OUTCROP ANALYSIS OF THE CRETACEOUS MESAVERDE GROUP: JICARILLA APACHE RESERVATION, NEW MEXICO

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**ABSTRACT**

This is the Phase One contract report to the United States Department of Energy, United States Geological Survey and the Jicarilla Apache Indian Tribe on the project entitled “Outcrop Analysis of the Cretaceous Mesaverde Group: Jicarilla Apache Reservation, New Mexico.” Field work for this project was conducted during July and August, 1998, at which time fourteen measured sections were described and correlated on or adjacent to Jicarilla Apache Reservation lands. A fifteenth section, described east of the main field area, is included in this report, although its distant location precluded use in the correlations and cross-sections presented herein. Ground-based photo mosaics were shot for much of the exposed Mesaverde outcrop belt and were used to assist in correlation. We conducted outcrop gamma-ray surveys at six of the fifteen measured sections using a GAD-6 scintillometer. The raw gamma-ray data are included in this report, however, analysis of those data is part of the ongoing Phase Two of this project.

Included in this report is a description and interpretation of the inner shelf, nearshore marine, estuarine, and alluvial plain sedimentary lithofacies that comprise the upper Mancos Shale, Point Lookout Sandstone, Menefee Formation, Cliff House Sandstone, and basal Lewis Shale in the northeastern San Juan Basin. Six discrete shorelines were recognized and mapped in the area between Puerto Chiquito (T.27 N., R.1 E.) and Briggs Mesa (T.31 N., R.1E.).

Our work places the entire Mancos Shale to Lewis Shale interval within a sequence stratigraphic framework that includes description of two previously undocumented sequence bounding unconformities. From oldest to youngest this series includes:

- **Late highstand systems tract** - Mancos, Point Lookout and Menefee shallow marine and alluvial deposits prograde basinward under conditions of decreasing sediment accommodation space,
- **Lowstand systems tract** - base level fall and erosion produces sequence boundary SB1 and an incised valley within the middle Menefee and upper Point Lookout - minor accumulation of fluvial strata within the valley,
- **Transgressive systems tract** - incised valley backfills with bayhead delta and heterolithic fluvial strata in the Point Lookout and Menefee - equivalent transgressive shallow marine deposits lie north of the field area,
- **Highstand systems tract** - renewed shoreline progradation results in Menefee alluvial plain aggradation in field area,
- **Lowstand systems tract** - base level fall and erosion produces sequence boundary SB2 and a second incised valley within the middle Menefee - minor accumulation of fluvial strata within the valley,
- **Transgressive systems tract** - incised valley fills with Menefee fluvial strata and is overstepped by landward migrating Cliff House shallow marine sandstones - a transgressive surface separates Cliff House or Menefee strata (below) from Lewis Shale (above).

Using this stratigraphic framework, a number of hydrocarbon reservoir plays can be recognized and projected toward the subsurface. Late highstand Point Lookout shoreface and estuarine deposits underlying SB1 produce a very promising updip pinchout play that occupies the highest stratigraphic level within the marine progradational package. These rocks correlate along a ~N60W shoreline trend line to the Ignacio-Blanco field in southern Colorado. Our work suggests that this trend line separates two very different types of Mesaverde exploration strategies. Southwest of this line, complete Point Lookout shoreface sandstone packages will display the “step” and “bench” stacking patterns long familiar in the basin subsurface. These shoreline sandstones stacked vertically as they prograded seaward and thus have a thick landward-equivalent non-marine Menefee package.

Northeast of this trend line base-level fall and incised valley topography will greatly influence Point Lookout and Menefee reservoirs. Sediment eroded from the alluvial plain bypassed the San Juan Basin area (along surfaces SB1 and SB2) to accumulate north of the modern outcrop belt. Point Lookout shoreface sandstones in the northeastern San Juan Basin will be variably dissected with valleys and interfluves. Here the exploration strategies should include specific dip-aligned incised valley fill sandstones that extend from the top of the Point Lookout landward to the middle Menefee. Cliff House sandstones are present in only the extreme northeastern outcrops, suggesting their significance as reservoir units may be minimal in the northeastern part of the basin, especially on the Reservation.
LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

Mesaverde Group strata in the study area (Fig. 1) include a range of facies types that reflect deposition in inner shelf, nearshore marine, and coastal or alluvial plain settings. Complex intertonguing relationships make direct correlation of specific facies to individual formations difficult. In general, however, thick nearshore marine strata comprise the bulk of the Point Lookout Sandstone and its transition to the underlying Mancos Shale throughout the study area. Marine-influenced fluvial/estuarine and non-marine strata characterize the Menefee Formation, which locally contains thin wedges of Point Lookout and Cliff House coastal marine deposits. Nearshore coastal sandstones of the Cliff House Sandstone are preserved only on Briggs’ Mesa in the far northeastern part of the study area (Fig. 1). South of Briggs’ Mesa, poorly expressed, thin (0-7 feet) inner shelf sandstones and sandy fossiliferous lags at the base of the Lewis Shale mark passage of the Cliff House shoreline through the study area. The following lithofacies descriptions are based upon detailed measured section data presented in Appendix 1. Selected descriptive criteria are compiled in Tables 1 and 2.

Inner Shelf Strata

Very-fine Burrowed Sandstone Facies (Shelf-Modified Transgressive Lag)

Very fine sandstones contain mudrip clasts, wood imprints, shark’s teeth, and shell (including oyster) fragments as basal lag components. Flaggy, lenticular bedding (<2 feet thick) dominates the sandstones, with uncommon amalgamation to a maximum of seven feet. Rarely preserved physical sedimentary structures include parallel lamination and hummocky cross-stratification (HCS). Spectacular *Ophiomorpha* trace fossils are characteristic (Fig. 2a), and bioturbation commonly obscures physical sedimentary structures. Unique to this facies is strong silica cement, with lesser Fe-oxide cement imparting an orange color in outcrop. This facies has been observed only on cliff tops at the contact between the underlying Menefee Formation and overlying offshore marine Lewis Shale. It is interpreted to represent a major marine flooding surface and associated transgressive lag coincident with passage of the Cliff House shoreline through this horizon. Modern day erosion of the cliff tops has resulted in removal of most Lewis Shale outcrop, leaving these tightly cemented, burrowed sandstones in float and locally in place.

Nearshore Marine Strata

Interbedded Mudrock/Sandstone Facies (Offshore Transition)

Thinly interbedded shales, mudstones, siltstones and sandstones comprise this facies (Fig. 2b). The number, thickness, and amalgamation of sandstone beds tends to increase upward, however, thin (< 5 feet) fining-upward trends are locally present. Mudrock beds range from less than 1 inch to approximately 10 inches thick where homogenized by burrowing. Very fine-grained sandstones range in thickness from less than 1 inch to 2 feet, and amalgamate to form beds 3-5 feet thick. Sandstones have sharp bases that locally display tool marks and gutters. Tool marks oriented NNE-SSW correspond well with the N73°W shoreline trends (established by mapping up-dip foreshore strata). Sedimentary structures in sandstones include lenticular bedding, wave ripple stratification and HCS. Bioturbation ranges from 0 to 70%, including the trace fossils *Chondrites*, *Planolites*, *Skolithos*, and *Thalassinoides*.

The interbedded mudrock/sandstone facies grades downward into fine-grained mudrocks and shales of the Mancos Shale and is overlain by the massive marine sandstone facies of the Point Lookout Sandstone. The interbedded facies is interpreted to reflect sedimentation under variable energy marine conditions in the offshore transition zone. Thigh bedded mudrock components and delicate trace fossil assemblages reflect a low-energy, or fair-weather, well-oxygenated marine setting (*Cruziana* ichnofacies of Pemberton et al., 1992). Storm conditions, during which waves and storm surge currents impinged on the sea floor, produced the HCS and wave rippled sands with sharp bases, tool marks and gutters (Dott and Bourgeois, 1982; Morton, 1981; Swift et al., 1983). Upward increase in storm sand thickness and amalgamation is consistent with increased storm impact on a shoaling seafloor.

