Geology, Sequence Stratigraphy, and Oil and Gas Assessment of the Lewis Shale Total Petroleum System, San Juan Basin, New Mexico and Colorado

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By R.F. Dubiel

Chapter 5 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, Sequence Stratigraphy, and Oil and Gas Assessment of the Lewis Shale Total Petroleum System, San Juan Basin, New Mexico and Colorado

By R.F. Dubiel

Abstract

The Lewis Shale Total Petroleum System (TPS) in the San Juan Basin Province contains a continuous gas accumulation in three distinct stratigraphic units deposited in genetically related depositional environments: offshore-marine shales, mudstones, siltstones, and sandstones of the Lewis Shale, and marginal-marine shoreface sandstones and siltstones of both the La Ventana Tongue and the Chacra Tongue of the Cliff House Sandstone. The Lewis Shale was not a completion target in the San Juan Basin (SJB) in early drilling from about the 1950s through 1990. During that time, only 16 wells were completed in the Lewis from natural fracture systems encountered while drilling for deeper reservoir objectives. In 1991, existing wells that penetrated the Lewis Shale were re-entered by petroleum industry operators in order to fracture-stimulate the Lewis and to add Lewis gas production onto preexisting, and presumably often declining, Mesaverde Group production stratigraphically lower in the section. By 1997, approximately 101 Lewis completions had been made, both as re-entries into existing wells and as add-ons to Mesaverde production in new wells. Based on recent industry drilling and completion practices leading to successful gas production from the Lewis and because new geologic models indicate that the Lewis Shale contains both source rocks and reservoir rocks, the Lewis Shale TPS was defined and evaluated as part of this U.S. Geological Survey oil and gas assessment of the San Juan Basin.

Gas in the Lewis Shale Total Petroleum System is produced from shoreface sandstones and siltstones in the La Ventana and Chacra Tongues and from distal facies of these prograding clastic units that extend into marine rocks of the Lewis Shale in the central part of the San Juan Basin. Reservoirs are in shoreface sandstone parasequences of the La Ventana and Chacra and their correlative distal parasequences in the Lewis Shale where both natural and artificially enhanced fractures produce gas. The Lewis Continuous Gas Assessment Unit (AU 50220261) is thought to be self-sourced from and self-sealed by marine shales and mudstones deposited within the Lewis Shale that enclose clastic parasequences in the La Ventana and Chacra Tongues. The gas resource is thought to be a continuous accumulation sourced from the Lewis Shale throughout the depositional basin. In the Lewis Continuous Gas Assessment Unit (AU 50220261), for continuous gas resources, there is an F95 of 8,315.22 billion cubic feet of gas (BCFG) and an F5 of 12,282.31 BCFG, with a mean value of 10,177.24 BCFG. There is an F95 of 18.08 million barrels of natural gas liquids (MMBNGL) and an F5 of 47.32 MMBNGL, with a mean of 30.53 MMBNGL.

Introduction

This report presents the results of a geologic assessment of the undiscovered oil and gas resources of the Lewis Shale Total Petroleum System (TPS) within the San Juan Basin (SJB) Province of northwestern New Mexico and southwestern Colorado (fig. 1). The Cretaceous Lewis Shale TPS represents one of the four total petroleum systems defined for this project to assess the undiscovered hydrocarbon resources of the San Juan Basin (see chap. 1, this CD-ROM; fig. 3). The four total petroleum systems are, in ascending stratigraphic order, the Todilto TPS, Mancos-Menefee Composite TPS, Lewis Shale TPS, and Fruitland TPS.

The Lewis Shale TPS contains three distinct stratigraphic units deposited in genetically related depositional environments:

1. offshore-marine shales, mudstones, siltstones, and sandstones of the Lewis Shale, and marginal-marine shoreface to turbidite sandstones and siltstones of both

2. the La Ventana Tongue, and

3. the Chacra Tongue of the Cliff House Sandstone.

Although the La Ventana and Chacra Tongues had produced gas for many years prior to, and were included in, the 1995 USGS assessment of oil and gas resources in the San Juan Basin (Huffman, 1996), the Lewis Shale was not assessed as part of that effort. The Lewis Shale was not a completion target in the San Juan Basin in early drilling from about the 1950s through 1990. During that time, only 16 wells were completed in the Lewis where natural fracture systems were encountered while drilling for deeper objectives (Jennings and others, 1997a,b). Burlington Resources operates approximately 6,500 of more than 18,000 existing wells in the SJB (Dube and others, 2000). The Lewis Shale was drilled through but not tested, and thus is "behind pipe" in about 3,500 wells operated by Burlington Resources. Many of these wells extend down to the Mesaverde Group and older stratigraphic units (Jennings and others, 1997a,b; Dube and others, 2000; Bereskin, 2001a,b, 2003). In 1991, Burlington Resources began a program to recomplete existing wells that penetrated the Lewis Shale in order to fracture-stimulate the Lewis (Jennings and others, 1997; Dube and others, 2000) and to add Lewis production to preexisting, and presumably often declining, Mesaverde production. By 1997, Burlington Resources reported that approximately 101 Lewis completions had been made, both as re-entries into existing wells and as add-ons to Mesaverde production in new wells (Jennings and others, 1997; Dube and others, 2000). Burlington Resources had described a trend in the SJB that includes both the 16 Lewis completions from naturally fractured wells and successful new fracture-stimulated completions (Jennings and others, 1997; Dube and others, 2000; Shirley, 2001). This trend contains more than 3,500 existing wells operated by Burlington Resources that penetrate the Lewis (Dube and others, 2000). In addition, several recent publications have indicated that commercial gas production currently exists from the Lewis Shale (Jennings and others, 1997a,b; Dube and others, 2000; Shirley, 2001). For these reasons, and because new geologic models indicate that the Lewis Shale contains both source rocks and reservoir rocks, the Lewis Shale TPS was defined and evaluated as part of this U.S. Geological Survey (USGS) oil and gas assessment in the San Juan Basin. This report assesses the undiscovered gas resources within the Lewis Shale TPS in the San Juan Basin.

Geologic Setting

The Lewis Shale Total Petroleum System lies within the San Juan Basin in northwestern New Mexico and southwestern Colorado (fig. 1). The San Juan Basin is an asymmetric structural depression of Laramide age (fig. 2*A*) that contains strata ranging in age from Cambrian to Quaternary (Fassett and Hinds, 1971). Upper Cretaceous sediments in the SJB (fig. 2*B*) were deposited in the Cretaceous Western Interior Seaway, and, similar to most other Cretaceous strata in the SJB that were deposited in response to alternating marine transgressions and regressions, they form a series of interfingered continental, marginal-marine, and marine units. Continental fluvial and coal deposits on the southwestern margin of the SJB grade to the northeast into marginal-marine, estuarine, and shoreface strata. All of these strata continue to grade northeastward into offshore-marine rocks that originally were deposited in the depositional basin that extended eastward into Kansas and adjoining states (see for example, Molenaar, 1977; Roberts and Kirschbaum, 1995).

Stratigraphy

Strata within the Lewis Shale TPS include the Lewis Shale and rocks that are within or are correlative to the Mesaverde Group (fig. 2*B*). The Mesaverde Group was first described by Holmes (1877), but Collier (1919) later named the unit for exposures at the type locality in what is now Mesaverde National Park in southwestern Colorado. Numerous studies describe the stratigraphy in and around the San Juan Basin (Sears and others, 1941; Pike, 1947; Beaumont and others, 1956; Hollenshead and Pritchard, 1961; and many others). Many other regional studies related to economic coal and petroleum resources in the San Juan Basin have also addressed stratigraphic issues (for example, Fassett, 1977, 2000; Molenaar, 1983; Molenaar and others, 2002; and many others). Holmes (1877) also named the overlying Pictured Cliffs Sandstone, which interfingers with and progrades over the Lewis Shale to the northeast in the SJB (fig. 2*B*).

The Mesaverde Group in the San Juan Basin was deposited on the western shelf of the epicontinental Cretaceous Western Interior Seaway. The SJB lies south of a major subsiding Cretaceous foreland basin that was bounded on the west by the Sevier fold and thrust belt (Weimer, 1960; Molenaar, 1983). The SJB during the Cretaceous was bounded to the west by the Mogollon rim in central Arizona. During deposition of rocks forming the Lewis Shale TPS, the western shoreline of the Cretaceous Western Interior Seaway passed through the southwest part of the SJB with the seaway extending eastward through Kansas (Roberts and Kirschbaum, 1995). The Mesaverde Group comprises several stratigraphic units and facies, in ascending order: shoreface sandstones of the Point Lookout Sandstone, marginal-marine to continental deposits of the Menefee Formation, and shoreface sandstones of the Cliff House Sandstone. The marine strata of the Lewis Shale interfinger with and grade southwestward into shoreface sandstones of both the Cliff House Sandstone and the Pictured Cliffs Sandstone (fig. 2*B*).

Although the general stratigraphy of the Mesaverde Group was established long ago, more recent studies employing well-log cross sections and modern sedimentologic concepts have led to a greater understanding of the surface and subsurface marine shales and shoreface deposits, especially in the Cliff House Sandstone. The Cliff House comprises three units:

1. the basal Cliff House Sandstone,
2. the La Ventana Tongue, and
3. a unit designated by several names but most often called the Chacra Tongue (fig. 2*B*).

There has been much discussion in the literature as to the naming and designation of the "Chacra."

Dane (1936) named the Chacra sandstone member (lower case convention in use at that time) of the Mesaverde Formation, based on outcrops at Chacra Mesa in the southeastern SJB. This paralleled his designation of the La Ventana sandstone member of the Mesaverde Formation in the same

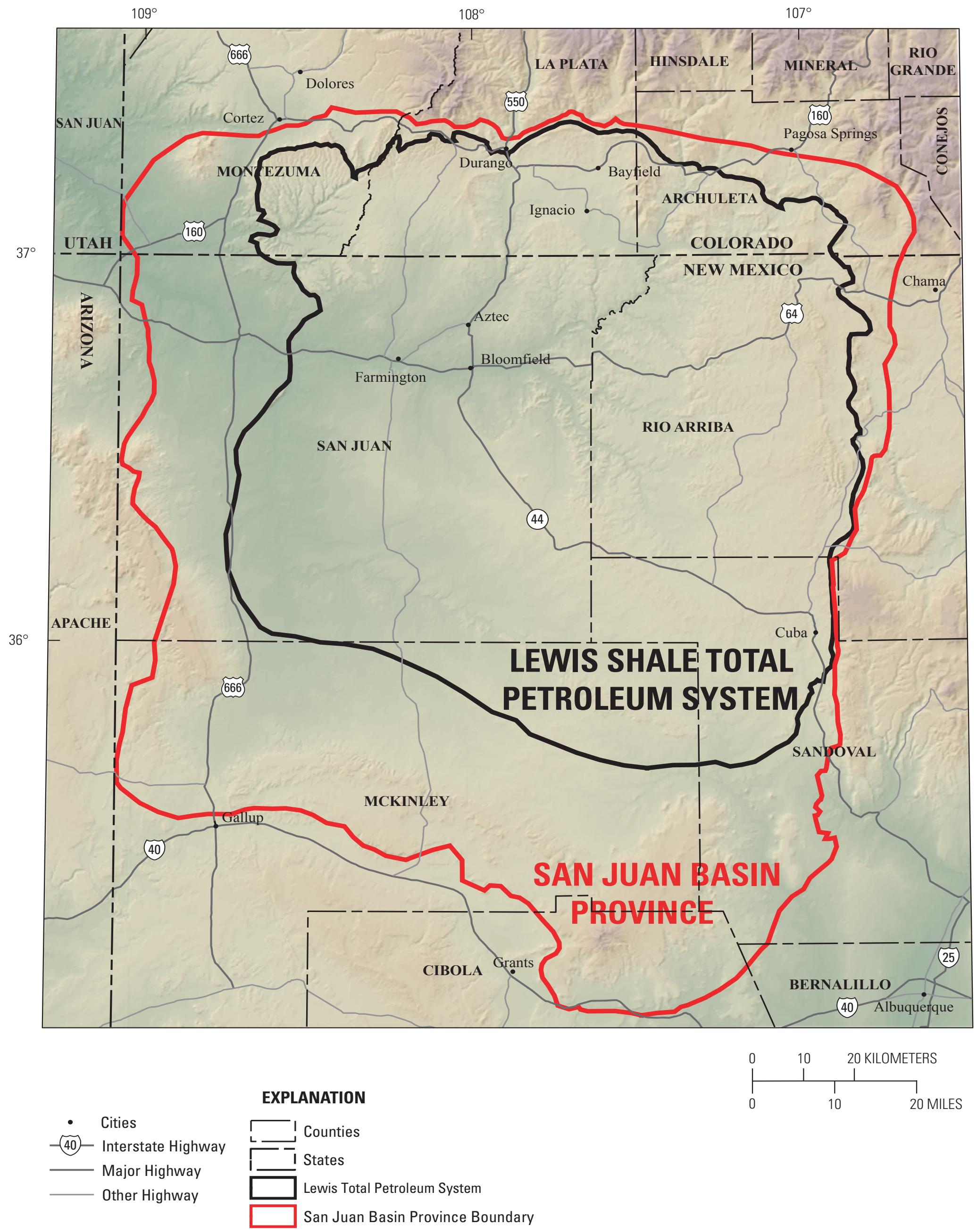


Figure 1. Index map of the San Juan Basin Province showing the outline of the Lewis Shale Total Petroleum System and the boundary of the San Juan Basin Province.

