion ripples (Ridgley, 1977; Reese, 1984). The upper part of the Entrada consists of two different styles of deposition (Ridgley, 1977; Reese, 1984). The base of the upper part contains low- to high-angle eolian crossbeds. These beds are overlain by massive, structureless, or parallel laminated beds, in which the lack of well-defined sedimentary structures suggests modification by marine incursion that was associated with early stages of the overlying Todilto transgression. Most of the oil is found in the upper and middle parts of the Entrada.

The relation of Entrada Sandstone reservoirs to overlying source and seal rocks of the Todilto Limestone Member is shown in a regional cross section (fig. 9*B*) and a cross section through the Papers Wash oil field (fig. 9*A*). Seismic studies of the Entrada, which is the most effective means of delineating the dune topography (Vincelette and Chittum, 1981; Nestor and Endsley, 1992; Massé and Ray, 1995), are commonly employed in order to delineate potential traps. However, published seismic studies are few. Seismic studies on the east side of the basin indicate that dune crests form ridges that are oriented north-northeast; ridge length may be as long as 15 mi and ridge width may vary from 0.5 to 2 mi (Vincelette and Chittum, 1981). South of these elongate ridges are isolated pods of thicker Entrada, possibly indicating a different dune type or sand sea, or other factors that influenced preservation of dune topography. All the oil fields are found in these thick isolated sand buildups (Vincelette and Chittum, 1981, their fig. 16).

Where the Entrada has been examined at the outcrop, the uppermost sandstones (oil reservoir beds) are fine to medium grained and moderately to well sorted (Ridgley, 1977; Reese, 1984). Quartz is the principal sandstone component, although rock fragments and clays are also present. Quartz grains are well rounded to subangular. Locally, the sandstone beds have been described as silty (Reese, 1984). Porosity in the Entrada changes regionally. In the northern part of the San Juan Basin,