Massive Sandstone Facies (Lower to Middle Shoreface)

Overlying and locally interfingering with the interbedded mudrock and sandstone facies is amalgamated massive sandstone (Fig. 2b). This facies displays a coarsening-upward transition from very fine to fine grained sandstone and an upward transition from (less common) hummocky cross-stratification (HCS) to swaley cross-stratification (SCS) and undulatory sub-parallel lamination. Swaley cross-stratification (Leckie and Walker, 1982) displays concave-upward erosional surfaces and fill over a scale of several feet. These surfaces broaden and flatten upward to yield undulatory sub-parallel lamination. Lower
Figure 1: (right) Base map of the study area from 1:100,000 Chama New Mexico-Colorado map showing major geographic localities and locations of measured sections 1 through 14 (circles).

(below) Stratigraphic chart for Mesaverde Group and associated Late Cretaceous rocks in the Chama Basin and northeastern San Juan Basin (from Lucas, et al., 1992). See Figure 12 for specific age ranges of Mesaverde Group strata.
bedsets (3-5 feet thick), which may be separated by thin (<3 feet) mudrock breaks, are more likely to display remnant HCS with clear convex-upward bounding surfaces. These bedsets give way over a short vertical distance, however, to sand-on-sand contacts and massive cliffs with few, if any, obvious bedding breaks. Where discernible, bedsets are on the order of 5-6 feet or more. The massive nature of the facies and its characteristic low angle sedimentary structures produced rounded-weathering outcrops that may superficially appear structureless.

Intraformational mud rip-up clasts (<1/2 inch in size) are present in isolated patches and along bedding horizons, typically within a few vertical feet of, or laterally adjacent to, a mudrock break. Such breaks can be discontinuous and local, or may correlate with laterally continuous parasequence-scale marine flooding surfaces. Bioturbation is generally less than 20% but can reach as much as 60%. Commonly recognized trace fossils are *Thalassinoides*, *Cylindrichnus*, and *Ophiomorpha*. The massive sandstone facies comprises a laterally continuous sheet that breaks out downdip into interfingered mudrock/sandstone facies and merges updip into trough cross-stratified sandstone.

Upward transition from HCS to SCS to undulatory parallel lamination records the effects of shoaling storm conditions (Leckie and Walker, 1982) along the prograding strandline. During storms, sediment eroded from the upper and middle shoreface is transported by down-welling storm surge currents and/or geostrophic currents (Morton, 1981; Swift et al., 1983) onto the lower shoreface and inner shelf transition zone. The amalgamation of sandstones, general lack of layered mudrock, and presence of mud rip-up clasts within these rocks suggests deposition in water depths shallower than those in which mud could be readily preserved. In this study, very fine sandstones that display HC and/or contain local thin mudrock layers are designated as lower shoreface. Middle shoreface sandstones are very fine to fine-grained, dominated by SCS, and are typically massive.

Trough-Crossbedded Sandstone Facies (Upper Shoreface)

Vertically above and/or up depositional dip from the massive sandstone facies, fine to medium grained sandstones comprise the trough-crossbedded sandstone facies (Fig. 2c). Individual trough crossbeds have a preserved thickness of 1-2 feet (rarely greater) and occur within bedsets 3-5 feet thick. The entire facies averages 20 feet thick (and as much as 30 feet) within a single parasequence. Mud rip-up clasts, which are common in underlying strata, are virtually absent in this facies. Uniformity or both grain size and sedimentary structure and the lack of mudrock interbeds yield a blocky weathering texture. Paleocurrents display a wide range of current directions, including landward, offshore, and along shore. Stratigraphic position and sedimentary structures in this facies are consistent with deposition in the upper shoreface zone influenced by asymmetrical shoaling waves and, possibly, migratory sand bars (Elliott, 1986).

Planar Laminated Sandstone Facies (Foreshore)

Capping the trough-crossbedded sandstone facies is fine to medium grained sandstone that displays tabular or wedge-shaped, seaward dipping planar lamination (Fig. 2c). Bedsets are 2-3 feet thick and comprise a total facies thickness of 5-10 feet where fully preserved. *Ophiomorpha* dominates the trace fossil assemblage, with lesser *Thalassinoides* and *Cylindrichnus*. Most burrows occur as scattered individual traces; however, the upper few feet of the facies can be fully churned and rooted. At several outcrop locations in which this facies is overlain by organic rich mudrock or coals a characteristic bleached appearance, or “whitecap,” extends downward for many feet. More commonly, a 1-2 foot thick mottled and strongly iron-cemented layer tops the facies.

Where recognized, the planar laminated sandstone facies marks the top of the Point Lookout Sandstone. Marine-influenced (estuarine) or non-marine coastal plain deposits overlie, and locally erode, these sandstones. Stratigraphic association and physical characteristics of the facies suggest deposition in the foreshore, under very shallow, high-energy plane bed conditions characteristic of the swash zone (Elliott, 1986).

Estuarine and Alluvial Plain Strata

Amalgamated Marine-Influenced Sandstone Facies (Estuarine Channels, Bayhead Delta)

These rocks abruptly overlie truncated shoreline sandstones along an extensive, irregular erosional surface with 50-60 feet of relief in the northern study area (Fig. 3). Regional significance of this erosional surface (SB 1) is discussed later in this report. Found on Horse Lake, Tecolote, and Briggs’ mesas (sections 8-14), this facies forms an amalgamated, sandstone-dominated sheet extending (within the
Figure 2: (A) Ophiomorpha (Oph) and Thalassinoides (T) burrows in slab of very fine-grained silica-cemented sandstone lag at the base of the Lewis Shale. Hammer for scale. Location: Sulphur Canyon, measured section 9. (B) Interbedded mudrock/sandstone facies of the offshore transition (OT) zone overlain by massive lower to middle shoreface sandstones (SF). Main sandstone cliff is approximately 100 feet high. Location: Apache Mesa south, near measured section 4. (C) Trough crossbedded upper shoreface (USF) sandstones overlain by parallel-laminated foreshore sandstone (FS). Erosion surface at sequence boundary SB1 sits above the foreshore, marked by arrows. Location: Highway 64 roadcut at Monero, measured section 11, units 2-5.
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<tr>
<td>1. Very fine Burrowed Sandstone Facies</td>
<td>Thin-beded (2-6 inches) very fine grained sandstone with shell fragments, shark's teeth. Highly bioturbated to structureless. Fe-oxide and strong silica cement.</td>
<td>Ophiomorpha, Shark's teeth, Shell fragments</td>
<td>Inner Shelf, Transgressive Lag</td>
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<td>2. Interbedded Mudrock - Sandstone Facies</td>
<td>Thinly laminated shale, mudstone and siltstone interlayered with thickening-upward, v. fine sandstones. Mudrock bedsets up to 10 inches; sandstones to 24 inches. Sandstones display lenticular bedding, wave ripple stratification and HCS. Calcite and Fe-oxide cement.</td>
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<td>3. Massive Sandstone Facies</td>
<td>Moderately sorted, very fine to fine-grained sandstone with rare mudrock breaks. Upward transition from HCS to SCS and undulatory parallel laminations. Isolated patches and layers of mudrip clasts. Massive rounded weathering outcrops. Calcite and Fe-oxide cement.</td>
<td>Thalassinoides, Cylindrichnus, Ophiomorpha</td>
<td>Lower to Middle Shoreface</td>
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<td>5. Planar Laminated Sandstone Facies</td>
<td>Gently seaward-dipping planar parallel lamination in well-sorted fine to medium grained sandstone. Locally “whitecapped” or strongly Fe-cemented at top.</td>
<td>Ophiomorpha, Thalassinoides (rare)</td>
<td>Foreshore, Swash Zone</td>
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Table 1: Lithofacies descriptions for rocks interpreted to be of nearshore marine and inner shelf origin.
Figure 3: Amalgamated lenticular estuarine sandstones (bayhead delta deposits) overlie erosional sequence boundary (SB1, at arrows) incised into underlying Point Lookout middle shoreface sandstones at (A) Horse Lake Mesa, measured section 8, units 6-7, (B) Tecolote Mesa, measured section 9, units 25-26, and (C) Tecolote Mesa, measured section 10, units 3-5.
constraints of outcrop control) at least six miles parallel to paleoshoreline and an equivalent distance in the offshore direction (Fig. 4). Toward the south (paleo-landward) above the SB1 erosional surface, the amalgamated sandstone facies is replaced by a finer-grained, organic-rich heterolithic channel facies (described below). Toward the west the SB1 erosional surface climbs into an interfluve region (Fig. 4) and this amalgamated sandstone facies pinches out.