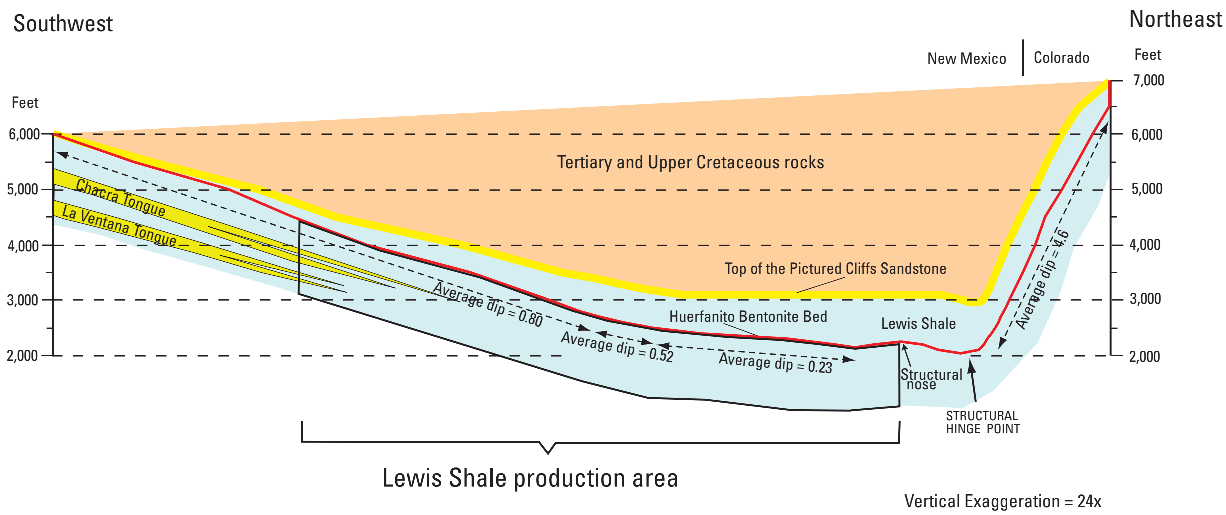
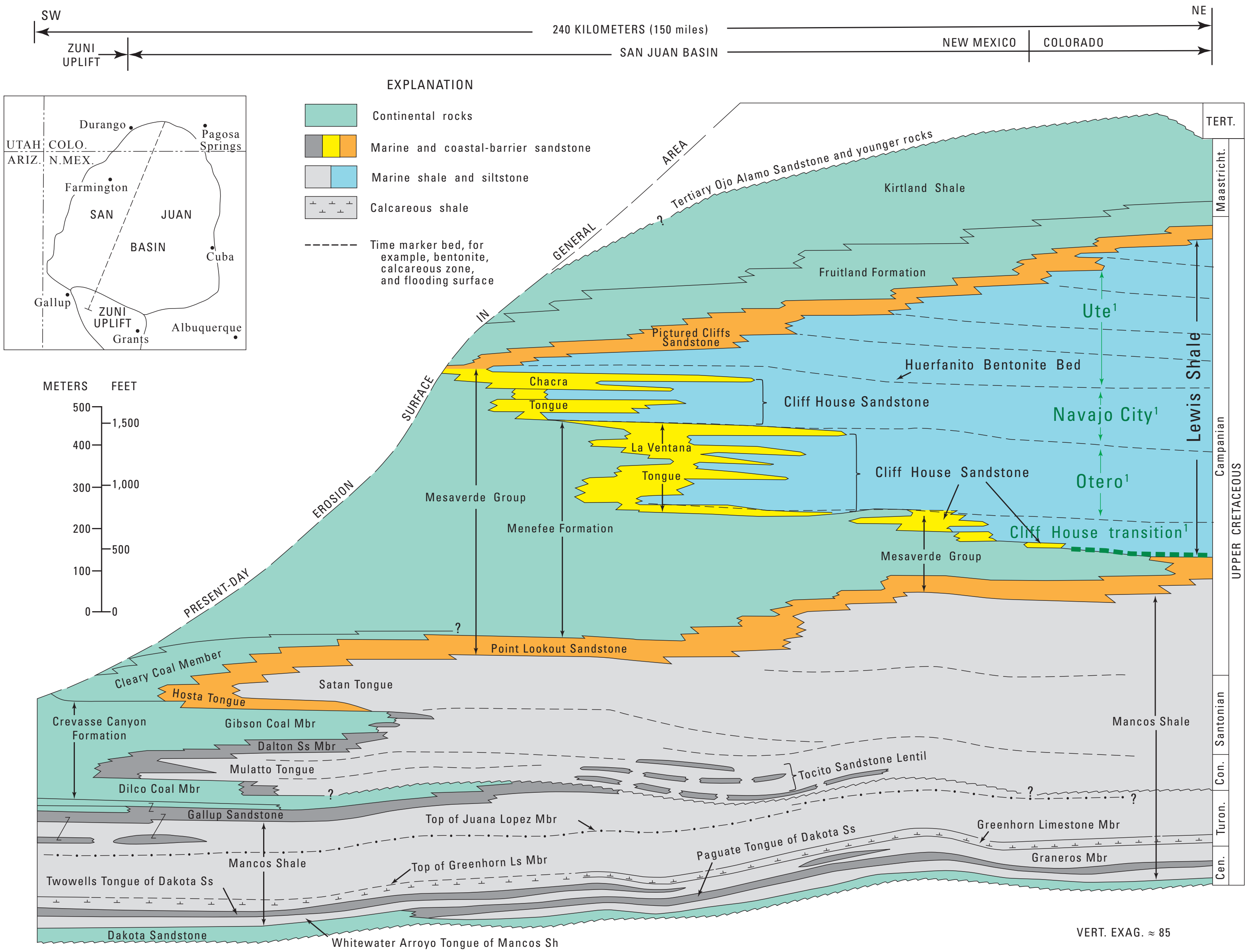
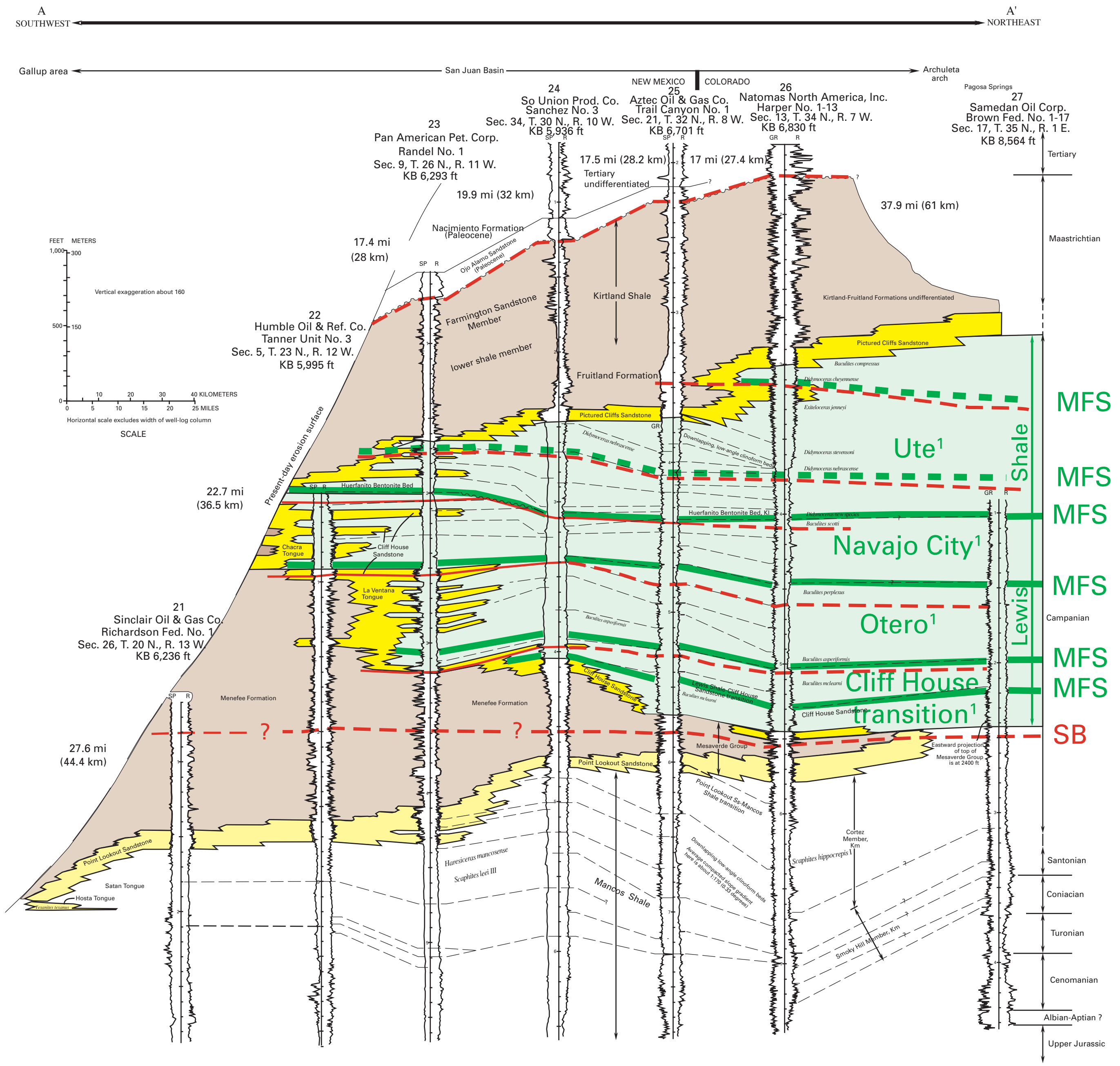


Figure 2*A*. Structural profile oriented southwest–northeast across the central part of the San Juan Basin, showing the Lewis Shale, La Ventana and Chacra Tongues of the Cliff House Sandstone, and overlying rocks. Top of profile is shown as flat because Tertiary and Cretaceous rocks are incompletely shown. Area of Lewis Shale production is shown with blue line. The San Juan Basin is shown at a vertical exaggeration of 24×. Modified from Fassett (2000, his fig. 23).



[1]Informal interval within Lewis Shale.

Figure 2*B*. Stratigraphic cross section of the San Juan Basin, highlighting depositional facies and units in the Lewis Shale Total Petroleum System. Modified from Molenaar (1977). Cen., Cenomanian; Turon., Turonian; Con., Coniacian; Maastricht., Maastrichtian; Tert., Tertiary; Ss, Sandstone; Ls, Limestone; Mbr, Member.



[1]Informal interval within Lewis Shale.

Figure 2*C*. Well-log cross section showing stratigraphic units and sequence stratigraphic units and surfaces used to analyze the Lewis Shale. Modified from Molenaar and others (2002). Kl, Lewis Shale; Km, Mancos Shale; Ss, Sandstone; MFS, maximum flooding surface; SB, sequence boundary.

EXPLANATION

Formation or member contact
? Contact that rises (uniformly or abruptly) in stratigraphic position. Queried where uncertain
Contact, position is uncertain
? Unconformity. Queried where uncertain.
SP Spontaneous-potential curve
GR Gamma-ray curve
R Resistivity curve
KB Kelly bushing

Borehole depths shown are in thousands of feet below elevation of Kelly bushing. Also note that only partial logs of boreholes are shown; upper and lower parts of logs are omitted where they are not applicable to this study.

CRETACEOUS ROCKS

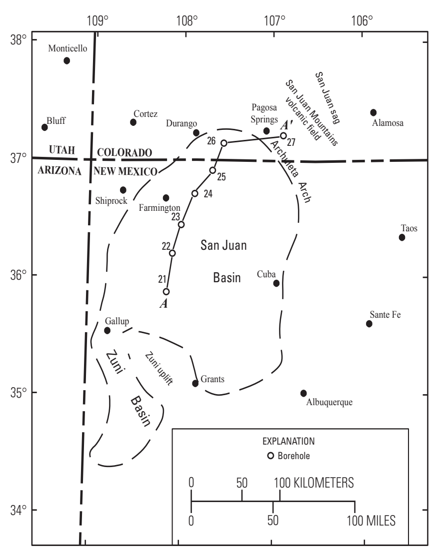
Nonmarine rocks (various formations)

Marginal-marine and shoreface sandstone (various formations)

Dominantly marine shale, mudstone, and siltstone (Lewis Shale)

Dominantly marine shale and siltstone (Mancos Shale)

Marine flooding surface (MFS) (dashed where inferred)
Sequence boundary (SB) (dashed where inferred)



INDEX MAP SHOWING LOCATION OF CROSS SECTION

Figure 2*C*. Well-log cross section showing stratigraphic units and sequence stratigraphic units and surfaces used to analyze the Lewis Shale. Modified from Molenaar and others (2002). Kl, Lewis Sahle; Km, Mancos Shale; Ss, Sandstone; MFS, maximum flooding surface; SB, sequence boundary; Ute[1], Navajo City[1], Otero[1], Cliff House transition[1], informal terms used by drillers and geologists in the basin.—Continued publication for outcrops near the town of La Ventana. At that time, neither Dane nor other workers had yet correlated sandstones from their study area in the southeast around the southern part of the San Juan Basin to the type section of the Cliff House Sandstone on the northwestern flank of the SJB. Beaumont and others (1956) abandoned Dane's original name "Chacra" in favor of the Cliff House Sandstone during their mapping around the southern SJB. However, they retained the name La Ventana Tongue of the Cliff House in the southeast SJB. Apparently they thought at the time that all of the La Ventana (and Danes's Chacra) was equivalent to the entire section of the Cliff House at the type section and on the northwest margin of the SJB. On a subsurface cross section of well logs, Fassett (1977) relabeled the "Chacra" as the unnamed tongue, despite indicating in the text that this unit correlated on outcrop to Dane's (1936) original "Chacra." He also suggested that the name Tsaya Canyon sandstone tongue of the Cliff House Sandstone be considered for the unit, but he did not formally rename it, because the publication was a guidebook. Fassett (1977) referred to sandstones below the La Ventana as basal Cliff House Sandstone. Fassett (1977) also indicated reasons against resurrecting the name Chacra, citing the recently proposed adoption of a similar name, "Chacra producing interval," by the New Mexico Oil Conservation Commission. The proposed "Chacra producing interval" would contain sandstones within both the Chacra and La Ventana. Additionally, Fassett (1977) indicated that some geologists working in the subsurface of the SJB had incorrectly identified the uppermost two sandstones of the La Ventana as Chacra, adding to the stratigraphic confusion.

Subsequently, Beaumont and Hoffman (1992) proposed the informal name Chacra Mesa tongue for the unit, again based on outcrops on Chacra Mesa. This proposal introduced yet another name for the same unit originally designated by Dane (1936). The fact that the La Ventana extends northwestward in the subsurface from outcrops near the town of La Ventana to the outcrop belt of the Cliff House south of its type section (Fassett, 1977) indicates that Dane's (1936) original stratigraphic interpretation of the La Ventana and Chacra was probably correct. Fassett (1977) stated that he and others had earlier suggested that Dane's (1936) original definition be restored, as did Beaumont and Hoffman (1992). Apparently, no outcrop studies document that the three stratigraphic subdivisions recognized within the Cliff House on the southeast margin of the SJB (basal Cliff House, La Ventana, and Chacra) can be correlated to similar subdivisions within the Cliff House on the northwest flank of the SJB. However, well-log cross sections (Molenaar and Baird, 1992; Molenaar and others, 2002) and subsurface correlation of well logs for this assessment study enable correlation of these units. A sequence stratigraphic study of the Cliff House Sandstone in Mancos Canyon in the northwest SJB near the type section of the Mesaverde identified complex packaging of shoreface sandbodies within the Cliff House (Olsen and others, 1999). Further studies of this kind have the potential for elucidating more detailed relations between the internal geometry of the Cliff House at the type section and the stratigraphic units designated by Dane (1936) in the southeast SJB. From the previously published regional well-log cross sections and those done for the present assessment study, Dane's (1936) original interpretation of major recognizable units within the Cliff House appears correct, and these units can be recognized and correlated in the subsurface cross sections used in this assessment. For these reasons, the present report refers to the unit in question as the Chacra Tongue of the Cliff House Sandstone to parallel Dane's (1936) original formal designation of the La Ventana Tongue and his original interpretation and designation of the stratigraphic relations of the "Chacra."