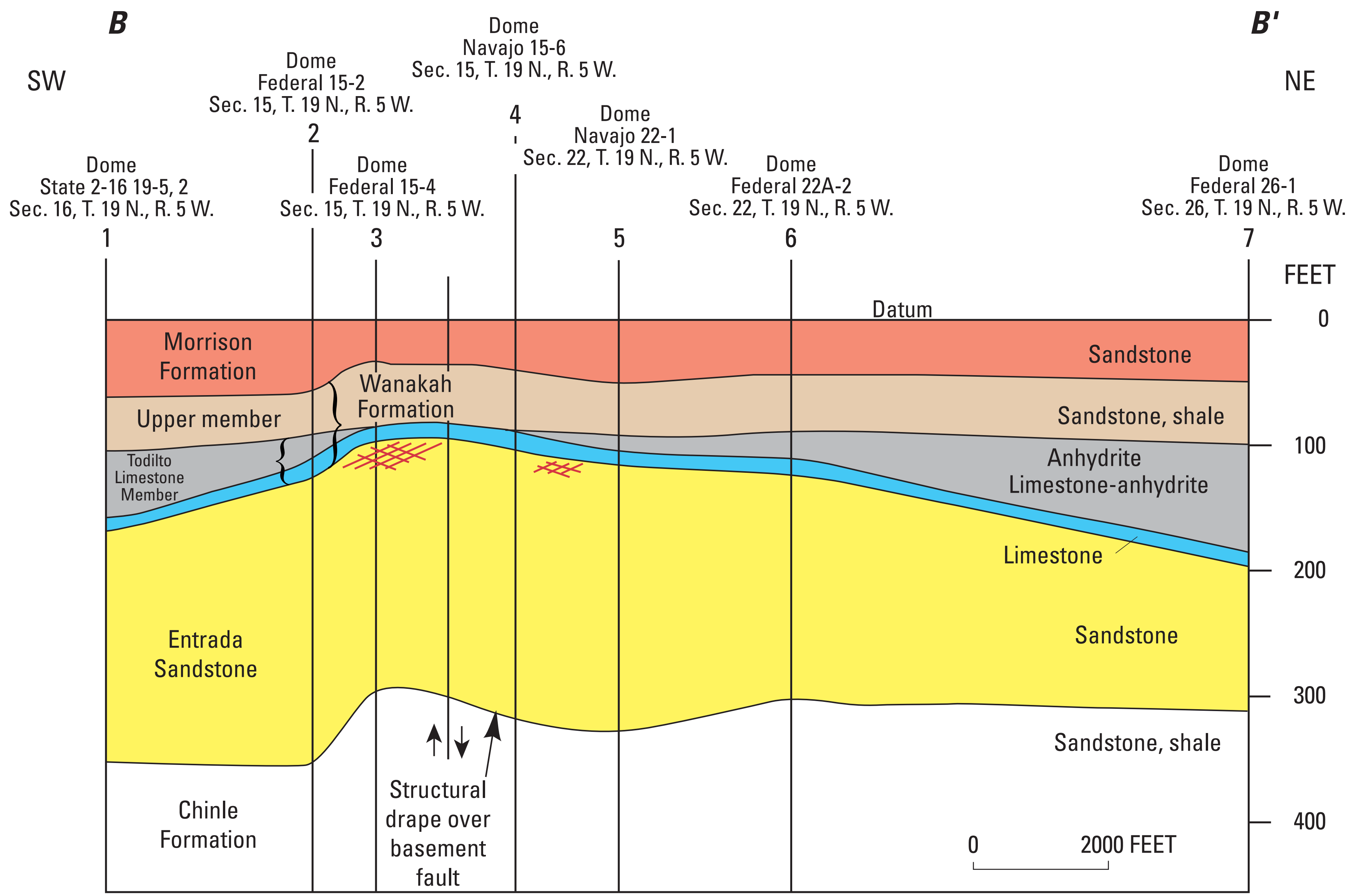



**Figure 9*A*.** Cross section *B–B′* extending from southwest to northeast across the Papers Wash Entrada oil field (modified from Vincelette and Chittum, 1981), showing relation of lithofacies of the Todilto Limestone Member of Wanakah Formation to relief on top of Entrada Sandstone. Datum, top of laterally continuous sandstone in the lower part of the Morrison Formation. Hachured (red), area of oil accumulation. Location of cross section shown on figure 1.

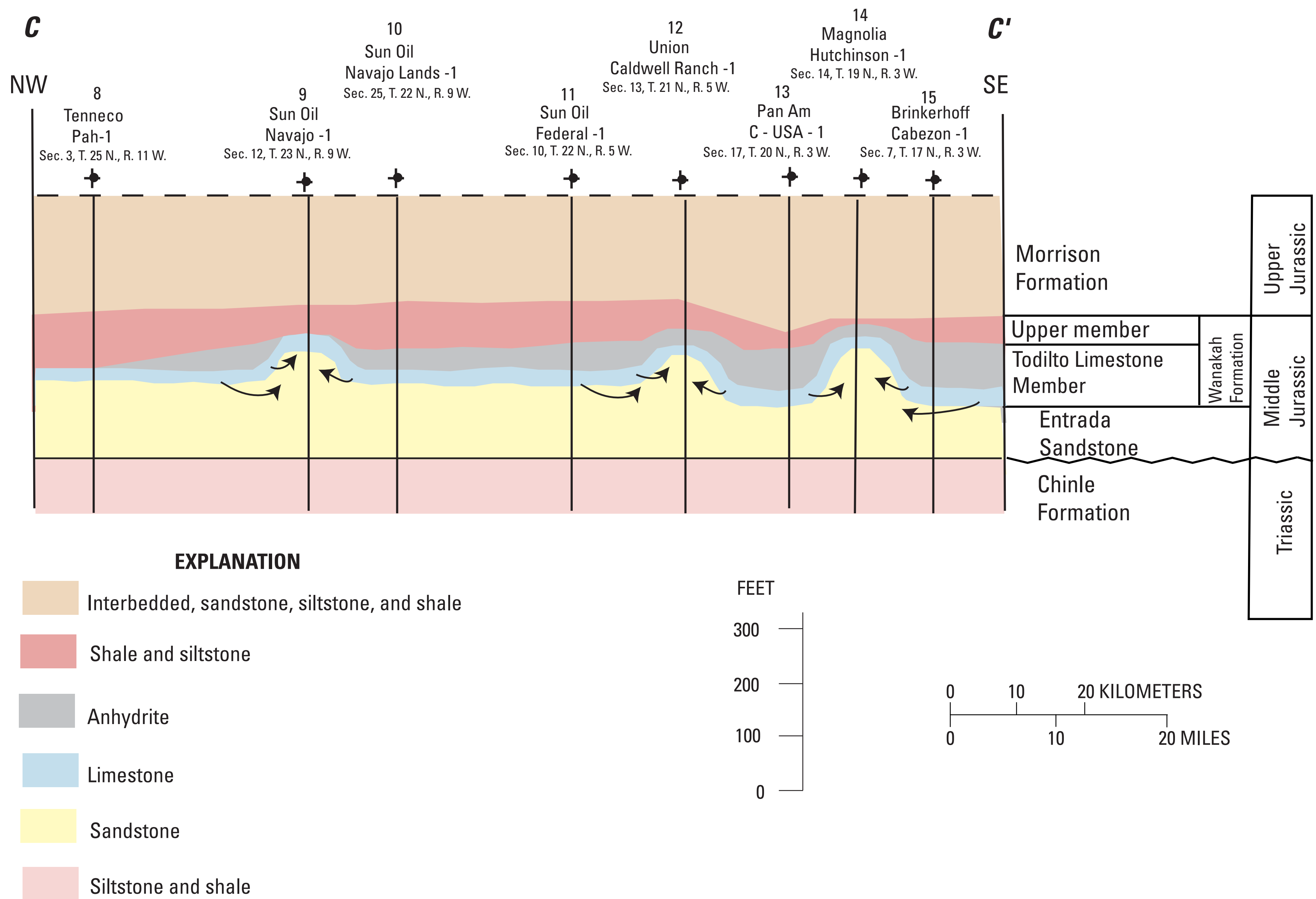



**Figure 9*B*.** Regional cross section *C–C′* extending from northwest to southeast through a part of the Todilto TPS, San Juan Basin (modified from Vincelette and Chittum, 1981). Datum, top of Chinle Formation. Arrows show direction of oil migration from Todilto Limestone Member of Wanakah Formation source beds into the Entrada Sandstone reservoirs. Location of cross section shown on enlargement in figure 1.