The amalgamated marine-influenced sandstone facies is characterized by moderately sorted, very fine to medium grained sandstone which, at the large scale, displays numerous scour surfaces and inclined bedding. Internally, the unit contains amalgamated, lenticular channel-fill sandstones. Wood and mud ripup clasts are abundant. Toward the top of the facies are lozenge-shaped (sigmoid) sandstone bodies approximately 1-2 feet thick and up to 9 feet long. These sand bodies display reactivation surfaces and mudrock siltstone drapes. Sedimentary structures include trough crossbeds, planar tabular crossbeds, and current ripples. Paleocurrent directions are variable N-NE and SE (offshore and along shore), with subordinate S-SW (landward). Organic material, ranging from “coffee grounds” laminations and wood fragments to large Teredo-bored logs, is abundant. *Thalassinoideas* and *Ophiomorpha* are locally found, particularly within thin, interbedded mudrocks. Northern outcrops display common marine burrows (measured sections 10, 14), decreasing to rare bioturbation toward the south (measured section 8).

Abundant scour-and-fill surfaces, moderately sorted organic sandstones, reactivation structures, and fine-grained mud drapes readily distinguish this facies from underlying, massive-weathering, well-sorted shoreface deposits (Fig. 3). Sparse *Thalassinoideas* and *Ophiomorpha* and abundant Teredolites argue strongly for marine proximity. Brackish or marine conditions must have at least periodically existed during deposition of this unit. Other indicators suggestive of marine proximity are the reactivation surfaces and sigmoid -shaped sandstones with mudrock drapes (reversing tidal currents and/or fluctuating water stage), as well as inclined heterolithic strata (laterally migrating intertidal point bars). Similar physical and biogenic structures are also seen in modern inner estuary (bayhead delta) estuarine point bars and sand bars (Allen and Posamentier, 1994; Roy, 1994). This facies, interpreted to reflect fluvial/estuarine deposition, also shares many attributes of tidally, or marine-influenced, channel systems in similar aged rocks of the Kaiparowits Plateau (Shanley, et al., 1992; Hettinger et al., 1993; and Shanley and McCabe, 1995).

Decreasing bioturbation from north to south and coincident development of heterolithic channel deposits (see below) marks the landward transition from bayhead delta to feeder channel systems (Fig. 4). In the study area, this transition occurs on Horse Lake Mesa (between sections 7 and 8). Evidence suggests that the bayline, or landward limit of the estuary, extended no farther south than section 7.

**Sandstone Channel Facies** (Fluvial and Tidally-influenced Fluvial)

Channel sandstones and surrounding fine-grained mudrock facies characterize much of the preserved Menefee Formation in the study area. While small channel deposits may occur throughout the Menefee, there are three specific intervals along which most large channels are concentrated. These are: (1) within the middle to lower Menefee (sections 1-12) where channel/overbank deposits directly overlie the SB1 erosional surface; (2) near the seaward depositional limit of the Menefee Formation (sections 11-14) where large channel sandstones fill almost the entire 80 feet thick Menefee interval, and; (3) within the upper Menefee (sections 1, 9) where channel deposits occur immediately beneath the Lewis Shale transgressive surface.

Channel/overbank deposits that directly overlie the SB1 erosion surface occupy a landward (sections 1-7) or flanking (sections 11, 12) stratigraphic position with respect to the previously described estuarine and bayhead delta deposits. Among these channelized deposits, sand-rich fill dominates toward the south (landward), being replaced by or overlain by heterolithic fill (alternating sandstone:mudrock) toward the north (seaward). Sand-rich channel fill deposits are a maximum of 30-40 feet thick and extend laterally approximately 300-500 feet. Mudrock breaks are present, but are greatly subordinate to sand-on-sand bedding contacts. Internally, bedsets (2-4 feet thick) display large-scale trough cross-stratification, lesser current ripple stratification, and sub-horizontal parallel laminations. These medium- to coarse-grained sandstones are moderately sorted, fine-upward, and commonly contain mica. Compound scour surfaces with basal mud clast lags suggest some degree of amalgamation of smaller channels. No biogenic structures have been observed within these sandstones.

Toward the north along the SB1 erosional surface, heterolithic channel fill and adjacent fine-grained organic deposits replace or overlie the sand-rich channel fill described above (section 7, units 3-6; section 11, units 4-8). Heterolithic rocks commonly display scour and undulatory, inclined bedding (Fig. 5a, b) and are characterized by alternating medium-grained sandstone (1-2 feet thick) and organic mudrock
Figure 4: Transition from fluvial channels to estuarine channels and bayhead delta deposits occurs from south to north between measured sections 7 and 8. A broad amalgamated estuarine sheet caps the Point Lookout Sandstone on northern Horse Lake Mesa, Tecolote Mesa, and portions of Briggs Mesa (sections 8-10, 14). The bayline, defined by the landward limit of this facies, falls between sections 7 and 8, with maximum marine influence at sections 10 and 14. The dashed line marks the approximate edge of a paleo-valley and adjacent interfluve region produced by erosion during development of the SB1 sequence boundary.
Numerous scour surfaces contain large clasts, mudrills, while heterolithic channels and material (especially apparent in sections 11–14). Sedimentary structures include large-scale trough- and planar-tabular crossbeds with lesser parallel laminations and deformation features. Abundant organic debris forms both paired and single laminae along trough and ripple foresets. Biogenic structures include *Teredolites* in woody material, and locally abundant *Thalassinoides* and *Ophiomorpha* in interbedded or laterally adjacent organic mudrocks.

Both the sand-rich and heterolithic channel deposits described above are interpreted as river channels with variably preserved, fine-grained overbank deposits. Several lines of evidence suggest that heterolithic strata were deposited in a more seaward position on the coastal plain (closer to time-equivalent shoreline) than sand-rich counterparts. Sand-rich channels tend to be coarser, contain fewer mud breaks, display more scour surfaces with coarse lag material, and have less preservation of overbank or floodplain mudrocks than heterolithic counterparts. Sand-rich channels show no evidence of direct marine influence, while heterolithic channels and overbank material locally contain marine trace fossils and *Teredo*-bored wood. Inclined heterolithic strata were produced by lateral accretion of migratory point bars. These display the abrupt lithologic alternation, persistent mud drapes, and paired organic laminae that are indicative of fluctuating fluvial discharge combined with tidal current variation in both modern and ancient intertidal/lower coastal plain rivers (Thomas, et al., 1987; Shanley, et al., 1992). The high organic content (including coals) of laterally adjacent overbank deposits further supports interpretation of a low gradient, poorly-drained coastal plain setting for these heterolithic units.

The second area of significant channel development occurs east of Monero along Brigg's Mesa (sections 11–14). In this area, the Menefee Formation thins to less than 100 feet as it approaches its (preserved) seaward pinchout. Outcrop observations (this study) and Menefee drill-hole data (Hoffman, 1991) indicate that fine-grained, coal-rich deposits west of Monero yield to increasingly sandstone-rich facies toward the east. Erosional surface SB2 (Fig. 5b), at the base of this sandstone facies, truncates underlying coal-bearing (heterolithic) fluvial (sections 11–13) or estuarine rocks (section 14) with a minimum of 25 feet of erosional relief. Channel-fill is moderately- to well-sorted, fine- to medium-grained sandstone with local gray shale breaks. Bedsets, <1 ft to 4 feet thick, are dominated by large scale trough- and planar-tabular crossbeds with lesser parallel laminations and soft-sediment deformation features. Numerous scour surfaces contain large coal clasts, mudrills, wood, and sandstone concretions as basal lag material (especially apparent at section 14). No marine trace or body fossils have been observed in either the channel sandstones or interbedded shales.