The Huerfanito Bentonite Bed is a laterally extensive unit within the Lewis Shale formed from altered volcanic ash that can be traced in well logs and on the outcrop throughout the San Juan Basin (fig. 2*A*) (Fassett, 2000). The Huerfanito Bentonite Bed extends across the deeper part of the original depositional basin and overlies the Chacra Tongue in the southwest part of the San Juan Basin (fig. 2*B*). The Huerfanito can be identified in well logs and used as a subsurface stratigraphic marker. It demarcates the Lewis Shale into two parts (Fassett and Hinds, 1971; Manfrino, 1984). The Lewis Shale has been subdivided in industry reports since the 1990s into three informal intervals, the Ute, Navajo City, and Otero intervals (fig. 2*B*) (see for example, Bereskin, 2001a; Jennings and others, 2001). However, the names "Navajo City Chacra interval" and "Otero Chacra interval" were used at least as early as 1983 (Meibos, 1983). In addition, more recent studies also refer to a fourth interval within the basal part of the Lewis Shale as the upper Cliff House (Bereskin, 2001a, 2003) or the Cliff House transition interval (Jennings and others, 1997a,b; Dube and others, 2000; Molenaar and others, 2002; Mavor and others, 2003). In this assessment report, the Lewis Shale comprises, in ascending order, the Cliff House transition, Otero, and Navajo City intervals below the Huerfanito Bentonite Bed and the Ute interval above the Huerfanito (fig. 2*B*).

Sequence Stratigraphy

In basins or fields with extensive well-log control, the application of sequence stratigraphic concepts can result in a high-resolution stratigraphic framework for subsurface correlation and for analyzing reservoir, source, and seal distribution (Van Wagoner and others, 1990). The application of sequence stratigraphic concepts and designation of sequence stratigraphic units and surfaces is particularly enlightening in terms of reservoir and source rocks. A sequence stratigraphic interpretation of the Lewis Shale TPS allows depositional units to be evaluated in light of the processes that formed them, processes that are also germane to the designation of components of the TPS such as reservoirs and source rocks, and the processes of generation, migration, and accumulation of hydrocarbons.

The marine rocks of the Lewis Shale TPS were deposited first during the youngest major transgression of the Cretaceous sea in the early part of the Campanian (fig. 2*B*) and subsequently during the last Cretaceous marine regression in the latter part of the Campanian (see for example, Weimer, 1960; Peterson and Kirk, 1977; Haq and others, 1988). The Cliff House transition, Otero, and Navajo City intervals of the offshore Lewis Shale that were deposited during the Campanian transgression are laterally equivalent to associated marginal-marine and shoreface deposits of the basal Cliff House Sandstone and to the La Ventana and Chacra Tongues of the Cliff House Sandstone. The Huerfanito Bentonite Bed (Fassett and Hinds, 1971) was deposited during the maximum Campanian marine transgression and represents altered volcanic ash that accumulated along the maximum flooding surface of this probable second-order sea-level cycle. The Ute interval of the offshore Lewis Shale above the Huerfanito Bentonite Bed was deposited during the major marine regression in the latter part of the Campanian. In this upper part of the section, the Lewis Shale grades to the southwest into progradational shoreface sandstones of the Pictured Cliffs Sandstone.

The Campanian transgression and regression within the Lewis Shale and associated shoreface sandstones likely represents a second-order relative sea-level cycle. Well-log cross sections and correlation of ammonite-bearing zones within the Lewis Shale (Molenaar and others, 2002) indicate down-lap of strata within the Ute interval onto the Huerfanito Bentonite Bed and associated shales, both of which extend to the southwest over the Chacra Tongue. The Huerfanito and associated marine shales represent the condensed section associated with the maximum marine flooding surface (MFS) during the Campanian (fig. 2*C*), corresponding to the farthest southwestward transgression of the Campanian Western Interior Seaway in the SJB. The maximum marine flooding surface separates strata of the second-order transgressive system tract (TST) below the Huerfanito and MFS, comprising the Lewis Shale, Cliff House Sandstone, and La Ventana and Chacra Tongues, from progradational strata of the highstand system tract (HST) above, including the Lewis Shale and laterally equivalent part of the Pictured Cliffs Sandstone. Additionally, the transgressive nature of the TST in the lower part of the Lewis Shale is indicated by the back-stepping pattern of shoreface sandstones in the Cliff House transition that are successively overlain to the southwest by the La Ventana Tongue and subsequently by the Chacra Tongue (fig. 2*C*). A second-order sequence boundary likely exists near the top of the uppermost sandstone of the progradational Point Lookout Sandstone and within the laterally equivalent part of the Menefee Formation, but below the stratigraphically lowest sandstones of the Cliff House. This sequence boundary is expected here because the large basinward shift in shoreface facies demonstrated by the strongly prograding Point Lookout Sandstone and the laterally equivalent continental facies of the Menefee were most likely deposited in response to a slowing of relative sea-level rise and/or lowering of sea level prior to the major transgression represented by the back-stepping pattern of the shoreface sandstones and marine rocks of the overlying Cliff House Sandstone and Lewis Shale, respectively. The corresponding candidate for a second-order sequence boundary at the top of the Lewis Shale perhaps lies at the unconformity separating the Kirtland-Fruitland Formations (undifferentiated) from the overlying Tertiary Ojo Alamo Sandstone. These two sequence boundaries define a second-order sequence encompassing the Lewis Shale and correlative units (Haq and others, 1988).

One previous report (Dube and others, 2000) refers to the intervals within the Lewis Shale as four informal members, each capped by a regional flooding surface. Within the Campanian second-order sequence, the present assessment study recognizes five, and possibly a sixth, third-order sequences within the Lewis, each replete with third-order sequence boundaries and maximum flooding surfaces (fig. 2*C*). Three of the third-order sequences are within the lower part of the Lewis Shale, and the fourth, fifth, and the possible sixth third-order sequences lie within the Lewis Shale above the Huerfanito Bentonite Bed. Each MFS is identified on well logs as a shale-rich interval that extends across the basin and overlies a parasequence set of shoreface sandstones to the southwest. Two third-order maximum flooding surfaces that extend from the central part of the SJB to the southwest can be identified in Lewis Shale well logs and cross sections below the Huerfanito (fig. 2*C*). The first maximum flooding surface (MFS) overlies the Cliff House Sandstone and the corresponding Cliff House transition interval of the Lewis. The second maximum flooding surface (MFS) overlies the La Ventana Tongue and the laterally equivalent Otero interval of the Lewis. The overlying Chacra Tongue and laterally equivalent Navajo City interval are overlain by the maximum marine flooding surface associated with the Huerfanito Bentonite. Here, the second-order and the third-order maximum flooding surfaces coincide. Each of these three maximum flooding surfaces can be traced basinward on well logs throughout the Lewis Shale in the SJB. Within the upper part of the Lewis Shale, in the thick Ute interval, there are two additional shale-rich intervals that extend westward over slightly back-stepping parasequence sets of the correlative Pictured Cliffs Sandstone. The lower of the two shale intervals extends southwestward over a slightly backstepping parasequence set of shoreface sandstones in the Pictured Cliffs. In addition, the lower shale interval is overlain by a downlapping clinoform pattern of time lines based on ammonite correlations in the well-log cross section (fig. 2*C*) (Molenaar and others, 2002). The uppermost shale interval is associated with an aggradational parasequence set of shoreface sandstones in the Pictured Cliffs Sandstone. This aggradational pattern was investigated by Roberts and McCabe (1992) and attributed by them to a slight pause in shoreline progradation. This aggradational pattern is interpreted here to be associated with the third-order MFS at this position. These two additional shale breaks in the Ute interval appear to delineate the fourth and fifth, and the possible sixth, third-order sequences within the Lewis Shale.

In addition to serving as sequence-stratigraphic markers for well-log correlation, the third-order maximum flooding surfaces form the natural breaks in the Lewis Shale that have been historically used to divide the Lewis into four informal intervals, which are, in ascending order,

1. the Cliff House transition,
2. Otero,
3. Navajo City, and
4. Ute intervals (figs. 2*B* and 2*C*).

Although sequences are typically defined as lying between sequence boundaries (Van Wagoner and others, 1990), the Cliff House transition, Otero, and Navajo City intervals of the Lewis Shale as previously defined lie between the third-order maximum flooding surfaces and not the associated sequence boundaries. Additionally, previous reports have not recognized the additional third-order sequences in the Ute interval described in this assessment report.

In addition to the maximum flooding surfaces, third-order sequence boundaries can also be recognized on the figure 2*C* cross section. The third-order sequence boundaries associated with the maximum flooding surfaces are inferred from the stacking pattern of the shoreface parasequence sets within the Cliff House transition, La Ventana, Chacra, and Pictured Cliffs discernable in electric logs and by the landward shift in facies and the subsequent deepening events indicated by the marine shale intervals. The critical observations of basinward shift in actual facies associated with the sequence boundaries are not possible without direct observations of the facies from core or outcrops, which were not made in the present study. Despite this limitation, sequence stratigraphic concepts require a sequence boundary between maximum flooding surfaces (Van Wagoner and others, 1990). At the top of each of the third-order backstepping parasequence sets of the Cliff House transition, Otero, and Navajo City intervals there is a marked progradation of the sandbody at the top of the parasequence set. The sequence boundary is thus placed just below this sandbody, on the presumption that it represents a slight basinward shift in facies due to a relative sea-level drop or stillstand.

The shoreface sandstones recognized on the cross section (fig. 2*C*) within the basal Cliff House and La Ventana and Chacra Tongues represent third-order parasequences in sequence-stratigraphic terms. Within the basal Cliff House Sandstone, the shoreface parasequences form a back-stepping pattern except for the uppermost sandstone, which builds out slightly basinward. The subtle progradation of this uppermost sandstone may be due to it overlying the third-order sequence boundary and thus being part of the HST in this third-order sequence. Alternatively, it may be part of a thin low-stand systems tract overlying the sequence boundary. The sandstone parasequence set of the basal Cliff House is then overlain by the marine flooding surface separating the Cliff House transition from the overlying Otero interval (fig. 2*C*). The backstepping pattern results in a vertical well-log pattern in which successively higher coarsening-upward units are slightly more distal in facies than those immediately underlying. This backstepping accounts for the observed slight “fining-upward” character of the Cliff House transition interval of the Lewis (Mavor and others, 2003), despite its generally coarser grain size compared to the overlying intervals in the Lewis Shale. In a detailed study of basal Cliff House sandbodies on the northwest side of the SJB, Olsen and others (1999) documented high-order prograding parasequence sets within the generally backstepping basal Cliff House sandbody. These prograding sandbodies probably represent fourth-order parasequence sets.

The La Ventana Tongue of the Cliff House Sandstone, located stratigraphically above and farther to the southwest than the basal Cliff House Sandstone, internally displays a more vertical aggradational pattern of shoreface parasequences, with a slight progradational parasequence at the top. The subtle progradation of this uppermost parasequence again may be due to its deposition as the uppermost part of the third-order HST, or it may be a small remnant of the lowstand systems tract above the third-order sequence boundary. The La Ventana shoreface parasequences extend into the Otero interval of the Lewis Shale where they form the siltstones and mudstones that produce gas from this part of the section in the central SJB. The La Ventana is also overlain by a third-order marine flooding surface as demonstrated by the marine shale signature in the well logs, extending to the southwest from the Lewis Shale over the top of the La Ventana shoreface parasequence set. The Chacra Tongue of the Cliff House Sandstone, again located stratigraphically higher and farther to the southwest than the underlying La Ventana, internally forms a slightly forward-stepping package of shoreface parasequences. These progradational parasequences and their distal equivalents extend into the Lewis Shale and form the sandy to silty mudstone beds in the Navajo City interval that commonly produce gas. Again, the uppermost parasequence builds out basinward, suggesting it overlies the third-order sequence boundary near the top of the Navajo City interval. The Chacra Tongue is also overlain by a marine flooding surface—this one coincident with the second-order maximum marine flooding surface in the basin represented by the shale interval that contains the Huerfanito Bentonite Bed.

Similar to the designated internal intervals within the Lewis Shale below the Huerfanito Bentonite Bed, the Ute interval above the Huerfanito contains several third-order maximum flooding surfaces and sequence boundaries. The strongly prograding shoreface sandstones within the Pictured Cliffs Sandstone are punctuated by at least two backstepping intervals (fig. 2*C*). Each of these intervals likely contains both a third-order sequence boundary and a maximum flooding surface similar to those described for the lower part of the Lewis Shale below the Huerfanito. The three resulting intervals in the Ute are thus of the same order of magnitude in thickness and duration as the three intervals in the lower part of the Lewis. The duration of each of the six intervals is approximately 1 to 1.5 million years based on the ammonite zonations (Obradovich, 1993; Roberts and Kirschbaum, 1995; Molenaar and others, 2002). This duration of 1 to 1.5 million years compares favorably with the duration of third-order relative sea-level cycles on the global sea-level chart (Haq and others, 1988).

Recognition of the third-order sequence boundaries and marine flooding surfaces allows subsurface correlation between the La Ventana and Chacra Tongues shoreface sandstones and the equivalent distal sandstones and siltstones within the corresponding informal intervals designated in the Lewis Shale. In addition, it suggests that cycles similar in magnitude to those within the Cliff House transition, Otero, and Navajo City intervals of the lower part of the Lewis Shale are also present within the much thicker Ute interval in the upper part of the Lewis Shale. Application of these sequence stratigraphic concepts allows an interpretation not only of the stratigraphic and sedimentologic relations between the units but also of the genetic relation of depositional units and significant surfaces as potential reservoirs, source rocks, and migration pathways for hydrocarbons within the Lewis Shale Total Petroleum System. In addition, the sequence stratigraphic interpretations indicate that concepts applied to exploration for and production of gas from the lower part of the Lewis Shale may also be applicable to the Ute interval of the Lewis Shale above the Huerfanito Bentonite Bed, and to similar Cretaceous third-order sequences in other basins. Recognition of third-order cycles in the Ute interval on the scale of those previously recognized in the Cliff House transition, Otero, and Navajo City intervals suggests that additional similar reservoirs and source rocks may be present in the upper part of the Lewis Shale associated with the third-order sequence boundaries and maximum flooding surfaces.

The Lewis Shale Total Petroleum System

The Lewis Shale Total Petroleum System includes all major outcrops and subsurface deposits of the Lewis Shale and laterally equivalent rocks of the La Ventana and Chacra Tongues of the Cliff House Sandstone of the Mesaverde Group (fig. 3*A*). The Lewis Shale is thought to be the source rock for the Lewis Shale TPS (see following section on Hydrocarbon Source Rocks). The Lewis Shale and the laterally equivalent La Ventana and Chacra Tongues of the Cliff House Sandstone are the reservoir rocks for a continuous gas accumulation in the Lewis Shale TPS. The Lewis Shale TPS normally also would include rocks assigned to the basal part of the Cliff House Sandstone (those sandstones of the Cliff House Sandstone that interfinger with the Cliff House transition zone of the Lewis Shale; figs. 2*B* and 2*C*) because they are genetically related to the Chacra and La Ventana, they similarly interfinger basinward with the Lewis Shale, and they may have been charged with gas generated from the Lewis. However, for this study the basal Cliff House Sandstone of that interval is included in and assessed as part of the Mancos-Menefee Composite TPS (see chap. 4, this CD-ROM) because the database used for this assessment often included and designated wells producing from sandstones within the basal Cliff House as Mesaverde production. Thus, those sandstones are assessed as part of the Mancos-Menefee Composite TPS, which includes all the other Mesaverde units. This separation of basal Cliff House from La Ventana and Chacra production is in part an artifact of pool definitions by the New Mexico Oil Conservation Division (NMOCD).