below about 9,000 ft in the subsurface, or at about –2,000-ft subsea, the Entrada has been described as extremely tight due to compaction and quartz cementation. On the east side of the basin, some of the pore-filling cements, including quartz, may have formed during migration of fluids during emplacement of Tertiary intrusions (Vincelette and Chittum, 1981). The Entrada in this part of the basin is often used as a disposal interval for waters produced from coal-bed methane production in the Cretaceous Fruitland Formation.

In the area where most of the oil has been found, the Entrada has extremely good porosities, which average about 23 percent, and permeabilities, which average about 300 millidarcies (md). The high permeabilities have allowed introduction of younger water into the Entrada. The age of the post-depositional water is not constrained, but most likely is late Miocene to Holocene, the time period when extensive erosion of rock overlying the Entrada resulted in exposure of the formation along the eastern, southern, and western margins of the San Juan Basin. Recharge waters entering these outcrops may have been responsible for removal or flushing of oil from some potential reservoirs (Vincelette and Chittum, 1981). Table 1 shows characteristics of Entrada reservoir rocks and oil API gravities.

## Hydrocarbon Traps and Seals

There are four principal types of traps in the Entrada Sandstone reservoirs:

1. stratigraphic traps related to dune topography with closure of at least 20 ft;
2. structural traps that were influenced by syndepositional movement on basement faults that controlled the geometry, thickness, and possible orientation of individual dunes;
3. northeast regional dip of Todilto–Entrada rocks that tends to limit the area of closure for oil accumulation to the updip southern portions of dune ridges and affects subsequent hydrodynamic repositioning of hydrocarbons; and
4. local and regional porosity changes that help to preserve oil locally or delineate favorable areas for oil accumulation (Vincelette and Chittum, 1981; Nester and Endsley, 1992).

The first two types of traps formed early in the history of deposition of the Entrada. All of the producing Entrada fields are examples of trap type 1 above. Papers Wash field is an example of a combination of types 1 and 2 traps, where preserved dune topography combined with syndepositional structural movement on a basement fault is important in defining the limits of the field boundary. Traps of the third type, controlled by the regional tilt of the strata, began forming in latest Cretaceous time and were enhanced during formation of the basin in Paleocene through Miocene time. The regional dip is estimated at about 1°. Entrada fields influenced by this type of trap include Eagle Mesa and Media fields. The fourth type of trap formed continuously, from the time of deposition until present day, and reflects the degree of diagenesis and lateral facies changes in the Entrada. Low porosity and permeability zones have been documented for several wells, such as those in the Papers Wash field. These zones tend to inhibit water production and, where oil is present, enhance hydrocarbon recovery (Vincelette and Chittum, 1981).

Thin basal limestone and thick anhydrite beds in the Todilto provide both lateral and vertical seals, preventing migration of oil from underlying Entrada Sandstone reservoirs.

# Entrada Sandstone Conventional Oil Assessment Unit (50220401)

## Introduction

The boundary of the Entrada Sandstone Conventional Oil Assessment Unit (AU) (050220401) (fig. 1) was drawn to encompass the following areas:

1. those Entrada dunes with enough significant relict topography (at least 20 ft) below the limestone beds of the Todilto Limestone Member of the Wanakah Formation and within the area of the San Juan Basin where anhydrite beds (lateral seal) of the Todilto were deposited (fig. 3),
2. that part of the basin where the Todilto is mature enough to have generated oil, and
3. that part of the basin where Entrada sandstones have good porosity and permeability.

Key parameters of the Entrada Sandstone Conventional AU are discussed below and summarized on figure 10.

## Source

The principal source rock for petroleum in the total petroleum system is the Todilto Limestone Member of the Wanakah Formation.

## Maturation

Thermal maturation for oil in source rocks of the Todilto Limestone ranges from middle Paleocene to middle Eocene, and until the middle Miocene for gas generation in the area north of the AU.

## Migration

The migration distance of oil from the Todilto source beds into the underlying Entrada Sandstone reservoirs was short, probably within the dimensions of a single dune crest. The various Entrada fields do not appear to be linked along any regional migration pathway that might suggest fluid movement along regional faults or regionally through the Entrada Sandstone. All the oil fields occur where the Todilto is sufficiently mature to produce oil (present depths up to about 8,000 ft) and where isolated pods of thicker Entrada are found. The AU boundary was extended slightly south of the pod of active source rock to incorporate that part of the Chaco slope immediately adjacent to the central basin. In this area, limited well data indicate the presence of thin Todilto and hence probable relict dune topography in the Entrada (figs. 1 and 6). Also, this area would be the most likely to host hydrocarbon accumulations outside the pod of mature source rock because migration distances from the mature source pod to potential reservoirs would be the shortest. The Entrada Sandstone Conventional Oil AU is mostly confined to the pod of active source rock.