Channel geometry, abundant erosional scour surfaces, sedimentary structures, and lack of marine indicators support interpretation of these deposits as fully non-marine channel fill and adjacent overbank deposits. Erosional surface SB2 appears to have removed at least 25 feet of underlying material, much of which had undergone some degree of early cementation or compaction (as supported by the presence of cemented concretions among the lag material). There is no evidence to date that surface SB2 eroded through the underlying SB1 surface, but the two nearly merge at section 13 on Brigg’s Mesa.

The final horizon along which thick channel deposits developed is in the uppermost Menefee, beneath the marine flooding surface at the base of the overlying Lewis Shale (sections 1, 9). These channel fill deposits contain fining-upward, fine to medium grained sandstone with discontinuous organic mud breaks. Sedimentary structures include large-scale trough- and planar-tabular cross beds. As with previously described channel sandstones, these contain numerous internal scour surfaces. Intraformational mud clasts dominate the lag material. Logs with *Teredolites* borings are common, and locally dramatic (Fig. 5c). Marine bioturbation (*Thalassinoides, Ophiomorpha*) occurs both within the sandstones, and at the basal contact to underlying mudrocks and coals. As is the case for marine-influenced sandstones described previously, *Thalassinoides, Ophiomorpha* and abundant *Teredolites* argue strongly for marine proximity. These deposits accumulated under estuarine or nearshore fluvial conditions associated with the landward incursion of the Lewis sea (itself marked by the overlying transgressive surface and inner shelf shark tooth lag).

**Organic Mudrock Facies (Alluvial floodplain)**

Much of the Menefee Formation consists of very fine-grained mudrock with discontinuous thin sandstones and varying amounts of organic material. In outcrop, these deposits are poorly preserved on dip slopes and are prone to cover; thus only very general facies descriptions were made during this study. Exposures permitting, however, efforts were made to specifically locate included coals and coaly shales in measured sections. The facies includes mottled organic shales, gray fissile shales, siltstones, discontinuous rippled organic sandstones, and coals. Plant fossils (Fig. 6) and disseminated organic flakes are common. Color ranges from gray to light brown/black with increasing organic content. Most coals are discontinuous.
or shale layers (<0.5 feet thick). Wood fragments, iron nodules and mud ripups are common lag materials. Sedimentary structures include trough-crossbedding, current ripple stratification, and sub-horizontal and less than 2 feet thick, although several northwest trending zones in the Monero area contain coals 3½ -5 feet thick (Hoffman, 1991). Mudrocks and associated thin sandstones range from <1″ to 3 feet, with less common isolated sandstone channels (up to 5 feet). Marine bioturbation is rare, and is restricted to thin horizons associated with locally intertonguing marine sandstones. The organic mudrock facies is interpreted to represent sediment accumulation on the floodplain. Zones of higher organic content and coal preservation are considered to have accumulated in more poorly drained, swampy portions of the coastal plain, while less organic (more gray) mudrocks and siltstones reflect better drained floodplain conditions (Collinson, 1986).

**STRATAL STACKING PATTERNS AND SEQUENCE STRATIGRAPHIC INTERPRETATION**

This chapter provides an overview of the stacking patterns of Mesaverde Group rocks in outcrops of the Jicarilla Apache Reservation and offers a sequence stratigraphic interpretation of these patterns. Two cross sections (Fig. 7), one oriented approximately along depositional dip (Plate 1) and the other along depositional strike (Plate 2) display these relationships.

**Strandplain Aggradation/Progradation (Highstand Systems Tract)**

Throughout the field area, the upper Mancos Shale and Point Lookout Sandstone display a classic regressive, or coarsening-upward profile, in which successively younger shoreline deposits overlie older, deeper marine rocks (Fig. 8). This regressive pattern was not, however, the product of a steady or continuous shallowing of the seaway. Hoffeishead and Pritchard (1961) noted that this regression produced a series of (aggradational) vertical steps and (progradational) seaward benches on a basinwide scale. Subsequent work has shown that, within this larger framework, much smaller scale marine coastal elements can be resolved and correlated (Wright, 1986; Devine, 1991) to enrich our understanding of the dynamics of Mesaverde shoreline movement.

These coastal elements correspond to genetically related shoreface packages (parasequences of van Wagoner, et al., 1988). Individual parasequences are separated from one another by high-frequency marine flooding surfaces that recorded periodic small landward and vertical shifts in the shoreline. These landward shifts produced erosional ravinement surfaces, where underlying strata were modified by the landward marching surf zone, or simple flooding surfaces, where underlying shoreface deposits were buried beneath deeper water facies. Because these modifications produce lithologic heterogeneity within shoreface deposits, parasequences can be readily traced in both outcrop and the subsurface (van Wagoner, et al., 1988; 1990). In this study, flooding surfaces were walked between sections and/or correlated using photomosaics to define seven distinct parasequences that are fairly completely represented in the field area. Parasequences were given local geographic names based upon the preserved landward limit of beach (foreshore) deposits. From south to north (Plate 1; Fig. 9) these are: North Llaves Beach, Puerto Chiquito Beach (upper and lower), Pounds Mesa Beach (upper and lower), Stinking Lake Beach, Stone Lake Beach, Horse Lake Beach, and Monero Canyon Beach. At least six parasequences older than North Llaves Beach are partially preserved in the southern part of the field area (Plate 1, sections 1-5), but these very distal elements were not individually named.

The top of the Point Lookout Sandstone displays a dramatic stratigraphic rise of approximately 130 feet over a distance of 4-6 miles in the southern part of the field area. Puerto Chiquito, Pounds Mesa, and Stinking Lake shoreline deposits stacked vertically (Plate 1, between sections 1 and 4) to form a progradational (almost aggradational) parasequence set (Fig. 10; van Wagoner, et al., 1990) that resulted in the thickest expression (>240 feet) of marine shoreface sandstones in the study area (measured section 3). Each of these marine parasequences is bounded by a well-defined flooding surface and each has a preserved coastal plain equivalent in landward, fine-grained Menefee Formation organic shales and coals. Compared to the Puerto Chiquito, Pounds Mesa, and Stinking Lake shorelines, the younger Stone Lake, Horse Lake and Monero Canyon parasequences display stronger progradation and much less stratigraphic rise (Plates 1, 2). While it is difficult to place the precise landward limit of these parasequences due to later erosion, flooding surface correlation and comparison to the Lewis Shale datum suggest there is less than 20 feet of stratigraphic rise between Stinking Lake and Stone Lake shorelines. There is little or no vertical rise between Stone Lake and Monero Canyon foreshore deposits (measured
Figure 6: Palm frond imprint (arrow) in Menefee sandstone float block. Location: Pounds Mesa, section 3.
Figure 7: Location of dip cross section (Plate 1) and strike cross section (Plate 2) and measured section control points.
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<th>Biogenic Components</th>
<th>Depositional Environment</th>
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<tr>
<td>Amalgamated Marine- Influenced Sandstone</td>
<td>Moderately sorted, very fine to medium grained sandstone. Amalgamated scours and channel fill. Sigmoid bedding, reactivation surfaces, mud drapes, trough/planar-tabular crossbeds, current ripple stratification. Abundant organic matter, wood, intraformational mud clasts.</td>
<td><em>Ophiomorpha Thalassinoides</em> Teredolites</td>
<td>Estuarine and Bayhead Delta</td>
</tr>
<tr>
<td>Sandstone Channel Facies (sand-rich)</td>
<td>Moderately sorted, medium to coarse grained (micaceous) sandstone. Individual channels with numerous internal scour surfaces. Large-scale trough crossbeds, current ripple stratification and horizontal laminations. Intraformational mud clasts, wood, coal clasts, and concretions as lag. Discontinuous mudrock breaks.</td>
<td>None</td>
<td>Non-marine Fluvial</td>
</tr>
<tr>
<td>Sandstone Channel Facies (sand-rich, marine-influenced)</td>
<td>Moderately to well-sorted, fine to medium grained sandstone. Large-scale trough and planar-tabular crossbeds. Intraformational mud clasts and wood as lag materials. Discontinuous (organic) mudrock breaks.</td>
<td><em>Ophiomorpha Thalassinoides</em> Teredolites</td>
<td>Marine-influenced Fluvial or Estuarine</td>
</tr>
<tr>
<td>Sandstone Channel Facies (heterolithic)</td>
<td>Alternating medium-grained organic sandstone (1-2 feet thick) and organic mudrock or shale (&lt;0.5 feet thick). Wood fragments, Fe nodules, and mud clasts as lag on scours. Inclined, lateral accretion bedding. Trough crossbeds, current ripple stratification, horiz. lams. Paired organic drapes.</td>
<td><em>Ophiomorpha Thalassinoides</em> Teredolites</td>
<td>Marine-influenced Fluvial</td>
</tr>
<tr>
<td>Organic Mudrock Facies</td>
<td>Mottled organic shales, gray fissile shales, siltstones, discontinuous rippled organic sandstones, and thin coals. Color ranges from gray to light brown/black.</td>
<td>None (except where associated with intertonguing marine ss)</td>
<td>Alluvial Floodplain</td>
</tr>
</tbody>
</table>