In 1977, the NMOCD defined a “Chacra line” running northwest to southeast across the SJB. This line delineates the down-dip limit of production from progradational shoreface sandstones of the La Ventana and Chacra Tongues, known collectively in industry terms as the “Chacra” sandstones or “Chacra producing interval.” North and east of the “Chacra line,” where the majority of Mesaverde production exists, the lower part of the Lewis Shale up to the Huerfanito Bentonite Bed was originally included in leases of the Mesaverde Group production in the Mesaverde pool definition (Dube and others, 2000). Since that original definition, the NMDOC revised the upper limit of the Mesaverde pool to include an additional 250 ft of Lewis Shale above the Huerfanito Bentonite Bed. Currently, completion or recompletion of the Lewis Shale producing interval in what are or were primarily Mesaverde wells is dealt with administratively as a pay-add; that is, the production of gas from the Lewis is commingled with and added to Mesaverde production from the same well, which also simplifies the regulatory approval process. It also maximizes Lewis economics because the Lewis can be completed with Mesaverde and/or Dakota Group production and does not require a separate well bore or production string. However, it complicates the assessment of gas produced solely from the Lewis Shale because that gas is co-mingled both as actual gas production and as reported in the IHS database used in this assessment (IHS, 2000a,b).

It was not possible to separate the Cliff House Sandstone (basal Cliff House interval) production from overall Mesaverde production simply by examining the production data as reported for Cliff House or Mesaverde wells in the IHS database (IHS, 2000a,b). Lewis gas is similarly comingled and produced with Mesaverde gas. It was possible to distinguish some of the Lewis Shale gas production from Mesaverde production using Estimated Ultimate Recovery (EUR) curves generated from the production database (IHS, 2000a) by isolating EUR curves that showed a significant spike in increased gas production since about 1990. This is the general onset date for the recent industry trend to establish Lewis gas production from recompletions in preexisting Mesaverde wells. In addition, all Mesaverde records in the IHS database (IHS, 2000a,b) for the SJB were individually checked, and those well records that reported a perforated interval for the Lewis Shale were used in the assessment of the Lewis TPS.

The stratigraphically younger shoreface deposits of the Pictured Cliffs Sandstone, although laterally equivalent to the Lewis Shale, are included in the overlying Fruitland TPS for the SJB assessment (see chap. 6, this CD-ROM). These

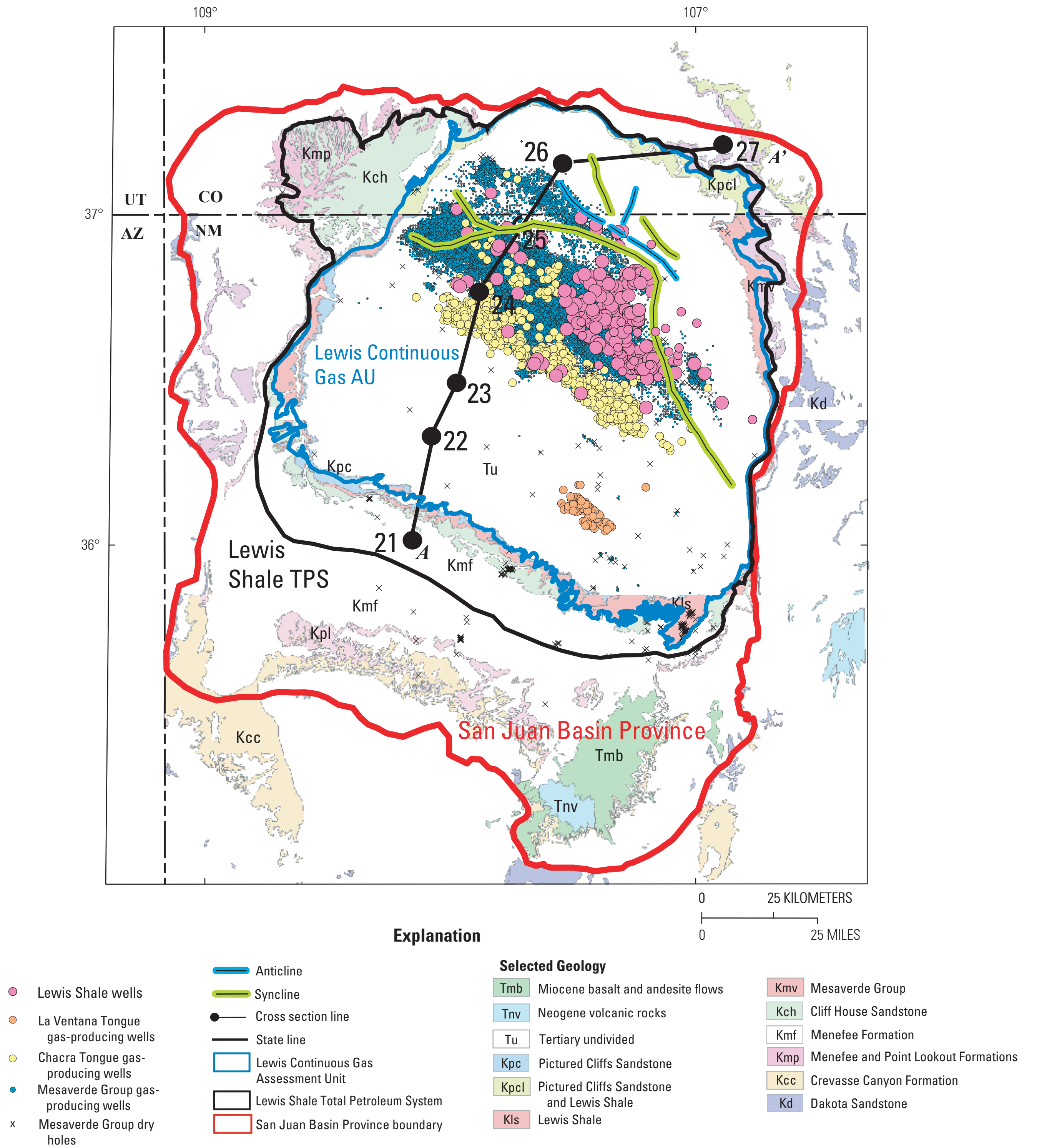


Figure 3*A*. Map showing geology of the San Juan Basin Province, Lewis Shale Total Petroleum System boundary, line of stratigraphic cross section shown on fig. 2*C*, structural elements, and oil and gas wells. Geology from Green (1997).

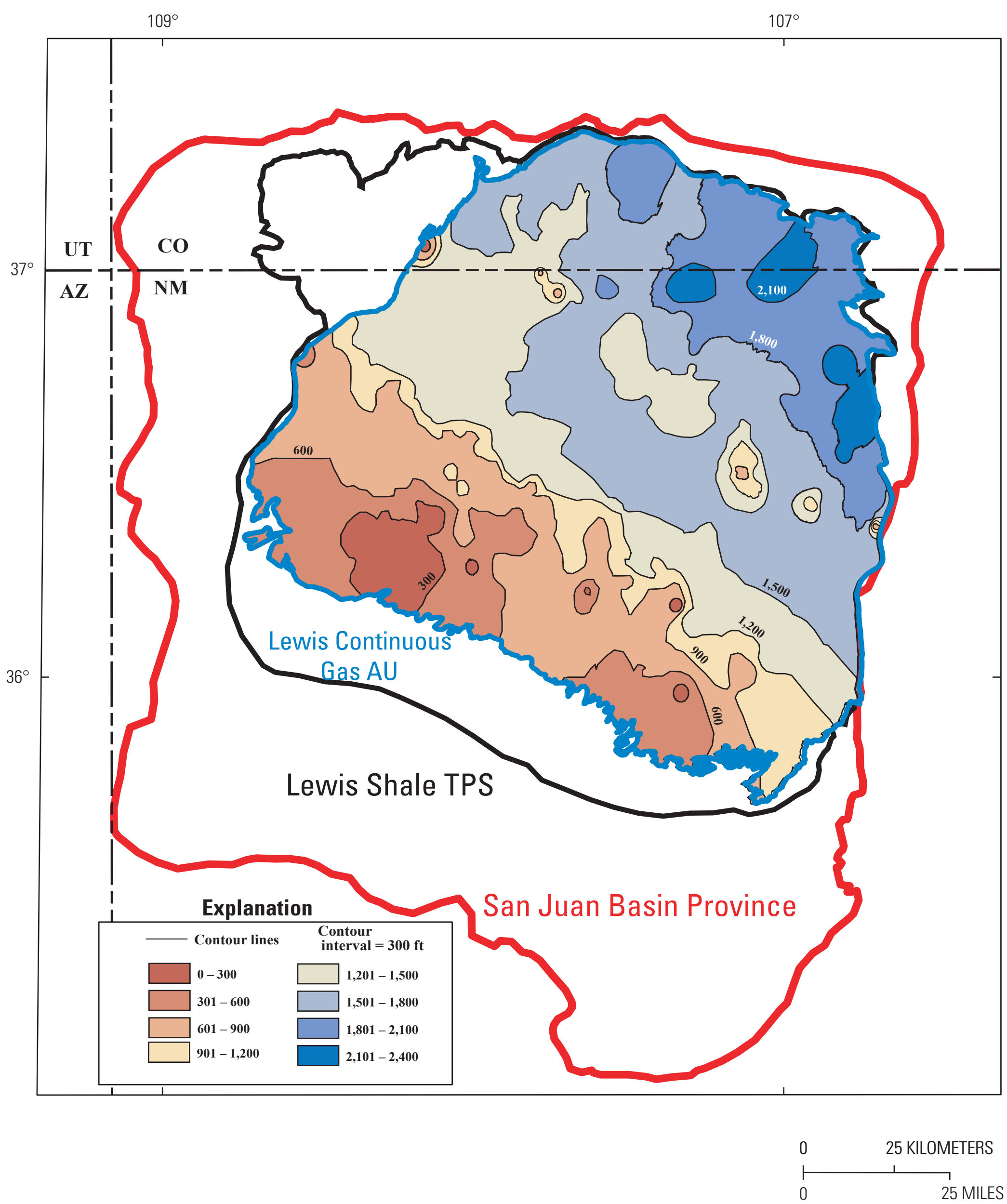


Figure 3*B*. Isopach map of the Lewis Shale constructed from IHS database (IHS, 2000b).

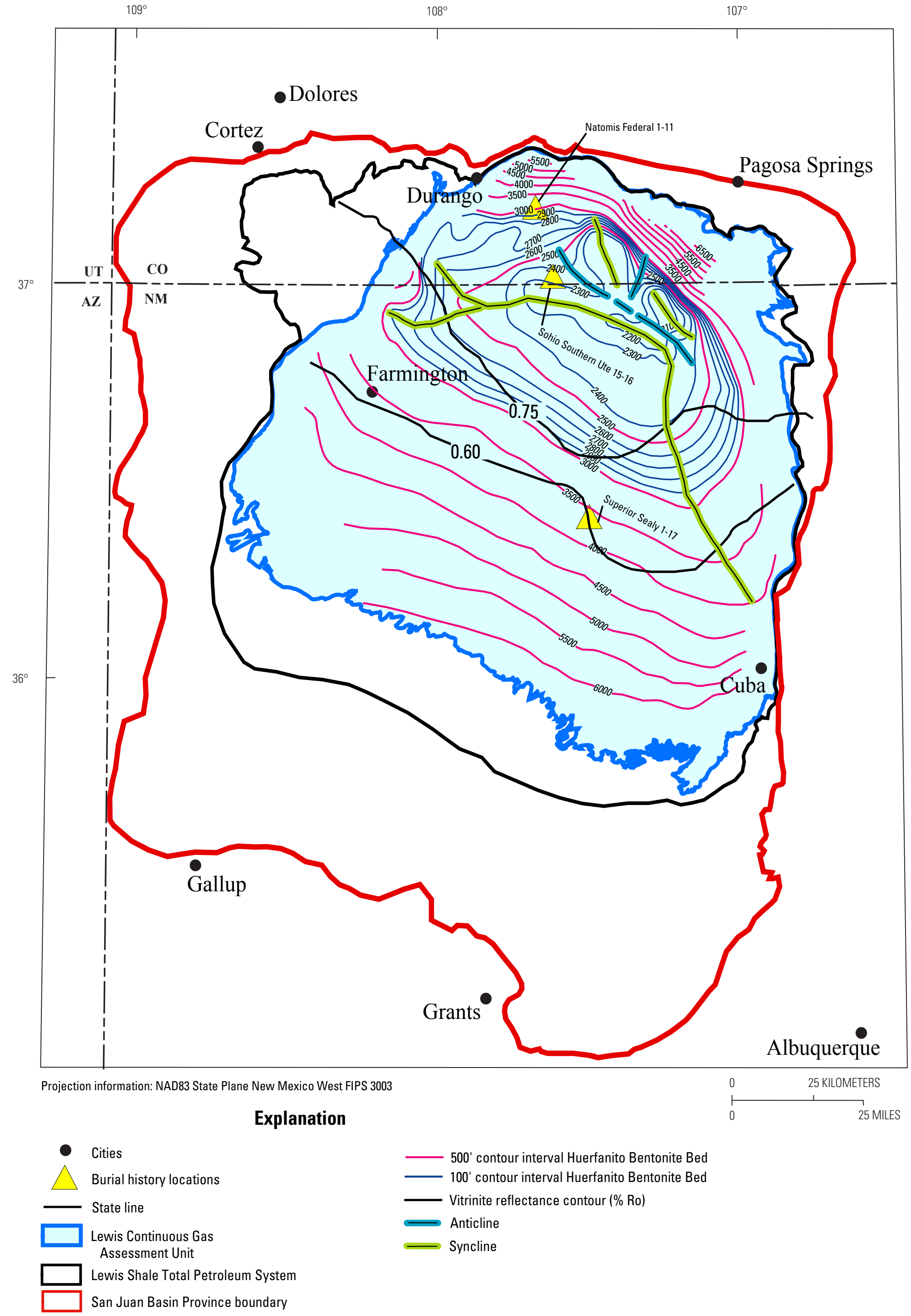


Figure 3*C*. Map of the Lewis Shale Total Petroleum System showing structure contours on the Huerfanito Bentonite Bed (from Fassett, 2000), structural elements, location of wells used in burial history curves, and vitrinite reflection contours. Vitrinite reflectance (RO) values contoured (in percent) from data in Fassett and Nuccio (1990), Law (1992), and Fassett (2000).