## Reservoirs

The reservoirs are the upper sandstone facies in the Entrada Sandstone in areas where the Entrada is thick, and relict dune topography is preserved below the overlying limestone and anhydrite sealing facies of the Todilto Limestone Member.

## Traps/Seals

Traps in the Entrada are mainly stratigraphic, due to the preservation of dune topography, and diagenetic. Regional tilt of the strata to the northeast has influenced structural trapping of oil, but also allowed for later introduction of water. Subsequent hydrodynamic forces have influenced the repositioning of the oil in some reservoirs and flushing in others. Seals are mostly the anhydrite and the limestone facies of the Todilto, which thin to as little as 10 ft over the crests of the dunes.

## Geologic Model

To date, oil in Entrada Sandstone reservoirs has been found at the extreme southern part of the central basin (figs. 1 and 4) near the intersection with the Chaco slope. Although the AU boundary was drawn to encompass the area where relict dune topography of at least 20–30 ft is preserved in the Entrada, oil has yet to be discovered in areas where long linear crests of dunes have been identified (Vincelette and Chittum, 1981). Rather, oil in the Entrada has only been found in some isolated Entrada dunes with 20–30 ft of closure below the limestone facies of the Todilto Limestone Member. Net pay in the fields averages 25 ft, but ranges from 16 ft at the Leggs field to nearly 30 ft at the Papers Wash field (table 1). Oil column height may range up to 45 ft, but not all the oil is moveable (Vincelette and Chittum, 1981). The presence of immoveable oil is probably related to partial flushing but also could be related to juxtaposition of local less permeable beds with those having higher permeability. The regional distribution of oil fields suggests that the spill point is rarely reached in the fields.

Traps in the Entrada are principally stratigraphic and are found where relict dune topography is preserved. The traps formed syndepositionally with the Entrada and were subsequently modified during deposition of the Todilto. The Todilto, source of the oil in the Entrada (Ross, 1980; Vincelette and Chittum, 1981), probably entered the window of oil generation in the middle Paleocene, and oil continued to be generated into the middle Eocene (fig. 10). Oil found in Entrada fields probably formed during this time. In the area north of the AU, oil may have continued to form, but because of the high heat history and greater depth of burial in this area, it would have cracked to gas. The period of generation–migration–accumulation of oil in the Entrada may well have ceased in the middle Eocene, near the end of the Laramide orogeny. However, the basin continued to subside well into the Miocene, and it is this later subsidence that might have aided migration of oil from source to trap.

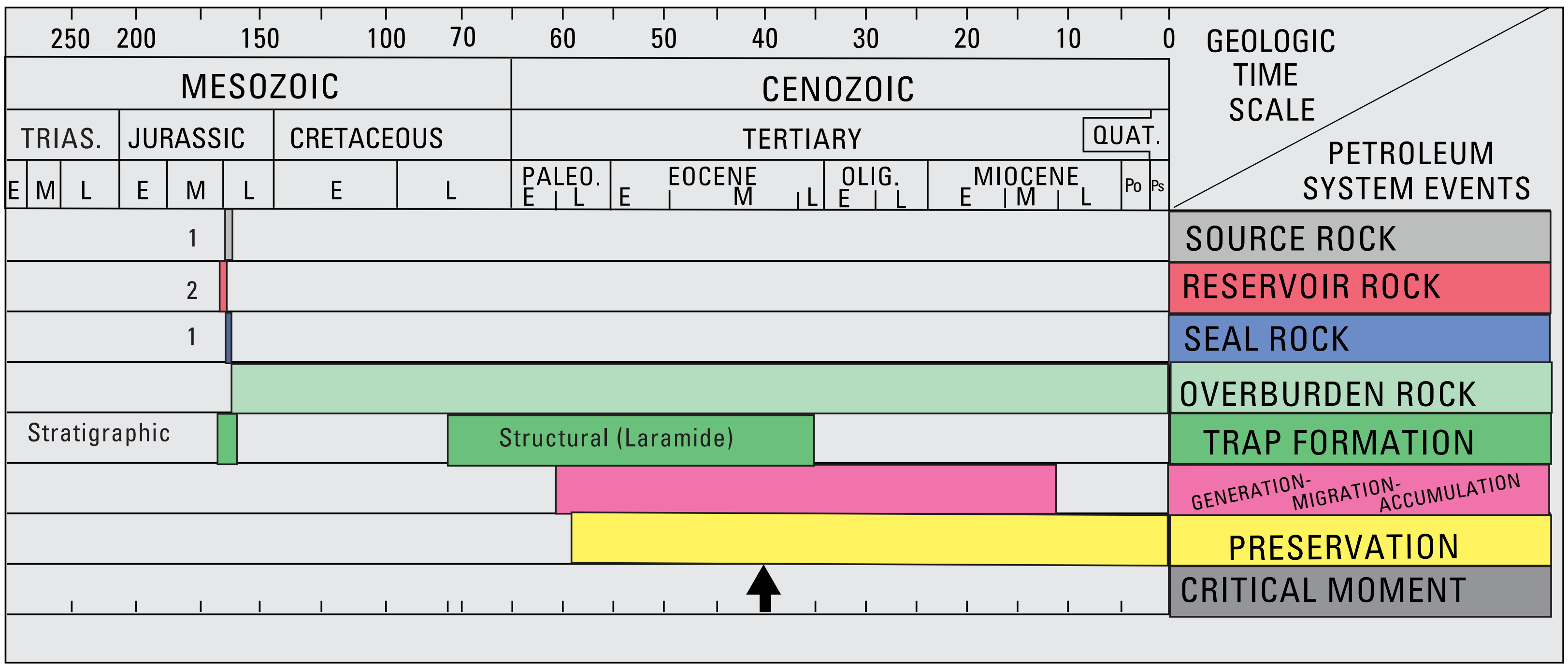
During the Miocene, strata in the southern part of the San Juan Basin were further tilted to the northeast. There is a slight break in the regional tilt between the Chaco slope to the south and the central basin to the north. All the oil fields are found near this break in slope (figs. 1 and 4). The oil fields, although isolated, are aligned northwest–southeast subparallel to the regional structural grain. When these fields are superimposed on the basement blocks (fig. 4), each field occurs within a block near the southern terminus where two blocks intersect. The blocks probably did not control migration of the oil, but rather may have controlled syndepositional thickness and preservation of thick Entrada. There has been some re-migration of oil out of traps; these sandstone traps are now water wet and some contain residual oil (Vincelette and Chittum, 1981). Flushing of traps probably occurred after the northeast regional tilt was developed, and erosion of rocks along the southern and eastern margin of the basin permitted inclusion of younger meteoric water.