Table 2: Lithofacies descriptions for rocks interpreted to be of alluvial plain and estuarine origin.
Figure 8: (A) Classic coarsening-upward profile produced by progradational-to-aggradational strandplain rocks. Interbedded very thin sandstones and mudrocks of the Mancos Shale offshore transition zone (OT) are overlain by thicker sandstones and mudrocks of the lower shoreface (LSF) and massive sandstones of the lower to middle shoreface (LMSF) in a series of unnamed stacked parasequences (see Plate 1, section 2). North Llaves Beach and lower Puerto Chiquito beach comprise the upper half of the massive cliff. Both contain upper shoreface and foreshore strata. Location: Pounds Mesa, immediately north of section 2. (B) Abrupt coarsening-upward profile produced by strongly progradational strandplain rocks. Mancos transition (OT) contains relatively little sandstone and there is little mudrock within the overlying Point Lookout lower shoreface (LSF). The Stone Lake (SL), Horse Lake (HL), and Monero Canyon (MC) parasequences comprise the Point Lookout marine section. Location: Briggs Mesa, immediately east of section 13.
Figure 9: Location of individual beach parasequences in the study area. Foreshore deposits constrain the location of the Puerto Chiquito, Pounds Mesa, and Stinking Lake shorelines. (Foreshore position of North Llaves beach is located somewhere to the south of the study area, and is therefore not shown.) Position for Stone Lake, Horse Lake, and Monero Canyon beaches is inferred due to later erosion of foreshore and upper shoreface by the SB1 surface.
sections 6 and 12), a downdip distance of approximately 12.5 miles. These strongly progradational younger parasequences are bounded by more subtle, yet recognizable, flooding surfaces and they have little or no preserved coastal plain equivalents in the updip Menefee Formation. A look at marine facies shows that the total thickness of stacked shoreface deposits thins northward (from ~240 feet at section 3 to ~130 feet at section 13). Also, the transition from distal Point Lookout sands to Mancos mudrocks becomes much more abrupt (compare figures 8a and 8b).

Thus, late stage deposition of the Point Lookout Sandstone and time-equivalent strata in the Menefee Formation and Mancos Shale display two distinct stacking patterns in the study area:

- progradation/aggradation (Puerto Chiquito through Stinking Lake parasequences) followed by strong progradation (Stone Lake through Monero Canyon parasequences). This arrangement can be attributed to variation in the balance between the rate of sediment deposition and the rate of sediment accommodation (Fig. 10, Van Wagoner et al., 1990). During the progradation/aggradation phase, the rate of deposition slightly exceeded the rate of overall sediment accommodation and dramatic stratigraphic rise accompanied a slight shoreline progradation. As accommodation space declined and/or deposition increased, progradation was enhanced and the younger shorelines built successively farther basinward with minimal or no stratigraphic rise. These characteristics suggest that the progradation/aggradation phase and subsequent strong progradation phase occupy a sequence stratigraphic position in the late highstand (Van Wagoner, 1995). The possibility was also considered that the late stage strong progradation could have accompanied a “forced regression” (Posamentier et al., 1992) in which accommodation space declined due to relative sea level fall. While the sharp base of the Stone Lake shoreface on Briggs Mesa (fig. 8b) could be consistent with this model (Plint, 1988), marine flooding surfaces still punctuate a thick overlying shoreface succession including the Stone Lake, Horse Lake, and Monero Canyon parasequences. These relationships are more compatible with a position in the late Highstand Systems Tract (HST), rather than Lowstand Systems Tract (LST), sequence stratigraphic position (Van Wagoner, 1995). Significantly, the top of the Point Lookout does drop in the seaward direction between sections 12 and 13 (Plate 2), however, this drop is attributed to syn-depositional faulting (post-Point Lookout, pre-Lewis) rather than forced regression.

**Incised Valley Formation (Sequence Boundary SB1)**

Throughout the study area an erosion surface truncates the top of Point Lookout strandplain deposits with up to 60 feet of relief (surface SB1, Plates 1 & 2). Parasequences most affected by erosion are Stinking Lake, Stone Lake, Horse Lake and Monero Canyon. Above this surface in the southern study area are fluvial channel and floodplain deposits. In the northern study area, bay head delta sandstones, estuarine channel deposits, or marine influenced mudflat strata overlie the erosion surface. Juxtaposition of these estuarine and alluvial plain deposits above lower and middle shoreface sandstones argues for a seaward shift in facies. The SB1 surface that separates these disparate facies is interpreted as an erosional sediment bypass surface, or sequence boundary (van Wagoner, et al., 1988). Facies relationships suggest that this erosional surface produced a roughly north-northeast trending fluvial valley in the study area, with an interfluve boundary to the west (Monero area) and an undetermined eastern boundary (Fig. 4). Sediment removed during valley excavation would have been transported toward the north-northeast (presumably beyond the limits of the study area) to accumulate in a lowstand, potentially isolated, shoreface deposit.

The transition from aggradation/progradation to strong progradation followed by incision (SB1) builds a strong case for declining accommodation space and base level fall at the end of Point Lookout deposition. This unconformity has been documented elsewhere in the northwestern San Juan Basin (Wright Dunbar et al., 1992; Crandall, 1992), where a series of fluvial channel belts dissects the upper Point Lookout (Fig. 11). Recognition of similar relationships in rocks on the Jicarilla reservation confirms the widespread nature of this surface. Chronostratigraphic control on the seaward limit of the Mesaverde Group constrains the age of the unconformity to the Baculites sp. (weak flank ribs) ammonite zone, between 80.7-80.9 mya (Fig. 12a,b).
Figure 10. Parasequence stacking patterns in parasequence sets from Van Wagoner and others (1990).
Figure 11: Map of Point Lookout Sandstone outcrops in southern Colorado showing major fluvial channel belts observed in outcrop or interpreted from core (Mildred Wright, Ilamae Dunagan) and well logs (well data from Molenaar and Baird, 1993). Within each of these channel belts the uppermost Point Lookout is interpreted to contain an erosional unconformity correlative with SB1 in this study and an overlying fluvial sandstone fill. (from Zech and Wright Dunbar, unpublished data).
Fluvial/Estuarine Aggradation (Lowstand and Transgressive Systems Tracts)

From south to north (seaward), the deposits overlying the SB1 erosion surface undergo transition from 1) sand-rich fluvial to 2) sand-rich fluvial and heterolithic to 3) sand-rich estuarine (Plate 1). Where these facies are juxtaposed vertically (e.g. measured section 7) there is an upward transition from coarser grained, sand-dominated fluvial channel deposits to heterolithic fluvial deposits with *Teredolites* borings. Thus, there is evidence for a vertical, as well as a seaward, increase in marine influence within the valley-filling strata. Zaitlin et al. (1994) highlight the evolution of a valley-filling sequence similar to that described in this study (Fig. 13). In their model initial valley incision (SB1 of this study) produces valley and interfluve topography. Sediment is bypassed offshore as part of a Lowstand (Fan) Systems Tract (beyond the limits of this study area). Accumulation of fluvial fill in the valley begins with the Lowstand (Wedge) Systems Tract (LST) during which time rivers maintain a declining, yet sufficient, gradient to base-level. The coarse sand-rich channel fill preserved in landward sections (e.g. measured section 4) and at the base of deeper valleys (measured section 7) in this study may have begun accumulating during this phase of valley-filling, however it is not possible to determine whether these deposits accumulated under LST or subsequent transgressive conditions.