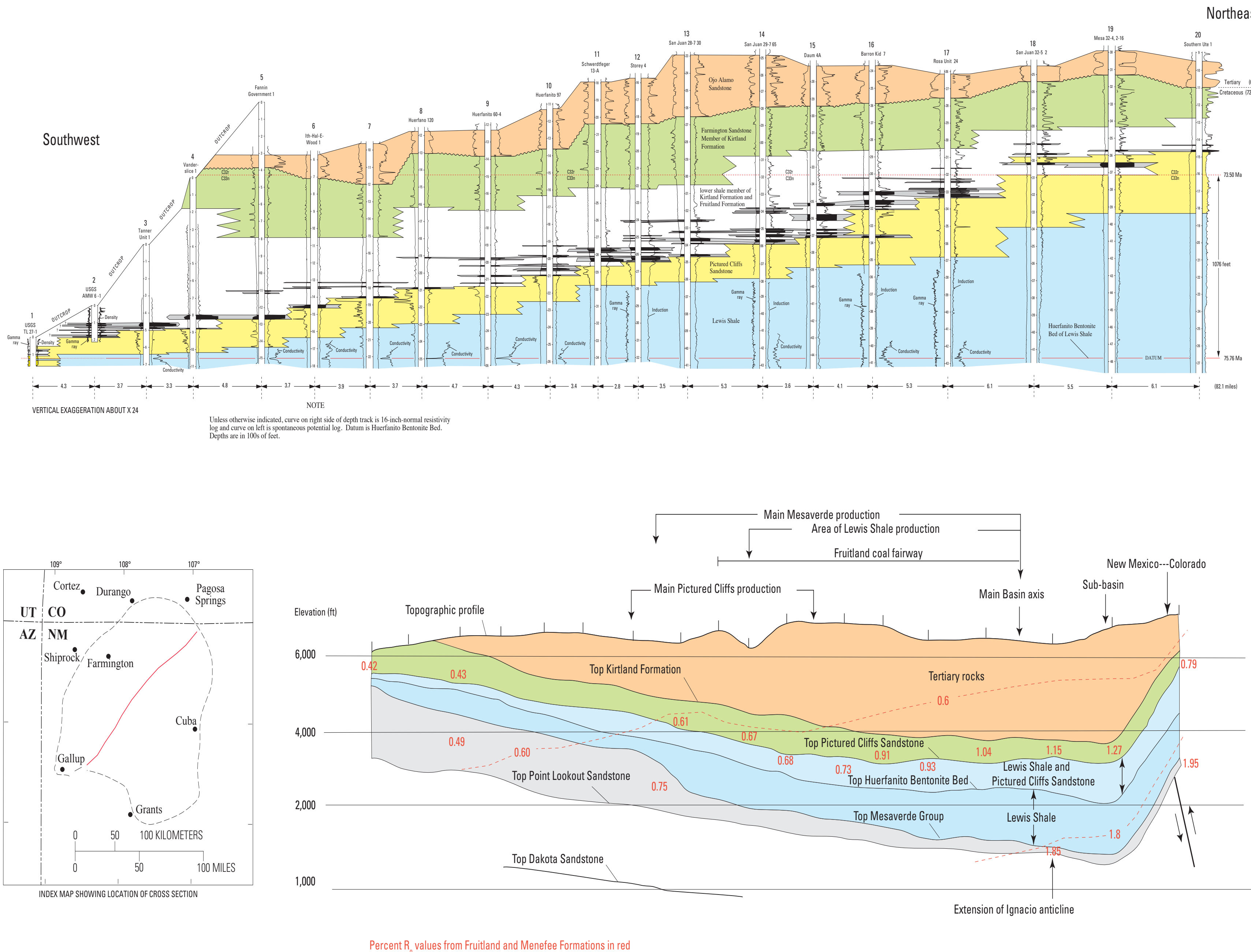


Figure 3*D*. Cross sections of the San Juan Basin showing vitrinite reflectance values (below) and stratigraphic units bounding the Lewis Shale (above). (Modified from Fassett, 2000, plate 1).

Pictured Cliffs progradational shoreface sandstones interfinger with and grade distally into offshore marine strata of the Lewis Shale (fig. 2*C*), but the gas produced from Pictured Cliffs reservoirs geochemically appears to have been sourced primarily from coals of the Fruitland Formation (J.R. Hatch, USGS, written commun., 2003). Based on the gas production that could be assigned to Lewis Shale source rocks and reservoirs, the Lewis Shale TPS boundary was drawn to include the subsurface and outcrop extent of the Lewis Shale and the La Ventana and Chacra Tongues of the Cliff House Sandstone (fig. 3*A*). The TPS boundary does not include small isolated outcrops of any of these units outside the main contiguous outcrop belt. The boundary extends to the southwest and to the northeast a short distance into the outcrop belt of the Menefee Formation because the well-log cross section indicates that several of the shoreface sandstones of the La Ventana Tongue may extend into the main body of the Menefee. The TPS boundary was drawn to include any of these minor sandstones or associated fluvial sandstones in the Menefee that might have been charged with gas from the Lewis Shale.

The Lewis Shale TPS has been interpreted as a continuous gas accumulation (Masters, 1979). The Lewis Shale is thought to be the source rock for the continuous gas accumulation based on modest levels of total organic carbon (TOC) and as much as 2,400 ft of formation thickness (Mavor and others, 2003). Reservoirs are thin sandstones and siltstones within the Lewis Shale itself and sandstones and siltstones of the adjacent La Ventana and Chacra Tongues, producing from natural and artificially stimulated fractures and charged from the Lewis Shale. EUR curves from La Ventana and Chacra wells are similar to EUR curves from other continuous gas reservoirs in that they show declining water and gas production curves (Troy Cook, USGS, oral commun., 2000). There are only minor associated liquid hydrocarbons in the TPS in the form of condensate produced with the gas. Solid bitumen has been observed in sandstone pores and fractures (Parris and others, 2002). These two observations are evidence for present and past liquid hydrocarbons in the Lewis Shale despite very low oil yields from Lewis reservoirs (Parris and others, 2003; Fishman and others, 2004).

The La Ventana and Chacra Tongues and their distal equivalents in the Lewis Shale are typical of low-porosity and low-permeability “tight” gas sandstones. Presumably, in more proximal settings, the La Ventana and Chacra sandstones have slightly greater porosity and permeability resulting from deposition in slightly higher energy shoreface depositional environments. A map plot of water production from wells in the La Ventana and Chacra shows increased water production to the southwest with the highest water production at the up-dip southwest margin of the gas-producing trend (IHS, 2000a,b). The marine Lewis is transitional in lithology from the proximal shoreface sandstones and siltstones of the La Ventana and Chacra Tongues to more distal thin-bedded marine siltstones, shales, and mudstones in the central part of the SJB. Gas production in the Lewis Shale is from natural fractures and fracture-stimulated clastic-rich zones in the primarily mudstone-dominated parts of the wells (Frantz and others 1999; Dube and others, 2000). These clastic-rich zones contain numerous interbeds of brittle siltstones and thin sandstones that are susceptible to fracturing (Jennings and others, 1997a; Mavor and others, 2003).

Hydrocarbon Source Rock

The organic-carbon-rich marine rocks of the Lewis Shale (figs. 2*C* and 3*A–D*) are thought to be the source for the continuous gas accumulation in the Lewis Shale TPS; however, there is little definitive data in the published literature on Lewis gas analyses or composition. The Lewis Shale is as much as 2,400 ft thick (fig. 3*B*); the thickest section being in the deepest northeastern part of the structural basin. This increased thickness is due both to greater accommodation space in the original depositional basin in that area and to facies changes because to the southwest, shoreface strata are assigned to the La Ventana and Chacra Tongues and the Pictured Cliffs Sandstone. Structure contours on the Huerfanito Bentonite Bed (fig. 3*C*) within the Lewis Shale depict both the present structure in the Lewis and the general structure of the San Juan Basin. Rocks dip to the northeast on the Chaco slope in the southwestern part of the basin, and they dip less steeply into the central part of the San Juan Basin (fig. 3*C*). In the structurally deeper distal part of the basin, essentially flat-lying Lewis Shale near the SJB axis is disrupted by a small anticline (fig. 3*C*). North of that, two small synclines displace the Lewis Shale to its greatest depth in the basin. The beds dip steeply up to the outcrop on the northeast margin of the basin.

The depositional environment of the Lewis Shale in part dictated its role as a hydrocarbon source rock in the SJB. The Lewis Shale was deposited under marine conditions during both the early Campanian relative sea-level rise and the subsequent relative sea-level fall in the latter part of the Campanian. The Lewis Shale is predominantly sandy siltstone and silty to sandy mudstone, with minor thin sandstones and organic-carbon-rich shale, all of which interfinger and grade to the southwest into the fine- to coarse-grained sandstones and siltstones of the basal Cliff House, La Ventana and Chacra Tongues, and the Pictured Cliffs Sandstone. All of these marginal-marine and shoreface clastics were supplied by depositional systems prograding into the SJB from the southwest. The Lewis Shale was deposited primarily in offshore marine settings, with clastic material derived from the fluvial and deltaic systems to the southwest. These deltas supplied terrestrial organic carbon (type-III kerogen) to the Lewis depositional basin in addition to the clastic material. Marine organisms living in the water column in the Cretaceous Western Interior Sea provided type-II kerogen to the Lewis Shale. Below the Huerfanito Bentonite Bed, the lower part of the Lewis Shale that was deposited under an overall marine transgression would be expected to have a predominance of marine organic matter (type-II kerogen) because clastics were being preferentially deposited in more proximal nearshore settings. In contrast, the upper part of the Lewis Shale above the Huerfanito was deposited under regressive marine conditions with progradation of nearshore and continental systems that would have deposited a proportionally larger component of terrestrial organic matter (type-III kerogen) mixed with marine organic matter and a relatively higher component of clastic material. Similar relations have been documented by at least one other detailed study between transgressive and regressive shales above and below the Tocito Sandstone Lentil within the Mancos Shale of the San Juan Basin (Pasley and others, 1993). In those units, the distribution of petroleum source rocks was based on analysis of the architecture of the depositional sequence. For the Mancos Shale, the transgressive shale above the Tocito Sandstone Lentil contained predominantly marine organic matter, whereas the shale below the Tocito contained a larger proportion of terrestrial organic material (Pasley and others, 1993). This relation documents the variable distribution of marine dominated organic material in transgressive shales versus the abundance of terrestrial organic matter in regressive marine shales that is predicted from sequence stratigraphic concepts. The sequence stratigraphic analysis and the recognition of the third-order maximum flooding surfaces in the Lewis Shale TPS allow similar predictions for the richest organic source beds within the Lewis Shale. These third-order marine flooding surfaces represent times of maximum transgression of the Lewis seaway, and thus, would also represent times of minimum clastic input into the deeper part of the basin, corresponding to times of potentially maximum marine organic-matter accumulation. These marine-dominated organic-carbon-rich shale intervals at the third-order maximum marine flooding surfaces are postulated here to represent the richest source beds within the Lewis Shale. The marine flooding surfaces that delineate the Cliff House transition, Otero, and Navajo City intervals in the lower part of the Lewis Shale were deposited in an overall transgressive system of the second-order TST. Thus, they would be expected to contain a proportionally greater component of marine organic matter than the third-order maximum flooding surfaces identified in the Ute interval of the Lewis Shale. This parallels the expectation that, in general, the Lewis Shale deposited as part of the second-order TST below the Huerfanito Bentonite Bed should contain a greater proportion of marine organic matter than the Lewis Shale that is part of the second-order HST above the Huerfanito. The marine shales deposited adjacent to the Huerfanito Bentonite Bed correspond to both the second-order and the third-order maximum flooding surfaces, and they should contain the highest percentage of marine organic matter and represent the best hydrocarbon source rock in the Lewis Shale TPS.

This link between the maximum flooding surfaces and organic-rich shale beds has not necessarily been recognized in previous sampling of the Lewis Shale for organic-carbon analyses. Reported geochemical analyses generally do not refer to the specific stratigraphic interval or the corresponding sequence stratigraphic unit from which the samples were collected. Thus, previously collected samples may not represent the richest source rocks present in the Lewis. The marine rocks of the Lewis Shale are reported to have total organic carbon (TOC) contents that range from 0.45 to 2.5 percent and average about 1.0 percent (Dube and others, 2000). Mavor and others (2003) report TOC varies from 0.5 to 2.5 percent with an average TOC of 1.3 percent. The hydrogen index (HI) varies from 150 to 270 mg/g, values expected to produce wet and/or dry gas (J.R. Hatch, written commun., 2002), although Mavor and others (2003) report a HI from 25 to 49 mg/g, and an OI (oxygen index) from 2 to 16 mg/g. Organic matter was primarily marine in origin in the offshore part of the depositional basin, with a southwest-sourced terrestrial organic matter component contributed from the continental clastic-source depositional systems. It is thus likely that the organic matter in the Lewis contains a mixture of type-II and type-III kerogen. Based on the distribution of vitrinite reflectance values bracketing the Lewis Shale (see next section on Source Rock Maturity), its known gas production (Jennings and others, 1997; Dube and others, 2000), EUR curves for Lewis wells that respond similarly to wells in other known continuous gas fields (Troy Cook, USGS, oral commun., 2000), and recent distribution of and production from wells recompleted in the Lewis (Jennings and others, 1997; Dube and others, 2000), the Lewis Shale in this assessment is considered to host a self-sourced continuous gas accumulation, as previously indicated by Masters (1979).

Despite the fact that wells in the Lewis TPS primarily produce gas, it is apparent from petrographic studies that at least some oil probably was generated early in the maturation history of the Lewis Shale (Parris and others, 2003; Fishman and others, 2004). The overall low organic content of the rocks based on TOC values, the mixture of type-II and type-III organic matter present, and the extent of time the rocks have been in the dry gas generation window probably limited the volume of oil generated. There is only minimal condensate reported from Lewis production (IHS, 2000a,b).

Source Rock Maturation

Thermal maturation contours in the Lewis (fig. 3*C*) are drawn primarily from previous work and analyses on organic-carbon-rich rocks above and below the Lewis Shale (Rice, 1983; Law, 1992). A stratigraphic cross section (fig. 3*D*) (see chaps. 4 and 6, this CD-ROM; adapted from Fassett, 2000) illustrates the distribution of vitrinite reflectance (Ro) values from the Fruitland and Menefee Formations, which stratigraphically bracket the Lewis Shale in the SJB (fig. 3*C*). Mavor and others (2003) reports vitrinite reflectance (Ro) from 1.79 to 1.88 percent in the Lewis Shale. In the structurally deepest part of the SJB, the Lewis has attained a thermal maturity sufficient to generate wet and/or dry gas (figs. 3*C* and 3*D*). Recent petrographic work on Lewis cores suggests that some parts of the Lewis Shale may have contained an oil precursor (Parris and others, 2003).