Exploration efforts to find oil in the Entrada should focus on areas where

1. relict dune topography of sufficient closure on the top of the Entrada is preserved below the limestone facies of the Todilto Limestone Member of the Wanakah,
2. relict dune facies occurs in conjunction with the anhydrite facies of the Todilto,
3. the Todilto source beds are in the window of oil generation because migration distances from source beds into the sandstone reservoirs are short,
4. the Todilto and Entrada occur between depths of 5,000 and 8,000 ft in the basin (the shallow end of the range would be the most prospective)—depths at which better porosity and permeability in the Entrada are preserved, and
5. the break in the regional slope between the central basin and Chaco slope is located.

Finding oil in the Entrada will be difficult because of the small size of the dune crests, which are best identified by seismic studies. The difficulty of finding new oil plays was demonstrated by Massé and Ray (1995) in a 3-D seismic study of the Entrada Sandstone on the east side of the San Juan Basin. Their study did not define any new Entrada plays, and their results downplayed the potential for new plays in this area.

Entrada Oil Assessment Unit




Rock Units:
1. Todilto Limestone Member of Wanakah Formation
2. Entrada Sandstone

**Figure 10.** Events chart that shows key geologic events for the Entrada Sandstone Conventional Oil Assessment Unit. Black arrow shows critical moment (Magoon and Dow, 1994) for oil generation. Trias., Triassic; Quat., Quaternary; Paleo., Paleocene; Olig., Oligocene; Po, Pliocene; Ps, Pleistocene; E, early; M, middle; L, late. Geologic time scale is from the Geological Society of America web page *http://www.geosociety.org/science/timescale/timescl.htm*, last accessed 2/1/2008, and from Berggren and others (1995).

However, seismic studies have been successful elsewhere, especially in delineating favorable areas for expansion within existing fields (Nestor and Endsley, 1992).

## Assessment Results

The Entrada Sandstone Conventional Oil AU (50220401) covers 2,874,000 acres, which is somewhat smaller than the area used in the 1995 USGS assessment Entrada Play 2204 (Huffman, 1996). The AU of this study was restricted to the pod of Todilto source rock, which was mature enough to produce oil, and to where there was sufficient porosity and permeability preserved in the Entrada Sandstone. The AU was estimated at the mean to have potential additions to reserves of 2.32 MMBO, 5.56 BCFG, and 0.22 MMBNGL (table 2). The volumes of undiscovered oil, gas, and natural gas liquids estimated in 2002 for the Entrada Sandstone Conventional Oil AU are shown in Table 3. A summary of the assessment input data of the AU is presented on the data form in appendix A, which for this AU estimates the numbers and sizes of undiscovered accumulations. There are adequate charge, reservoir, traps, seals, access, and timing of generation and migration of hydrocarbons, indicating a geologic probability of 1.0 for finding at least one additional field with a total recovery greater than the stated minimum of 0.5 MMBO (grown) for oil.