In the Zaitlin et al. model, increasing rate of base-level rise produces the Transgressive System Tract (TST) in which the fluvial system loses gradient, becomes flooded, and is overstepped by marine and estuarine deposits. During this phase, older fluvial sediments are at risk of being removed and/or reworked into the overlying estuarine sediment package. The record of this base level rise in the study area is in the vertical transition from sand-rich non-marine channels to marine-influenced/heterolithic fluvial deposits and in the superposition of bay head delta deposits and estuarine channel sands directly above the SB1 unconformity surface. In this latter case, any pre-existing non-marine fluvial sediments must have been reworked during transgression.

Overall facies relationships in the study area indicate a relatively landward position within the incised valley system. Applying Zaitlin et al.’s (1994) longitudinal profile terminology (Fig. 14), Jicarilla outcrops display facies relationships of the inner incised valley (sections 1-6; fully fluvial throughout valley filling history) and middle incised valley (sections 7-14; estuarine/bay head delta over lain by fluvial) segments. At maximum marine transgression, a drowned valley estuary filled the northern study area. Nowhere in the study area have the more seaward facies of the outer incised valley segment (muddy central estuary or sand-rich backstepping barrier/inlet complexes) been observed at this stratigraphic level. Thus, somewhere to the northeast of Briggs’ Mesa these missing facies tracts may yet be found.

Alluvial Floodplain Aggradation (Highstand Systems Tract)

Overlying the sand-rich fluvial, heterolithic fluvial, and estuarine deposits throughout most of the study area are Menefee Formation fine-grained alluvial deposits, thin sandstones, and discontinuous coals. These are interpreted to represent the Highstand Systems Tract (HST) stage in Zaitlin et al.’s (1994) incised valley model in which the pre-existing topography becomes completely buried during renewed progradation of the shoreline and coastal plain (Fig. 14). Because outcrop exposures (dominated by vegetated dipslopes) did not permit broad correlation of facies and stratigraphic boundaries at this level, limited detailed work was done on these deposits. This may become critical for future work, however, in resolving the significance of a thick fluvial channel complex on far eastern Briggs Mesa (sections 13, 14) interpreted below.

Incised Valley Formation? (SB2 Sequence Boundary)

At the same stratigraphic level as the fine-grained HST Menefee mudrocks discussed above, a multi-story channel complex ero sively overlies (and locally removes) estuarine sandstones and marine-influenced mudrocks in the Monero and Briggs Mesa areas (sections 12-14). The SB2 erosional surface (figure 5b & Plate 2) at the base of the channel complex is a likely candidate for a second sequence boundary responsible for removing any aggradational Menefee HST deposits that may have been present as well as portions of the underlying TST estuarine strata. The fact that cemented sandstone concretions are included within the basal channel lag strongly suggests that some degree of early cementation had occurred within eroded underlying strata. This, combined with the fact that the channel fill is fully non-marine, makes it less reasonable to interpret this as an equilibrium channel eroding its contemporary marine-
Figure 12a: Campanian to early Maastrichtian chronostratigraphic correlation chart, New Mexico to Alberta. Modified from Krystinik and DeJarnett, 1995. Compare San Juan Basin Mesaverde Group (Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone) to sequence stratigraphic interpretation in figure 12b.
Figure 13. Idealized plan view of a simple, piedmont incised-valley system showing its evolution over one complete sea-level cycle (sea level fall to subsequent highstand). (A) Lowstand (fan) time showing the incised-valley system passing headward into a non-incised fluvial channel system. (B) Lowstand (wedge) time showing a lowstand delta at the mouth of the incised valley, and the beginning of fluvial deposition throughout the incised-valley system. (C) Transgressive systems tract time showing the development of a tripartite, wave-dominated estuarine system within the incised valley. (D) Highstand time with a progradational shoreface and alluvial plain that extends beyond the margins of the buried incised valley. From Zaitlin ad others, 1994.
influenced coastal plain. If further work confirms this SB2 surface as a sequence boundary, sediment
bypassed northward during incision would have accumulated offshore in yet another, potentially isolated,
lowstand shoreface.
The SB2 surface was not systematically traced to the south and its correlative position within the poorly
exposed upper Menefee outcrops at sections 1-10 is speculative. This would be an important sequence
stratigraphic surface to locate, however, as it would separate HST Menefee strata (below) from TST
Menefee strata (above) and mark the location within the landward alluvial plain that coincides with
backstepping Cliff House beach sandstones to the north.

Strandplain Aggradation/Retrogradation (Transgressive Systems Tract)

Only in the far northern field area, on Briggs Mesa, is good evidence preserved of landward-
encroaching Cliff House shorelines. Between measured sections 11 and 14 (and above the SB2 channel-fill
package) the upper 80 feet of the Menefee Formation contains the extreme landward limits of two
intertonguing nearshore marine sandstones, the Canon Amargo and Briggs Mesa beaches (Plate 2). Any
significant Cliff House sandstone buildup associated with the seaward merger of the Point Lookout and
Cliff House shoreline systems must therefore exist to the north of Briggs Mesa, where these sandstones
thicken to form well-developed shoreface deposits. South of Briggs Mesa (landward of these shorelines)
the upper Menefee Formation contains isolated channel sandstones and organic-rich fine grained mudrocks
interpreted to have aggraded on the coastal plain during the base level rise associated with this shoreline
transgression. The uppermost of these fluvial sandstones (measured section 1, units 23-25; measured
section 9, unit 49) displays strong estuarine evidence, signaling the southward encroachment of the Cliff
House shoreline.

This retrogradational Cliff House parasequence set (Fig. 10) marks the point in the basin filling
history in which the overall rate of sediment accommodation exceeded the rate of deposition. The flooding
surface associated with this transgression is marked throughout the area by the presence of a very thin,
silica-cemented transgressive lag (inner shelf very fine burrowed sandstone facies) that contains sharks’
teeth, shells, wood fragments and mudrip lag materials (Fig. 2a). Most commonly this lag separates
Menefee Formation strata (below) from Lewis Shale outcrops (above) with little evidence of the
intervening Cliff House shoreface.

RESERVOIR ANALYSIS

The sedimentary facies descriptions, sequence stratigraphic relationships and structural
interpretations made during the course of this outcrop study provide a framework for subsurface correlation
and assist in the prediction and prioritization of Mesaverde Group reservoir targets. The following
discussion presents an exploration view of potential reservoir units, and specifies correlation strategies that
may help resolve these in the subsurface.

Stratigraphic Reservoir Plays

Van Wagoner et al.’s (1990) and Van Wagoner’s (1995) sequence stratigraphic framework for
exploration plays on a ramp (foreland basin) margin provides a means by which Mesaverde Group reservoirs
in the northeastern San Juan Basin can be evaluated and prioritized. The following discussion summarizes for
each Mesaverde play type the common reservoir facies, bounding surfaces and potential seals, stratal stacking
patterns, general reservoir quality, and reservoir geometry. Major characteristics of these reservoirs are
summarized in Table 3. Figure 15 is a schematic diagram of Mesaverde Group stratal relationships and
hydrocarbon play types for the northeastern San Juan Basin.