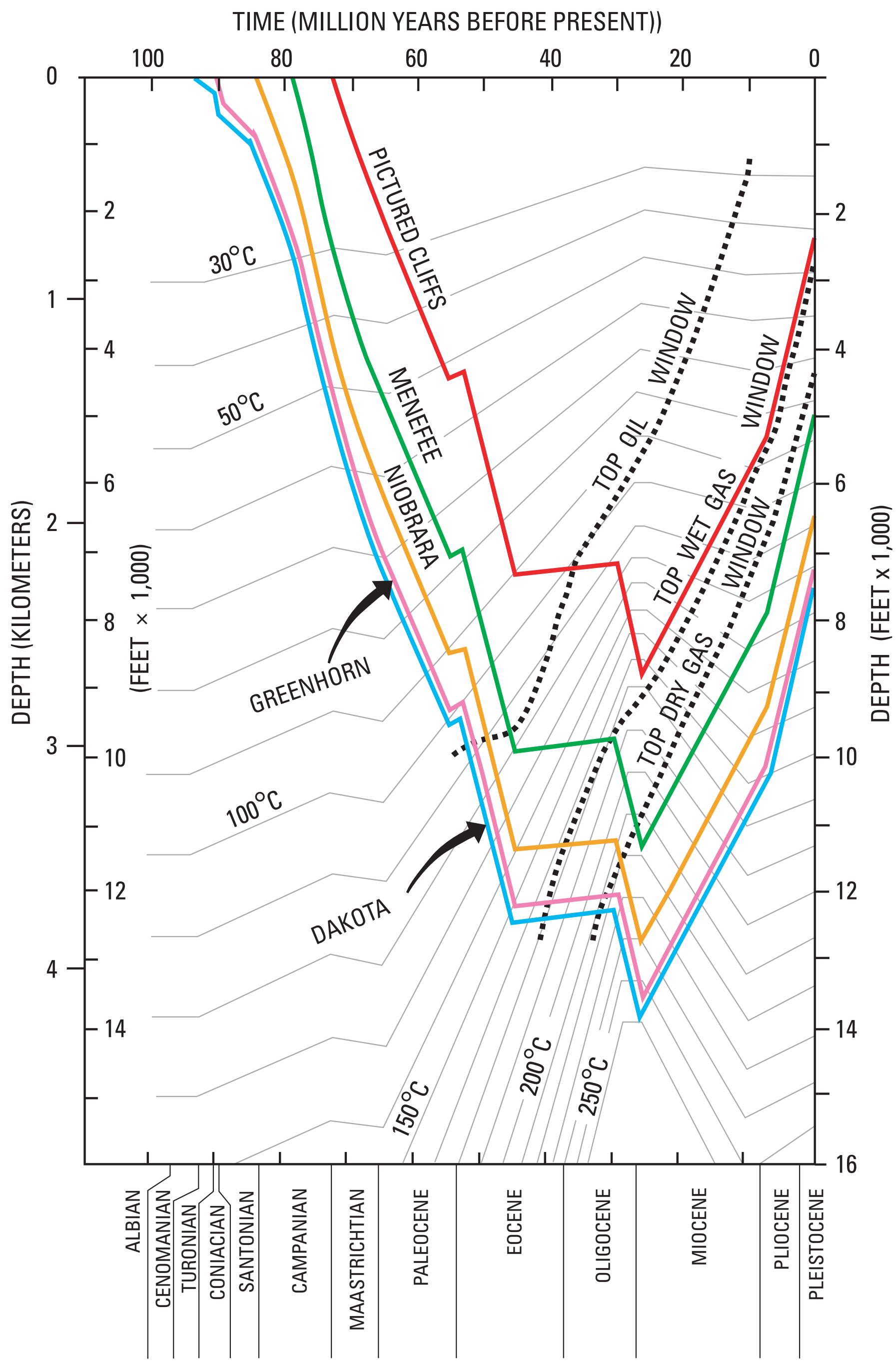


Figure 4*A*. Burial history curves from Natomas 1-11 Federal well in the Lewis Shale Total Petroleum System. Well is located on figure 3*C*. Modified from Bond (1984). See Bond (1984) for additional discussion.

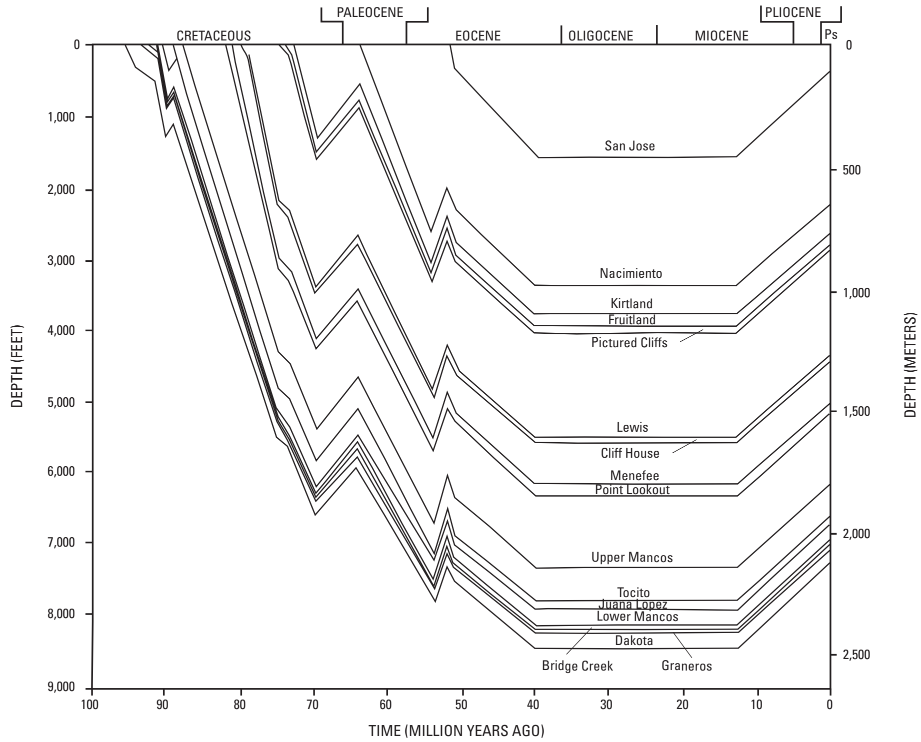


Figure 4*B*. Burial history curve from Superior Sealy 1-17 well in the Lewis Shale Total Petroleum System. Well is located on figure 3*C*. Modified from Law (1992)

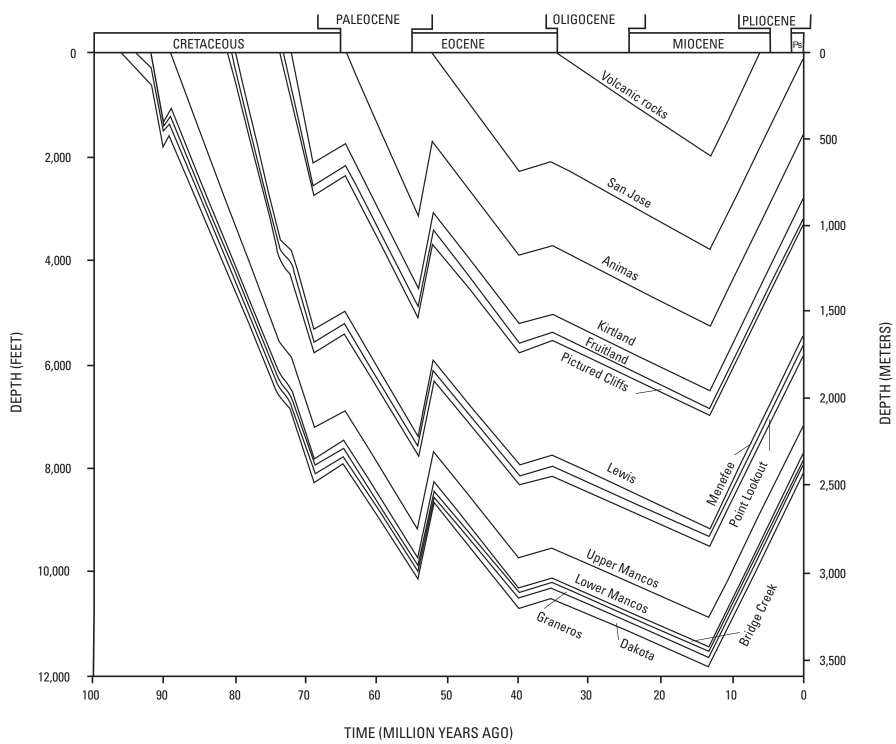


Figure 4*C*. Burial history curve from Sohio Southern Ute 15-16 well in the Lewis Shale Total Petroleum System. Well is located on figure 3*C*. See Law (1992) for additional discussion. Modified from Law (1992).

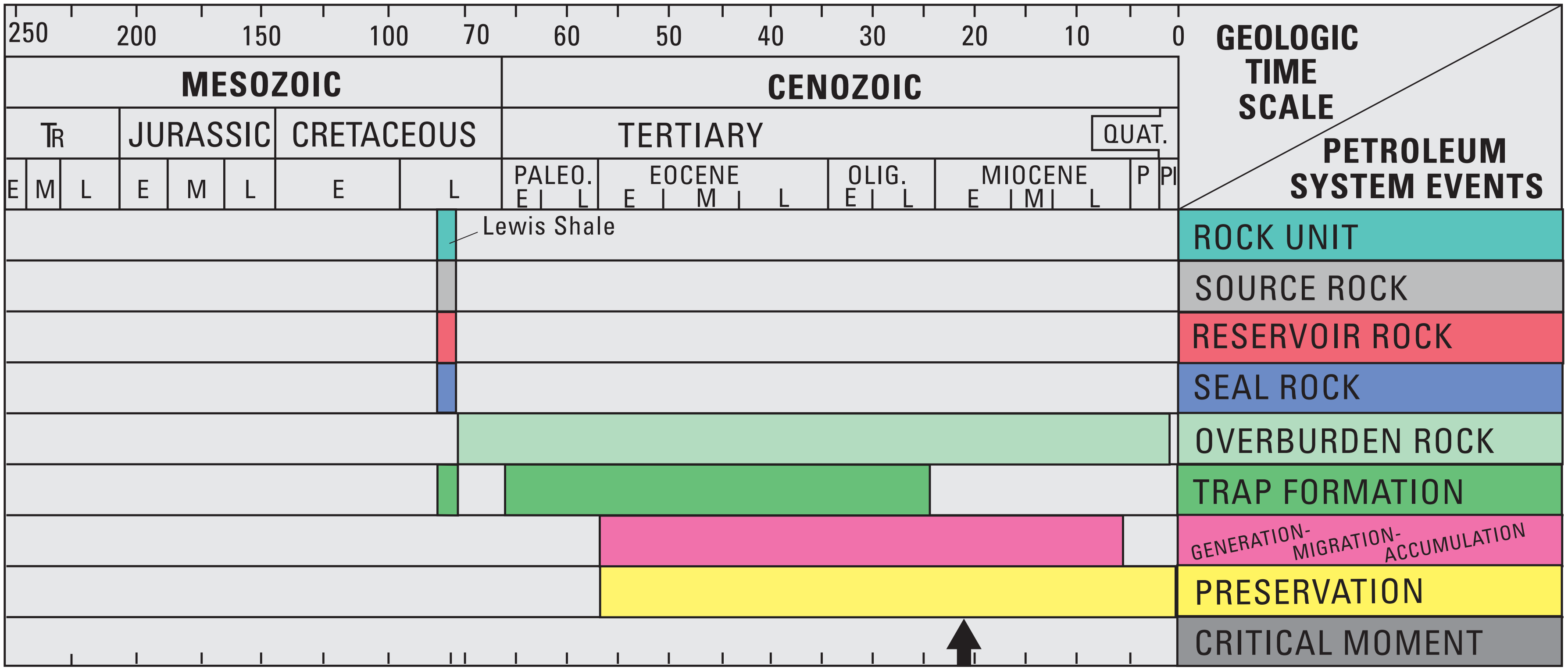


Figure 5. Petroleum system events chart for the Lewis Shale Total Petroleum System in the San Juan Basin. Tr, Triassic, Paleo., Paleocene; Olig., Oligocene; P, Pliocene; Pl, Pleistocene; Quat., Quaternary; E, early; M, middle; L, late.

The maturation history of the Lewis Shale can be summarized from burial history curves (figs. 4*A–C*) (Bond, 1984; Law, 1992). The Lewis Shale and adjacent La Ventana and Chacra Tongues were deposited during the Campanian on the western edge of the Cretaceous Western Interior Seaway (Molenaar, 1977). Accommodation space generated both by subsidence related to basin development and by relative sea-level fluctuations resulted in the deposition and preservation of Cretaceous sediments (Roberts and Kirschbaum, 1995). During the Laramide orogeny at the end of the Cretaceous, the San Juan Basin underwent significant relatively rapid structural deformation and subsidence. Tertiary strata were deposited over the Cretaceous rocks from the Paleocene to the Miocene. Maximum burial of Campanian strata, including the Lewis Shale source rock, occurred at about the Oligocene-Miocene boundary, the critical moment for the Lewis Shale source rock (fig. 5). From the Miocene to the present, there has been uplift and erosion. The Lewis Shale entered the top of the oil generation window toward the middle of the Eocene, and it entered the gas generation window at about the end of the Oligocene. Mavor and others (2003) also report a Tmax of 424° to 493° C for the Lewis Shale. This source rock maturation and burial history suggests that the organic-carbon-rich rocks of the Lewis Shale primarily generated dry gas from the middle Eocene onward. Recent petrographic studies (Parris and others, 2003; Fishman and others, 2004) suggest evidence for present and past minor liquid hydrocarbons in the Lewis despite very low oil yields from Lewis reservoirs.

Hydrocarbon Migration Summary

The Lewis Shale TPS contains a continuous gas accumulation in the Lewis Shale and the interfingered La Ventana and Chacra Tongues in a deep-basin gas trap (Masters, 1979). Despite little geochemical evidence to type the gas generated from the Lewis, and the fact that Lewis gas production is co-mingled with Mesaverde gas production, the gas in the Lewis is thought to be self-sourced, and it has not undergone significant migration, based on sequence stratigraphic analysis in this assessment and previously reported low but consistent TOC values over a stratigraphic thickness of as much as 2,400 ft (Dube and others, 2000). However, some local migration must have occurred to charge the laterally adjacent shoreface sandstones of the La Ventana and Chacra Tongues and the more distal equivalents of these sandstones and siltstones that extend basinward into the Lewis Shale. These sandstones and siltstones extend far into the basin where they interfinger with and are in direct contact with Lewis Shale source rock. Both distally in the basin and proximally in the southwest part of the SJB, gas-producing intervals are immediately adjacent to the third-order marine maximum flooding surfaces that delineate the four informal intervals in the Lewis and to other shale-rich intervals. The juxtaposition of organic-rich shales at these marine flooding surfaces to potential clastic reservoir facies provides the most likely mechanism and pathway for hydrocarbon migration into the clastic-rich units that are the principal gas reservoirs in the Lewis. The organic-carbon-rich mudstones deposited along the maximum flooding surfaces and other minor mudstone-rich intervals may also have acted as internal baffles and barriers to significant hydrocarbon migration as a result of their low porosity and permeability.