This assessment unit produces mostly oil with small quantities of associated gas (IHS Energy Group, 2002). The associated gas was not quantitatively assessed. In estimating undiscovered non-associated gas and the number and sizes of undiscovered oil accumulations, historical data from NRG Associates (2001) database were used. Only four of the eight Entrada oil fields meet the 0.5 MMBO cutoff. These are Eagle Mesa, Media, Media Southwest, and Papers Wash. No new oil accumulations have been found that meet the minimum accumulation size cutoff since the discovery of the Papers Wash field in 1976. New wildcat discoveries since then have resulted in only single-well fields or a few-well fields—all of which have currently produced below the minimum field-size cutoff, despite having been in production for many years (IHS Energy Group, 2002). Although activity in exploration for new Entrada fields has resulted in only small fields with production below the minimum cutoff, there is still a large area left for exploration. Taking these factors into consideration, it was estimated that a maximum of four oil accumulations meeting the minimum cutoff, could still be discovered. At the median, this value is two undiscovered oil accumulations and at the minimum, one undiscovered oil accumulation.

Figure 11 shows the sizes of grown accumulations for the first and second halves of the discovery period. The accumulations for each half are ranked by size, with rank 1 equating to the largest accumulation and rank 2 equating to the smallest accumulation. Using the discovery information for fields that meet the minimum cutoff, the median grown size of discovered accumulations is 1.38 MMBO for the first half of the discovery period and 2.07 MMBO for the second half (fig. 11), indicating that sizes of accumulations were larger in the second half of the discovery period. The grown size of undiscovered accumulations was estimated from the distribution of discovered accumulation size versus the discovery year (fig. 12). The largest grown

**Table 2.** Assessment results summary for the Todilto Total Petroleum System, San Juan Basin Province, New Mexico and Colorado.

[MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 denotes a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive only under the assumption of perfect positive correlation]

| Assessment unit | Field type | Total undiscovered resources | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Oil (MMB) | | | | Gas (BCF) | | | | NGL (MMB) | | | |
| | | F95 | F50 | F5 | Mean | F95 | F50 | F5 | Mean | F95 | F50 | F5 | Mean |
| Conventional oil and gas resources | | | | | | | | | | | | | |
| Entrada Sandstone Conventional Oil | Oil | 0.81 | 2.19 | 4.18 | 2.32 | 1.84 | 5.15 | 10.66 | 5.56 | 0.07 | 0.20 | 0.45 | 0.22 |

**Table 3.** Comparison of estimates from the 2002 Entrada Sandstone Conventional Oil Assessment Unit (50220401) and the 1995 Entrada Play 2204 assessments of the number, sizes, and volumes of undiscovered oil accumulations.

[Sizes, volumes of oil and natural gas liquids, and minimum size considered are in million barrels of oil; volume of associated gas in billion cubic feet. F95 indicates a 95 percent chance of discovering more than the amount tabulated. The F50 and F5 fractiles are similarly defined. 1995 data from Huffman (1996)]

| | | | | |
|---|---|---|---|---|
| **Number of Undiscovered Oil Accumulations** | | | | |
| **Assessment year** | **Minimum** | **Median** | **Maximum** | **Minimum size considered** |
| 2002 | 1 | 2 | 4 | 0.5 |
| 1995 | 5 | 10 | 25 | 1 |
| **Sizes of Undiscovered Oil Accumulations** | | | | |
| **Assessment year** | **Minimum** | **Median** | **Maximum** | |
| 2002 | 0.5 | 1 | 4 | 0.5 |
| 1995 | 1 | 2 | 4 | 1 |
| **Volume of Undiscovered Oil** | | | | |
| **Assessment year** | **F95** | **F50** | **F5** | **Mean** |
| 2002 | 0.81 | 2.19 | 4.18 | 2.32 |
| 1995 | 2.2 | 11.10 | 33.8 | 21.3 |
| **Volume of Undiscovered Associated Gas** | | | | |
| **Assessment year** | **F95** | **F50** | **F5** | |
| 2002 | 1.84 | 5.15 | 10.66 | 5.56 |
| 1995 | 0.20 | 1.00 | 3.04 | 1.90 |
| **Volume of Undiscovered Natural Gas Liquids** | | | | |
| **Assessment year** | **F95** | **F50** | **F5** | |
| 2002 | 0.07 | 0.20 | 0.45 | 0.22 |
| 1995 | 0 | 0 | 0 | 0 |