Highstand Reservoir Plays

The most promising reservoir plays within the highstand systems tract occur at the updip pinchout of
the Point Lookout Sandstone where marine shoreface deposits and locally associated estuarine sandstones
undergo landward transition into the Menefee Formation (Fig. 15). The seals in this situation are the
surrounding non-marine mudrocks, enhanced at the uppermost level by the basinward step in coastal plain
fluvial strata associated with the capping sequence boundary unconformity.

An example of this play type in the study area occurs at the landward depositional limits of the
Puerto Chiquito, Pounds Mesa, and Stinking Lake shorelines. These strata are arranged as slightly
progradational parasequences that intertongue with Menefee Formation mudrock seals and are bounded

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<td><strong>Highstand Systems Tract</strong></td>
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</tbody>
</table>
| Point Lookout Ss: Estuarine, foreshore, upper shoreface, and lower shoreface medium to very fine sandstones  
Mancos Shale: Offshore transition zone mudrocks and very fine sandstones | Marine: Coastal plain overbank and channel systems; organic mudrocks, siltstones, thin coals and fine to very fine sandstones  
Non-marine: | Internal bounding surfaces include parasequence marine flooding surfaces and landward equivalents. Systems tract is overlain by sequence boundary SB1.  
Non-marine: | Marine: Moderate to good in estuarine and shoreface sandstones, quality decreasing to poor basinward.  
| Marine: laterally continuous sheet sandstones up to 40 feet thick separated by thin continuous mudrock or cemented layers. Updip pinchout into coastal plain.  
Non-marine: isolated, discontinuous sandstones |
| **Lowstand Systems Tract** | | | | | |
| Point Lookout Ss: Foreshore, upper shoreface and lower shoreface medium to very fine sandstones (not observed in study area)  
Mancos Shale: Offshore transition zone mudrocks and very fine sandstones (not observed in study area) | Marine: Fluvial channel deposits dominated by fining-upward upper medium- to fine-grained sandstones (locally present in study area).  
Non-marine: | Underlain by sequence boundary (SB1 or SB2). Overlain by bay line flooding surface and its landward equivalent (SB1) or marine flooding surface and its landward equivalent (SB2).  
Non-marine: | Marine: Predicted as moderate to good in shoreface sandstones.  
Non-marine: Good quality in coarser sandstones  
| Marine: Predicted as a restricted, thin sandstone wedge bounded above and below by offshore marine mudrocks.  
Non-marine: Discontinuous preservation (0-35 feet thick) within incised-valley. |
Table 3: Summary of general reservoir characteristics for the Mesaverde Group (modeled after Van Wagoner, 1995)

| Transgressive Systems Tract | Point Lookout/Menefee: Estuarine channel fill and bay-head delta sandstones. Cliff House Ss: Foreshore, upper shoreface, lower shoreface sandstones medium to very fine sandstones. Lewis Sh: offshore marine mudrock with thin silica-cemented fossil lag at base. | Menefee Fm: Coastal plain overbank and channel systems; organic mudrocks, siltstones, coals and fine to very fine sandstones. Underlain by bay line flooding surface, commonly merged with sequence boundary SB1 (Point Lookout/Menefee), or underlain by marine flooding surface above SB2 (Cliff House/Lewis Sh). Overlain by downlap surface marking change to progradational marine parasequences (and landward equivalents) above. | Point Lookout/Menefee: aggradational to deepening-upward transition from fluvial/erosional (below) to estuarine sheet sandstone. Cliff House/Lewis Sh: aggradational to strongly retrogradational parasequence set. Menefee Fm: aggradational coastal plain | Transitional Marine: Moderate to good sandstone-dominated estuarine fill. Marine: Moderate to good in shoreface sandstones, quality decreasing to poor basinward. Non-marine: Moderate to good in channel deposits. | Transitional Marine: Estuarine sandstones form broad sheet up to 50 feet thick filling incised paleovalley. Marine: laterally continuous sheet sandstones up to 35 feet thick separated by thin continuous mudrock or cemented layers. Updip pinchout into coastal plain Non-marine: Discontinuous, isolated channel sandstones |
Figure 14. (A) Idealized longitudinal section of a simple, incised-valley system showing the location of schematic vertical profiles illustrated in (B). LST = lowstand systems tract; TST = transgressive systems tract; SB = sequence boundary; TS = transgressive surface; WRS = maximum flooding surface; MFS = maximum flooding surface; FCD = fluvial channel diastem; TRS = tidal ravinement surface; BHD = bayhead delta. No particular horizontal or vertical scale intended. From Zaitlin et al., 1994. Valley-fill deposits in this study are interpreted to fall within the middle and inner incised valley fill (similar to schematic profiles 4 and 5).
by aggradational non-marine and marine influenced coastal plain can be traced seaward from a stratigraphic position within the middle Menefee to produced in Lowstand Reservoir Plays. Lookout valley (Fig. 11). These deposits can be highly attractive reservoir targets because they are among the coarsest grained marine shales (Van Wagoner, et al., 1990). Field relationships suggest that this play is not of significance to Jicarilla exploration, however, because such a lowstand shoreface would lie northeast of the modern outcrop belt.

During late lowstand conditions (Fig. 13b) fluvial sediment may begin to backfill the incised valley. These deposits can be highly attractive reservoir targets because they are among the coarsest grained sandstones and (constrained by the incised valley geometry) have the highest potential for amalgamation and continuity within the non-marine depositional package. In the study area, sandstones interpreted as early valley filling deposits overlie unconformities SB1 and SB2 (Fig. 15). The sandstones above SB1 can be traced seaward from a stratigraphic position within the middle Menefee to a position in which they incise the Point Lookout shoreface. Throughout this interval the fluvial sandstones are overlain and sealed by aggradational non-marine and marine influenced coastal plain mudrocks. The north-northeast trending valley (Fig. 4) associated with the SB1 erosion surface is the only such feature within the study area for which a sense of scale and orientation is available (and even this is unconstrained to the east). Correlation efforts in the subsurface should use, as a starting point, a model of north-northeast trending valleys with a minimum width of six miles. Thickness of the basal fluvial fill ranges from zero (near channel edges and/or where reworked into younger estuarine fill) to 35 feet. Clearly, individual channels and tributaries will be of smaller scale than this and a detailed treatment of the paleo-topography and local fluvial distribution networks might yield complex results.

Recognition of these fluvial sandstones and their bounding unconformities is critical to mapping the axes of Menefee and Point Lookout incised valley reservoir targets in the subsurface. Where the unconformity cuts into the top of the Point Lookout Sandstone, fluvial channel sandstones will be directly superimposed upon marine shoreface sandstones. Every attempt should be made in the subsurface to distinguish subtle fining-upward sandstone trends at the top of the marine sandstone package that may indicate fluvial incision. Likewise, careful mapping of fluvial sandstone trends (channel belts) in the middle Menefee Formation (such as in Figure 11) will highlight the incised valleys and adjacent interfluves. Exploration plays that target the dip-aligned incised valleys will have the highest potential to intersect these basal fluvial deposits, as well as certain transgressive reservoir plays discussed in the subsequent section.

Valley fill sandstones above SB2 are interpreted only in the northern field area (on Briggs Mesa), and landward correlation of these units was not accomplished due both to limited time and poor exposure. Thus, an exploration model for these rocks applied to the southern subsurface should be considered speculative. Where documented, the sandstones are capped by transgressive shoreface deposits or by coastal plain mudrock of the transgressive systems tract. The latter is expected to dominate toward the
Figure 15. Schematic diagram depicting observed/predicted stratigraphic relationships and hydrocarbon play types for the Masaveada Group, northwestern San Juan Basin. Modeled after Van Wagoner et al., 1990. Approximate relationship to measured sections is indicated by schematic sections 1, 7, and 14.
south and the fluvial reservoir targets would be well sealed within the upper fine-grained Menefee. It is impossible to determine from the present data the extent to which these sandstones comprise a correlatable or significant sand-rich Menefee horizon (as can be demonstrated for the older SBI fluvial system).