Hydrocarbon Reservoir Rocks

Reservoir rocks in the Lewis Shale Total Petroleum System include the Lewis Shale itself, and the La Ventana and Chacra Tongues of the Cliff House Sandstone that interfinger with the Lewis (figs. 2*B* and 2*C*). The Lewis Shale is predominantly sandy siltstone and silty mudstone with minor thin sandstones and organic-rich shales all deposited in a marine setting, as indicated by the fine-grained lithology, dark-gray to black color, organic content, sedimentary structures, and inclusion of marine organisms such as ammonite fossils and numerous marine trace fossils. These fine-grained rocks were deposited as offshore marine strata in the deeper parts of the depositional basin. The Lewis thin-bedded fine-grained sandstones and siltstones are distal facies of, interfinger with, and grade into sandstones and siltstones of more proximal marginal-marine deposits of the Cliff House Sandstone, including the La Ventana and Chacra Tongues. These sandstones and siltstones were derived from clastic systems with a source area located southwest of the San Juan Basin. The Cliff House Sandstone forms a series of stacked shoreline deposits that grade basinward to the northeast into finer-grained offshore deposits (Fassett, 1977, 1983; Molenaar, 1977; Molenaar and others, 2002). The shoreface deposits are identified by an array of features including the stacking pattern of parasequences recognized on well logs, sedimentary structures observed in outcrop and in core, facies associations on outcrop, and stacked coarsening-upward parasequence patterns on well logs (Palmer and Scott, 1984; Beaumont and Hoffman, 1992). The depositional strike of the shoreface sandstones is NW.–SE., generally parallel to the structure contours in the Lewis Shale. The shoreface strata grade distally into thin-bedded, fine-grained sandstones and siltstones that interfinger with the marine shale and mudstones of the Lewis. These distal thin-bedded clastics were probably deposited by longshore currents and as sediment gravity flows and turbidites.

The Lewis Shale is predominantly sandy siltstone and silty mudstone, with thin beds of silty sandstone and organic-carbon-rich shale. It has porosity ranging from 2 to 8 percent, with matrix permeability averaging about 0.01 md (millidarcies). Mavor and others (2003) report porosity ranging from 2.9 to 5.44 percent and gas permeability from 0.2 to 215 md. Water saturation ranges from 20 to 100 percent, averaging about 70 percent (Dube and others, 2000). The continuous gas accumulation extends from the Lewis Shale into the La Ventana and Chacra Tongues. These units appear to produce from typical "tight" gas sandstones having low porosity and permeability. Sandstones have porosity of 8 to 14 percent, permeabilities of 0.15 to 0.3 md, and water saturation of about 30 to 45 percent (Hoppe, 1978a,b,c,d,e). Most of the wells that produce gas are underpressured at about 0.22 psi/ft (Dube and others, 2000).

Gas production from the main body of the Lewis Shale is reported to be due to the development of natural or artificially induced fractures in thin-bedded clastic units that are cemented and brittle compared to the adjoining shales and mudstones (Jennings and others, 1997; Frantz and others, 1999). Sandstones and siltstones in the La Ventana and Chacra Tongues are reservoirs that produce gas as typical "tight" gas sandstones, whereas intervals of interbedded shale, mudstone, siltstone, and sandstone in the Lewis Shale require natural fractures or fracture stimulation to produce gas (Jennings and others, 1997a). The self-sourced and self-sealing gas accumulation is underpressured at present at about 0.22 psi/ft. The underpressured reservoirs may indicate that gas has migrated up-dip into the water-saturated zone on the southwest margin of the basin. Adsorption isotherms generated for the quantification of the amount of adsorbed gas-in-place on organic matter in the Lewis Shale (Dubiel and others, 2000) indicate that with reservoirs underpressured at about 0.22 psi/ft, the pressure can not be reduced sufficiently in the present production wells to release the adsorbed gas.

Hydrocarbon Traps and Seals

The Lewis Shale TPS is thought to be self-sourced regarding hydrocarbon generation. The fine-grain size and low permeability of Lewis shales and mudstones likely resulted in a thick stratigraphic section of rocks that is essentially self-sealing with regard to hydrocarbon migration. The fine-grained mudrocks and shales of the Lewis Shale interfinger on a small scale with the interbedded and fractured fine-grained sandstones and siltstones. Many of these beds can be traced to the southwest where they grade into distal sandstones and siltstones of the basal Cliff House Sandstone, La Ventana Tongue, or Chacra Tongue. The back-stepping nature of the parasequence sets that form the basal Cliff House Sandstone, La Ventana, and Chacra Tongues resulted in shoreface parasequences and parasequence sets that are overlain by successively finer-grained rocks, allowing for trapping of gas in the shoreface and distal clastic strata by the shales and mudstones, which also form the seals or serve as impediments to gas migration.

In the Lewis Shale and the La Ventana and Chacra Tongues, the gas-producing intervals are within either the sandy shoreface parasequences or the correlative sandy or silty distal extensions of those parasequences that extend into the Lewis Shale. The producing intervals are in the sandy and silty strata in the Lewis presumably because they are more cemented, brittle, and therefore more susceptible to either natural or artificially induced fractures that produce gas. In addition, the sandy and silty upper parts of the parasequences commonly are overlain by organic-carbon-rich shale to mudstone that are associated with marine flooding surfaces. Thus the reservoir strata are immediately overlain and underlain by likely hydrocarbon-rich source rocks that also served as seals or impediments to gas migration.These facies relations indicate that the Lewis Shale itself is the primary intraformational seal for the continuous gas accumulation in siltstones and sandstones in the Lewis Shale TPS. The facies relations indicate that the trap and seal thus formed concomitantly with deposition of the strata. Presumably gas is trapped by a process that is diffusion dependent, whereby gas cannot effectively migrate through the fine-grained mudrocks and/or is trapped in the central part of the basin by infiltration and pore-space saturation by meteoric or migrating formation waters around the basin margins. Masters (1979) felt that the gas was in part trapped by the up-dip water in rocks at the margins of the San Juan Basin, a mechanism proposed for other basin-centered gas accumulations in Rocky Mountain basins (Brown and others, 1986).

Significant gas migration through and within the Lewis Shale TPS is dependent upon lateral continuity or juxtaposition of porous and permeable, thin clastic units and/or a natural fracture network. Gas production is enhanced by intercepting natural fractures in the well bore or by inducing fractures through artificial stimulation (Frantz and others, 1999).

Assessment of Oil and Gas Resources

The geologic events chart (fig. 5) summarizes the important elements and timing of processes that contributed to generation and accumulation of hydrocarbons in the Lewis Shale Total Petroleum System. Deposition of the Lewis Shale and laterally equivalent La Ventana and Chacra Tongues of the Cliff House Sandstone during the Campanian Stage of the Upper Cretaceous formed the source rocks, reservoir rocks, and seals for the hydrocarbons. The overburden rocks required to bury and to bring the Lewis Shale marine source rocks to thermal maturity include the Upper Cretaceous Pictured Cliffs Sandstone, Kirtland Shale, and Fruitland Formation, the Upper Cretaceous to Paleocene Ojo Alamo Sandstone and Animas Formation, and the Paleocene Nacimiento Formation. Deposition of the Eocene San Jose Formation and Oligocene to Miocene volcanic rocks further buried the Lewis Shale to a maximum depth of about 9,000 ft by the middle Miocene. Deposition of Paleocene to Miocene rocks was concommitant with structural downwarping of the San Juan Basin as part of the Laramide orogeny. Regional uplift of the San Juan Basin began about 13 million years ago resulting in erosion that exposed rocks as old as Cretaceous around the margins of the basin. Based on the burial history curves (figs. 4*A*–*C*), hydrocarbon generation began in the Eocene. Based on the distribution of producing gas wells, dry holes, water production, and the distribution of favorable reservoir- and source-rock facies, one assessment unit was defined, mapped and assessed for the Lewis Shale Total Petroleum System—the Lewis Continuous Gas Assessment Unit. The methodology employed for assessment of continuous gas accumulations is described by Schmoker (1996).

Lewis Continuous Gas Assessment Unit (AU 50220261)

The Lewis Continuous Gas Assessment Unit (AU 50220261) is defined by a combination of factors including the occurrence of known underpressured gas production in the Lewis Shale and La Ventana and Chacra Tongues of the Cliff House Sandstone, as well as known reservoir and source rocks, natural or artificially stimulated fractures in these rocks that enable gas production, and the extensive subsurface distribution of the Lewis Shale in the SJB. Production to date from the Lewis Shale is primarily from recompletions in preexisting Mesaverde wells that already penetrate the Lewis. However, the reservoir facies that produce gas from the Lewis in recompleted Mesaverde wells occur throughout the subsurface extent of the Lewis in the SJB, as do the presumed source rocks within the Lewis. In addition, the Lewis Shale throughout a large portion of the basin was buried deeply enough by Eocene time to generate hydrocarbons. Because the Lewis Shale is thought to be both self-sourced and self-sealed, trap formation and hydrocarbon accumulation likely occurred throughout a large area of the subsurface. The distribution of natural fractures is unknown, but artificially induced fractures are a successful completion and production practice in many Lewis recompletions. Thus, the Lewis Shale is potentially capable of producing gas in a large area of the SJB whether or not preexisting Mesaverde wells or natural fractures exist.

Known production in the Lewis is primarily from silty or sandy intervals that are susceptible to natural or artificially induced fractures. These intervals in the Lewis Shale represent the distal equivalents of parasequences that can be traced into more proximal facies in the La Ventana and Chacra Tongues. The proximal shoreface facies of the La Ventana and Chacra Tongues are present only in the southwest part of the San Juan Basin; however, the distal parasequences and the source rocks in the Lewis Shale extend virtually to the outcrop throughout the rest of the SJB. Examination of EUR curves from the IHS production database (Troy Cook, USGS, written commun., 2002) indicate that the La Ventana and Chacra wells behave in a manner consistent with a continuous gas accumulation. That is, they exhibit gas production curves that decline at rates consistent with wells in other known continuous gas accumulations.

Designation of the nature of the gas accumulation and the production curves for the Lewis Shale itself is more problematic due to the Lewis being produced from preexisting Mesaverde wells and co-mingling of the gas being produced and reported. No wells exist in the database that report solely Lewis gas production to evaluate whether the Lewis presents production EUR curves consistent with a continuous gas accumulation. However, wells that were recompleted in the Lewis were identified in the database, and EUR curves from those wells were examined.

Because the La Ventana and Chacra are producing from a continuous gas accumulation sourced from the Lewis Shale, and because EUR curves for those units display a “typical” production curve for a continuous gas accumulation (Troy Cook, USGS, written commun., 2000), it was plausible to include those two units in the Lewis Continuous Gas Assessment Unit. Thus, the Lewis Continuous Gas Assessment Unit (AU 50220261) is defined to include both the La Ventana and the Chacra Tongues and the Lewis Shale over the entire subsurface extent of the units.

Assessment Results

Data retrieval from the IHS well file identified over 5,000 Mesaverde wells in the San Juan Basin. By identifying which wells were recompleted since about 1990, and individually examining the well reports for perforated intervals, 1,144 tested cells were attributed to the Lewis Shale. To obtain EUR curves for these Lewis wells, it was necessary to examine individual Mesaverde EUR curves and identify those with production increase “spikes” within the last ten years, presumably due to Lewis recompletions. The presumed increased contribution to the gradually declining production curve was interpreted as Lewis Shale production. Based on the EUR curves, a minimum total recovery per cell was established at 0.02 BCF gas (appendix A). Wells with gas production below this minimum value were not included, because they have production too small to be representative of the assessment unit. This left 1,087 tested cells with EURs greater than or equal to the minimum EUR. The total number of producing wells was divided by three, separating the production data into three thirds. The EURs for the producing wells were plotted separately for the first third of the wells, the second third, and the third third. The median EUR is 0.5 BCFG for the first third of the producing wells, 0.25 BCFG for the second third, and 0.22 BCFG for the third third. There is adequate access, charge, reservoir, trap, seal, and timing and generation of hydrocarbons, indicating a geologic probability of 1.0 for finding at least one additional untested cell with total recovery greater than the stated minimum of 0.02 BCFG.

GIS techniques were applied to geographic coverages for the assessment unit to determine the total assessment-unit area, the area per cell of untested cells, and the untested area (appendix A). The median area of the assessment unit is 4,804,000 acres. The uncertainty of the location of the line defining the assessment unit is about 10 percent, so that the maximum area is 5,284,000 acres and the minimum area is 4,324,000 acres.

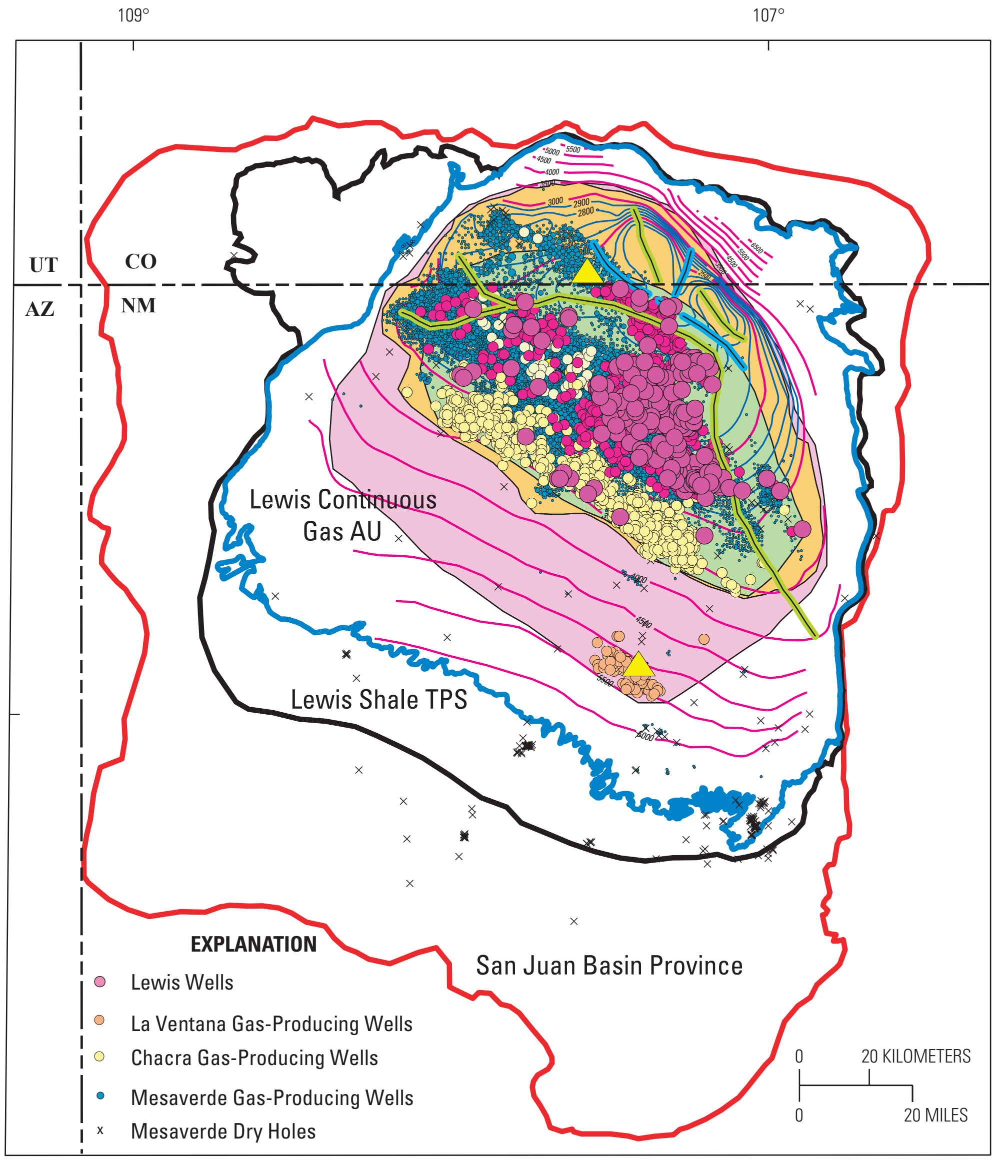


Figure 6. Map of the Lewis Continuous Gas Assessment Unit (AU 50220261) showing producing wells in the Chacra and La Ventana Tongues of the Cliff House Sandstone (yellow and orange circles, respectively) and Lewis Shale (pink circles), Mesaverde Group dry holes (x), and maximum (pink), median (orange), and minimum (green) assessment unit areas (see text for discussion).