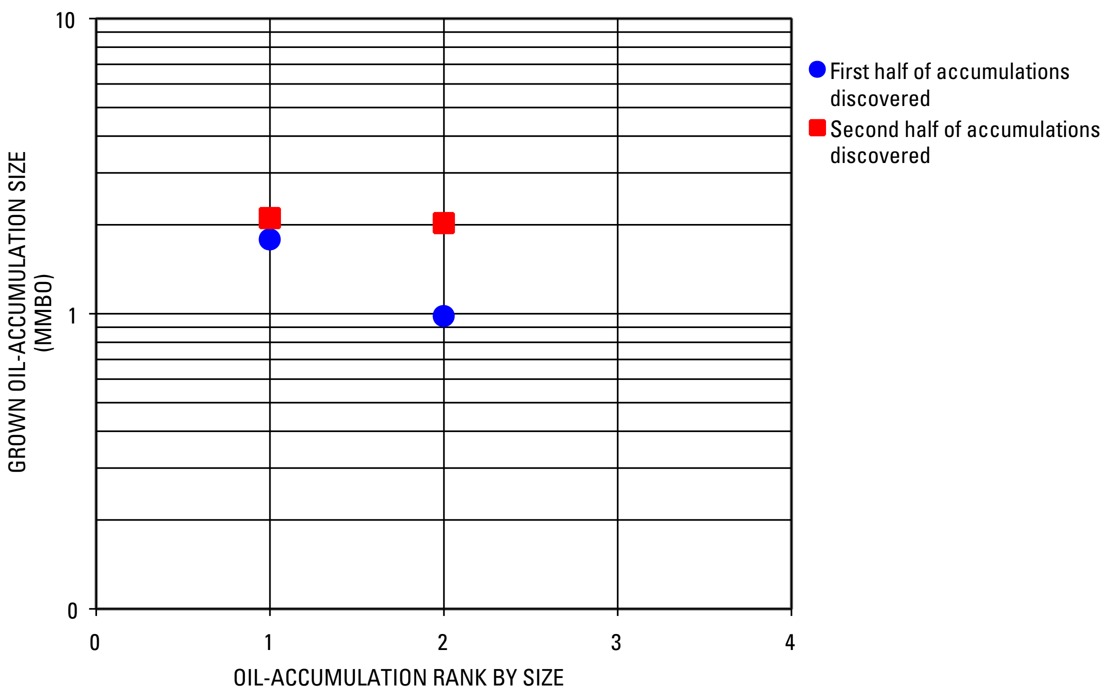



**Figure 11.** Graph showing distribution by halves of grown oil-accumulation size versus rank by size for the Entrada Sandstone Conventional Oil Assessment Unit (50220401). Data from NRG (2001). MMBO, million barrels of oil.

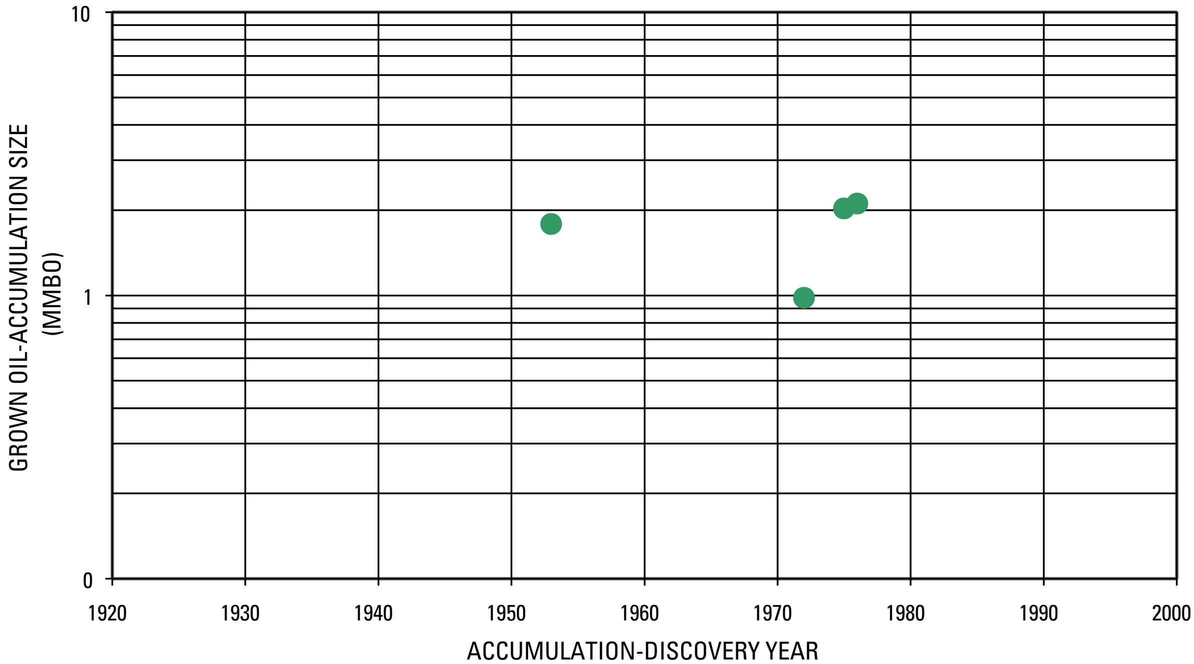



**Figure 12.** Graph showing sizes of grown oil accumulations versus year of discovery of accumulations (fields) for the Entrada Sandstone Conventional Oil Assessment Unit (50220401). Data from NRG (2001). MMBO, million barrels of oil.

oil field (Papers Wash) is about 2 MMBO. Using these data, the maximum estimated size of undiscovered accumulations is 4 MMBO, the median size is 1 MMBO, and the minimum size is 0.5 MMBO.

The number and sizes of undiscovered oil accumulations in this 2002 assessment are lower than those estimated in 1995 (table 2), even though a smaller minimum size was used in this assessment. This lower estimate reflects the discovery of very small field sizes since 1976, few new productive wildcats, and geologic factors, such as hydrodynamic flushing, which may diminish the occurrence of accumulations whose size at least meets the minimum cutoff. The 2002 estimated undiscovered oil, associated gas, and natural gas liquids for the Entrada Sandstone Conventional Oil AU are, at the mean, 2.32 MMBO, 5.56 BCFG, and 0.22 MMBNGL. These values represent a decrease in undiscovered oil resources, but an increase in associated gas and natural gas liquids resources relative to the 1995 assessment (table 2) (Huffman, 1996).