The area per cell of untested cells is related to the drainage area of a well. The closest drilling of Mesaverde wells in the basin at present is 40 acres, and this is the presumed minimum size of cells for Lewis wells. The median is 100 acres, and the maximum is 200 acres. At the median, the untested area of the assessment unit is 97.5 percent, with a minimum of 97 percent and a maximum of 98 percent.

The Lewis Continuous Gas Assessment Unit (AU 50220261) includes strata of the Lewis Shale and the La Ventana and Chacra Tongues of the Cliff House Sandstone. The distribution of existing producing wells in the Lewis Shale TPS in the San Juan Basin is related to two factors:

1. the distribution of subsurface shoreface parasequences and distal equivalents in the La Ventana and Chacra Tongues and the four informal intervals of the Lewis Shale and
2. the preexisting wells completed in the Mesaverde below the Lewis Shale.

The sandstones of the La Ventana Tongue produce gas in a small area in the southeast part of the SJB and from more distal equivalents of the uppermost parasequences in the central part of the SJB. The small area is part of a northwest-trending belt on the southwest side of the SJB (fig. 6) where the La Ventana occurs in the subsurface (see for example, Fassett, 1977). The Chacra produces gas from shoreface sands that exist in a northwest-trending belt in the subsurface. In contrast, the present distribution of producing wells in the Lewis Shale is, at least for the time being, related to the distribution of preexisting Mesaverde wells that are being recompleted in the Lewis, primarily by Burlington Resources. Similar productive facies in the Lewis Shale probably exist anyplace in the Lewis where sandy and silty interbeds were deposited that are susceptible to either natural or artificially induced fracturing and where they are adjacent to hydrocarbon source rocks. In the farthest northeast portion of the SJB, no production is presently known from the Lewis Shale north of the small anticline in the deepest part of the SJB. Limited data from individual wells and an examination of cumulative water production from wells in the database (IHS, 2000a,b) indicate that distal very fine grained sandstones and siltstones within the Lewis Shale may be too “tight,” that is they lack sufficient permeability to produce gas in that area. In addition, previous publications indicate that gas-bearing sandstones in the SJB are water saturated updip on the basin margins, forming part of the trapping mechanism for the basin-centered gas (Masters, 1979). Examination of the cumulative water production from wells producing gas from the Chacra sandstones, for example, indicate that water production within individual wells increases to the southwest of the Chacra producing trend, corroborating the interpretation that water saturation of those sandstones increases toward the southwest basin margin. Thus, production of gas from the La Ventana and Chacra Tongues and the Lewis Shale appears to be limited to the southwest by water saturation of the updip sandstones. Toward the other margins of the basin, production appears to be limited by a combination of water saturation in the sandstones and lack of permeability and porosity in the finer-grained distal sandstones and siltstones within the Lewis Shale.

Coupled with this understanding of the geologic controls on the distribution of known production in the assessment unit, GIS techniques again were used to define the minimum, median, and maximum untested areas of the assessment unit that have potential for additions to reserves in the next 30 years. The maximum untested area (fig. 6) was determined to include the area of La Ventana production farthest to the southwest and follows the depositional strike of the shoreface sandstones of the La Ventana to the northwest. In the northwest, northeast, and southwest margins of the basin, the maximum area was determined based on the presumed updip limit of water saturation that limits gas production in the underlying Mesaverde rocks on the basin margin, based on the distribution of Mesaverde producing wells. The maximum percentage of the untested assessment unit area that has potential for addition to reserves is 40 percent. The median area was determined to include all wells to the southwest that produced from the Chacra, including those wells that have smaller total gas production and higher water production than most wells in the northwest-trending depositional facies trend of shoreface sandstones in the Chacra Tongue (fig. 6). To the northwest, northeast, and southeast the median area was determined along the structural contour on the Huerfanito Bentonite Bed that marks the presumed limit of the majority of producing wells in the Chacra. This line was determined on the premise that Chacra gas production is in part limited by depositional facies and updip water saturation in the Chacra Tongue. The median percentage of the untested area that has potential for addition to reserves is 34 percent. The minimum area (fig. 6) was determined to encircle the tight distribution of Chacra production on the southwest basin margin that appears to be controlled by the depositional strike of the shoreface sandstones and the updip limit of significant gas production imposed by water saturation within the updip rocks. To the northeast, the minimum area line was determined along the axis of the small anticline that also marks the northeast limit of significant gas production in Mesaverde wells (fig. 3*A*). Presumably the lack of porosity and permeability coupled with updip water saturation limits Mesaverde production in this direction and would limit Lewis Shale production as well. On the southeast and northeast basin margins, the minimum area line was determined to include all known Lewis and Mesaverde producing wells because Mesaverde exploration over the last few decades has apparently delimited the extent of productive rocks in these areas based on water saturation in the updip basin margins. The minimum percentage of the untested area that has potential for addition to reserves is 23 percent.

The results of the assessment of undiscovered gas resources in the Lewis Continuous Gas Assessment Unit (AU 50220261) are presented in appendix B. Allocations of those resources to State and various Federal lands are in appendix A. The Monte Carlo simulations, verified by the analytical probability method, provide the following results for the assessment unit. In the Lewis Continuous Gas Assessment Unit (AU 50220261), for continuous gas resources, there is an F95 of 8,315.22 BCFG and an F5 of 12,282.31 BCFG, with a mean value of 10,177.24 BCFG. There is an F95 of 18.08 MMBNGL and an F5 of 47.32 MMBNGL, with a mean of 30.53 MMBNGL.

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Appendix A. Data form for the Lewis Continuous Gas Assessment Unit (AU 50220261).

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 8, 8-16-02)

IDENTIFICATION INFORMATION

Assessment Geologist:…	R.F. Dubiel	Date:	9/24/2002
Region:……………………	North America	Number:	5
Province:…………………	San Juan Basin	Number:	5022
Total Petroleum System:.	Lewis Shale	Number:	502202
Assessment Unit:……….	Lewis Continuous Gas	Number:	50220261
Based on Data as of:……	PI/Dwights 2001		
Notes from Assessor…..			

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: **Oil** (<20,000 cfg/bo) **or** **Gas** (≥20,000 cfg/bo) Gas
What is the minimum total recovery per cell?… 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 1144
Number of tested cells with total recovery per cell ≥ minimum: …….. 1087
Established (>24 cells ≥ min.) X Frontier (1-24 cells) ____ Hypothetical (no cells) ____
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st 3rd discovered 0.5 2nd 3rd 0.25 3rd 3rd 0.22

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum ……	1.0
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	1.0
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum………..	1.0

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

4. **ACCESS:** Adequate location for necessary petroleum-related activities for an untested cell with total recovery ≥ minimum ……………………………………………………………… 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES IN THE NEXT 30 YEARS

1. Total assessment-unit area (acres): (uncertainty of a fixed value)
   minimum 4,324,000 median 4,804,000 maximum 5,284,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres):
   (values are inherently variable)
   calculated mean 105 minimum 40 median 100 maximum 200

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
   minimum 97 median 97.5 maximum 98

4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum)
   (uncertainty of a fixed value) minimum 23 median 34 maximum 40

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TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves in next 30 years:
(values are inherently variable)

(mmbo for oil A.U.; bcfg for gas A.U.)	minimum	median	maximum
	0.02	0.5	6

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)………………………..…….			
NGL/gas ratio (bngl/mmcfg)…………………….			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)……………..……	1	3	5

SELECTED ANCILLARY DATA FOR UNTESTED CELLS
(values are inherently variable)

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)…………….……….			
Sulfur content of oil (%)………………………...…			
Drilling depth (m) ……………...…………….……			
Depth (m) of water (if applicable)……………….			
Gas assessment unit:			
Inert-gas content (%)…………………………....…..	0.00	1.50	10.00
CO_2 content (%)…………………………………..…..	0.00	1.00	3.00
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)………………………………….	500	1200	2500
Depth (m) of water (if applicable)……………….			

Success ratios:	calculated mean	minimum	median	maximum
Future success ratio (%).....		60	90	95

Historic success ratio, tested cells (%) 95

Assessment Unit (name, no.)
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ALLOCATIONS OF POTENTIAL ADDITIONS TO RESERVES TO STATES
Surface Allocations (uncertainty of a fixed value)

1. Colorado represents 14.63 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:	minimum	median	maximum
Volume % in entity……		15	
Portion of volume % that is offshore (0-100%)..		0	

2. New Mexico represents 85.37 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:	minimum	median	maximum
Volume % in entity……		85	
Portion of volume % that is offshore (0-100%)..		0	

3. ____ represents ____ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

4. ____ represents ____ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

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5. ______________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

6. ______________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

7. ______________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

8. ______________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

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ALLOCATIONS OF POTENTIAL ADDITIONS TO RESERVES TO LAND ENTITIES
Surface Allocations (uncertainty of a fixed value)

1. Federal Lands represents 37.81 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………		38	
Portion of volume % that is offshore (0-100%)..		0	

2. Private Lands represents 17.33 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………		17	
Portion of volume % that is offshore (0-100%)..		0	

3. Tribal Lands represents 40.73 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………		41	
Portion of volume % that is offshore (0-100%)..		0	

4. Other Lands represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

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5. CO State Lands represents 0.28 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity			
Portion of volume % that is offshore (0-100%)			

Gas in gas assessment unit:	minimum	median	maximum
Volume % in entity		0	
Portion of volume % that is offshore (0-100%)		0	

6. NM State Lands represents 3.86 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity			
Portion of volume % that is offshore (0-100%)			

Gas in gas assessment unit:	minimum	median	maximum
Volume % in entity		4	
Portion of volume % that is offshore (0-100%)		0	

7. ______ represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity			
Portion of volume % that is offshore (0-100%)			

Gas in gas assessment unit:	minimum	median	maximum
Volume % in entity			
Portion of volume % that is offshore (0-100%)			

8. ______ represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity			
Portion of volume % that is offshore (0-100%)			

Gas in gas assessment unit:	minimum	median	maximum
Volume % in entity			
Portion of volume % that is offshore (0-100%)			

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ALLOCATIONS OF POTENTIAL ADDITIONS TO RESERVES TO FEDERAL LAND SUBDIVISIONS
Surface Allocations (uncertainty of a fixed value)

1. Bureau of Land Management (BLM) represents 30.75 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity……………………………………		31	
Portion of volume % that is offshore (0-100%)..		0	

2. BLM Wilderness Areas (BLMW) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

3. BLM Roadless Areas (BLMR) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

4. National Park Service (NPS) represents 0.05 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity……………………………………		0	
Portion of volume % that is offshore (0-100%)..		0	

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5. NPS Wilderness Areas (NPSW) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

6. NPS Protected Withdrawals (NPSP) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

7. US Forest Service (USFS) represents 6.67 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity……		7	
Portion of volume % that is offshore (0-100%)..		0	

8. USFS Wilderness Areas (USFSW) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity……			
Portion of volume % that is offshore (0-100%)..			

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9. USFS Roadless Areas (USFSR) represents ____ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

10. USFS Protected Withdrawals (USFSP) represents ____ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

11. US Fish and Wildlife Service (USFWS) represents ____ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

12. USFWS Wilderness Areas (USFWSW) represents ____ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

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13. USFWS Protected Withdrawals (USFWSP) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

14. Wilderness Study Areas (WS) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

15. Department of Energy (DOE) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

16. Department of Defense (DOD) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

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17. Bureau of Reclamation (BOR) represents 0.34 areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................		0	
Portion of volume % that is offshore (0-100%)..		0	

18. Tennessee Valley Authority (TVA) represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

19. Other Federal represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

20. ______ represents ______ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity......................................			
Portion of volume % that is offshore (0-100%)..			

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ALLOCATIONS OF POTENTIAL ADDITIONS TO RESERVES TO ECOSYSTEMS
Surface Allocations (uncertainty of a fixed value)

1. Grand Canyon Lands (GDCL) represents 3.13 areal % of the assessment unit

	minimum	median	maximum
Oil in oil assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………		5	
Portion of volume % that is offshore (0-100%)..		0	

2. Navajo Canyonlands (NVCL) represents 72.31 areal % of the assessment unit

	minimum	median	maximum
Oil in oil assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………		80	
Portion of volume % that is offshore (0-100%)..		0	

3. South-Central Highlands (SCHL) represents 9.53 areal % of the assessment unit

	minimum	median	maximum
Oil in oil assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………		5	
Portion of volume % that is offshore (0-100%)..		0	

4. White Mountain-San Francisco Peaks (WMSF) represents 15.03 areal % of the assessment unit

	minimum	median	maximum
Oil in oil assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………		10	
Portion of volume % that is offshore (0-100%)..		0	

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5. ________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………			
Portion of volume % that is offshore (0-100%)..			

6. ________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………			
Portion of volume % that is offshore (0-100%)..			

7. ________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………			
Portion of volume % that is offshore (0-100%)..			

8. ________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………			
Portion of volume % that is offshore (0-100%)..			

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9. ________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

10. ________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

11. ________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

12. ________________ represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			
Gas in gas assessment unit:			
Volume % in entity……………………………………			
Portion of volume % that is offshore (0-100%)..			

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ALLOCATIONS OF POTENTIAL ADDITIONS TO RESERVES TO LAND ENTITIES
Subsurface Allocations (uncertainty of a fixed value)

Based on Data as of: ____________________

1. All Federal Subsurface represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity…………………………………			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity…………………………………			
Portion of volume % that is offshore (0-100%)..			

2. Other Subsurface represents ________ areal % of the assessment unit

Oil in oil assessment unit:	minimum	median	maximum
Volume % in entity…………………………………			
Portion of volume % that is offshore (0-100%)..			

Gas in gas assessment unit:			
Volume % in entity…………………………………			
Portion of volume % that is offshore (0-100%)..			

Appendix B. Summary of assessment results for the Lewis Continuous Gas Assessment Unit (AU 50220261).

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Minimum, for conventional resources this is the minimum field size assessed (MMBO or BCFG); for continuous-type resources this is the minimum cell estimated ultimate recovery assessed. Prob., probability (including both geologic and accessibility probabilities) of at least one field (or for continuous-type resources, cell) equal to or greater than the minimum. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

	Undiscovered Resources											
Field	Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
Type	F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Lewis Continuous Gas												
Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas					8,315.22	10,105.95	12,282.31	10,177.24	18.08	29.25	47.32	30.53
Total	0.00	0.00	0.00	0.00	8,315.22	10,105.95	12,282.31	10,177.24	18.08	29.25	47.32	30.53

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