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**Appendix A.** Input data form used in evaluating the Todilto Total Petroleum System, Entrada Sandstone Conventional Oil Assessment Unit (50220401), San Juan Basin Province. See Klett and Le (this CD-ROM) for a detailed description of the data input form.

**SEVENTH APPROXIMATION**
**DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (NOGA, Version 5, 6-30-01)**

**IDENTIFICATION INFORMATION**

| | | | |
|---|---|---|---|
| Assessment Geologist:…….. | J.L. Ridgley | Date: | 9/25/2002 |
| Region:……………………….. | North America | Number: | 5 |
| Province:……………………… | San Juan Basin | Number: | 5022 |
| Total Petroleum System:…… | Todilto | Number: | 502204 |
| Assessment Unit:…………… | Entrada Sandstone Conventional Oil | Number: | 50220401 |
| Based on Data as of:………. | PI/Dwights 2001, NRG 2001 (data current through 1999) | | |
| Notes from Assessor………. | | | |

**CHARACTERISTICS OF ASSESSMENT UNIT**

Oil (<20,000 cfg/bo overall) **or** Gas (>20,000 cfg/bo overall):… Oil

What is the minimum accumulation size?………. 0.5 mmboe grown
(the smallest accumulation that has potential to be added to reserves in the next 30 years)

No. of discovered accumulations exceeding minimum size:……… Oil: 4 Gas: 0
Established (>13 accums.) ____ Frontier (1-13 accums.) X Hypothetical (no accums.) ____

Median size (grown) of discovered oil accumulation (mmbo):
1st 3rd 1.38 2nd 3rd 2.07 3rd 3rd ____
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd ____ 2nd 3rd ____ 3rd 3rd ____

**Assessment-Unit Probabilities:**

| Attribute | Probability of occurrence (0-1.0) |
|---|---|
| 1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. > minimum size…………… | 1.0 |
| 2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. > minimum size…… | 1.0 |
| 3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. > minimum siz | 1.0 |

***Assessment-Unit GEOLOGIC Probability*** (Product of 1, 2, and 3):……...……....…. 1.0

4. **ACCESSIBILITY:** Adequate location to allow exploration for an undiscovered accumulation > minimum size………………………………………………..………………..……..………… 1.0

### UNDISCOVERED ACCUMULATIONS

**No. of Undiscovered Accumulations:** How many undiscovered accums. exist that are ≥ min. size?:
(uncertainty of fixed but unknown values)

| | | | | | | |
|---|---|---|---|---|---|---|
| Oil Accumulations:…………………min. no. (>0) | 1 | median no. | 2 | max no. | 4 |
| Gas Accumulations:……………….min. no. (>0) | 0 | median no. | 0 | max no. | 0 |

**Sizes of Undiscovered Accumulations:** What are the sizes (**grown**) of the above accums?:
(variations in the sizes of undiscovered accumulations)

| | | | | | |
|---|---|---|---|---|---|
| Oil in Oil Accumulations (mmbo):….....…min. size | 0.5 | median size | 1 | max. size | 4 |
| Gas in Gas Accumulations (bcfg):….....…min. size | | median size | | max. size | |

---

### AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

| Oil Accumulations: | minimum | median | maximum |
|---|---|---|---|
| Gas/oil ratio (cfg/bo)……………………...……… | 1200 | 2400 | 3600 |
| NGL/gas ratio (bngl/mmcfg)……………………...…. | 20 | 40 | 60 |

| Gas Accumulations: | minimum | median | maximum |
|---|---|---|---|
| Liquids/gas ratio (bliq/mmcfg)….………..…….. | | | |
| Oil/gas ratio (bo/mmcfg)………………………….… | | | |

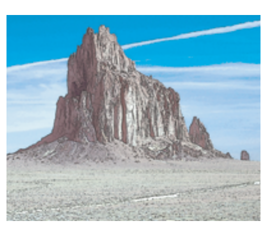
---

### SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS

(variations in the properties of undiscovered accumulations)

| Oil Accumulations: | minimum | median | maximum |
|---|---|---|---|
| API gravity (degrees)…………………….………… | 30 | 33 | 35 |
| Sulfur content of oil (%)………………………...….. | 0.1 | 0.5 | 1 |
| Drilling Depth (m) ……………...…………….…….. | 1400 | 1600 | 1800 |
| Depth (m) of water (if applicable)……………...….. | | | |

| Gas Accumulations: | minimum | median | maximum |
|---|---|---|---|
| Inert gas content (%)………………………....…… | | | |
| $CO_2$ content (%)………………………………...…. | | | |
| Hydrogen-sulfide content (%)……………….……… | | | |
| Drilling Depth (m)…………………………………… | | | |
| Depth (m) of water (if applicable)…………………. | | | |



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