Another intriguing, yet speculative, consideration is that the position of these deposits on northeastern Briggs Mesa may have been controlled by syn-depositional faults (see Structural Reservoir Plays). In such a case, fault block orientation, rather than regional paleoslope, may guide correlation to the south.

**Transgressive Reservoir Plays**

While a basal component of the incised valley fill may have accumulated under lowstand conditions, the bulk of the valley fill is interpreted as transgressive, having accumulated under conditions of rising base level and back-flooding of the fluvial system to form estuaries, bays, and aggrading fluvial channels (Fig. 13c). This process can generate two significant reservoir targets (Fig. 15). At the estuary mouth a transgressive barrier may develop, stepping landward over time and terminating in an updip pinchout into fine-grained central basin estuarine fill. At the head of the estuary, sand-rich estuarine channel and bayhead delta deposits may aggrade in step with rising base level and the landward-migrating barrier.

Transgressive estuary mouth deposits were not observed during the course of this study, and if developed, these and any central basin fine-grained deposits must have been present north of the modern outcrop belt. The bayhead delta system, on the other hand, could be a significant facies component of incised valley targets in extreme northeastern basin plays. These sand-rich estuarine deposits overlie a bayline flooding surface that is typically merged with the underlying SBI sequence boundary. Merger of these surfaces suggests that any lowstand fluvial sand present in this part of the valley during estuarine inundation was reworked into the overlying estuarine sediment package.

Bayhead delta reservoir targets are incised into Point Lookout marine shoreface sandstones. They are sealed above by coastal plain mudrocks and are transitional updip within the valley into heterolithic (muddy) fluvial strata. Reservoir quality is considered moderate to good (at best) in these deposits, which are less well-sorted and more heterogeneous than upper shoreface sandstones. Although incompletely preserved in outcrop, these deposits form an amalgamated sandstone sheet at least 36 miles square and up to 50 feet thick.

A different transgressive reservoir play in the area is expressed on Briggs Mesa where landward-stepping Cliff House marine sandstones display updip pinchout into the upper Menefee Formation (Fig. 15). These aggradational to retrogradational shoreface sandstones share many of the same strong reservoir characteristics as the previously described highstand Point Lookout shoreface deposits, however this buildup of the Cliff House is specifically situated at the seaward preserved limit of fine-grained Menefee strata. The better “reservoir” sandstones here are located in outcrop toward the north, and do not have specific analogs in the southern subsurface. Younger Cliff House transgressive reservoirs do exist in the subsurface toward the southwest (Molenaar and Baird, 1991) and may prove of interest to Jicarilla exploration.

A final type of transgressive reservoir play observed during this study is in the uppermost Menefee. Here medium grained, sand-rich estuarine deposits, preserved beneath the ravinement level of the Cliff House/Lewis marine transgressive surface, sit encased within fine-grained continental and marine mudrocks. Although there is no evidence to suggest these sandstones have the same degree of amalgamation or lateral continuity as estuarine facies within the incised valley fill, attention might be paid to them as secondary, opportunistic reservoir targets.

**Structural Reservoir Plays**

Syn-depositional fault movement may have influenced sediment accumulation at least in the northeastern part of the field area. The detailed structural fieldwork confirming this observation has not been accomplished, and these comments should, consequently, be taken as a working hypothesis to guide subsurface correlation. With the Lewis Shale marine flooding surface as a horizontal datum, the top of the Point Lookout foreshore drops approximately 40 feet down-to-the-east along an inferred fault between measured sections 12 and 13 (Plate 2) on Briggs Mesa. A southern extension of the fault is suggested to lie between sections 8 and 9 (Plate 1) near Horse Lake, where approximately 50 feet of down-to-the-east motion best explains the observed stratigraphic relationships. Additional work is required to confirm these offsets as fault controlled and to achieve the level of correlation control necessary to confidently define the specific time of movement. The timing appears to be post-Point Lookout, based upon offsets in shallow marine sandstones and bayhead delta deposits, and syn-depositional with the Menefee, based upon thickness changes documented on Briggs Mesa.
It is interesting to note that: (1) SB1 incised valley estuarine deposits thin and undergo landward facies change west-southwest across the fault, (2) the overlying SB2 incised valley fluvial deposits thin west-southwest across the fault, and (3) the retrogradational Cliff House marine sandstones thin west-southwest across the fault. Although there could be unrelated facies explanations for these patterns, the vertical coincidence of these changes strongly suggests that Cretaceous topography (higher in the Monero area, lower toward the east) may have been fault controlled. If substantiated, these results suggest that incised valley reservoir targets in the subsurface may preferentially follow an inherited structural grain.
REFERENCES


Crandall, G.A., 1992, Fluval influence on high-frequency sedimentary cycle geometry: the transition from strandplain to deltaic deposition in the Cretaceous Point Lookout Sandstone, San Juan basin, Colorado [M.A. Thesis]; Rice University, Houston, Texas, 140pp.


APPENDIX 1
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Bed sets</th>
<th>Sedimentary structures</th>
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</table>

Mudrips
Moderate glauconite, abundant calcite

Mudrips
Trace glauconite, abundant calcite

No glauconite, abundant calcite

Continuous to discontinuous thin-bedded breaks

No glauconite, abundant calcite

Covered shaley slope

Moderate glauconite
Covered shaley slope
Mudrip layers, moderate glauconite

Covered break
Abundant glauconite

Discontinuous mud breaks
Muddy sands, thin beds

Measured Section 1: Puerto Chiquito. Measured by AM, MKJ

36°31'52" N, 106°47'55" W
Fe stained break with Fe concretions and paper shale
Large mudrips
Scattered mudrips
Moderate glauconite
Top of lower sand body is Fe stained
Continuous thin bedded break

Moderate glauconite
Mudrip layers; 0.5-1" Fe concretions forming cont.
Fe horizon
Moderate glauconite

Occasional discontinuous thin-bedded breaks

Moderate glauconite
Scoured base
Outcrop slopes back into cover, then becomes muddy sand notch. Hard to identify contact. 2-3 mud breaks at top (visible laterally)

Trace glauconite, whiter sands

Measured Section 1: Puerto Chiquito. Measured by AM, MKJ 36°31'52" N, 106°48'55" W
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<thead>
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</table>

**Biologic**

**Mud**

**Sedimentary**

**Structures**

- Troughs
- X-beds
- Troughs
- Und. / lams
- Lams
- X-beds
- Troughs
- Notes

**Trace glauconite**

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<thead>
<tr>
<th>Depth (ft)</th>
<th>Description</th>
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<tr>
<td>120</td>
<td>Semi-continuous notch w/ muddy sands, thinly bedded w/ muds; paper shale beds.</td>
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<tr>
<td>130</td>
<td>Prominent notch-muddy sands</td>
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<td>140</td>
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<tr>
<td>150</td>
<td>White massive sand w/ occasional discontinuous breaks. Discontinuous Fe cement and Fe concretion. Large topographic setback.</td>
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<td>NORTH LAKES BEACH</td>
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<td>190</td>
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<td>180</td>
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</table>

Covered slope with isolated sands and ss float

Very white sands

Very mottled rocks—bioturbation?

Mudrips

Continuous Fe-capped notch—thin mud layer?

Measured Section 1: Puerto Chiquito. Measured by AM, MKJ 36°31'52" N, 106°48'55" W
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts × 1,000</th>
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Measured Section 1: Puerto Chiquito. Measured by AM, MKJ 36 31'52" N, 106 48'55" W
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<td>Coarse- to medium-grained sandstone</td>
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<td>Coal bed, shale beneath</td>
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Measured Section 1: Puerto Chiquito. Measured by AM, MKJ 36°31'52" N, 106°48'55" W
Measured Section 1: Puerto Chiquito. Measured by AM, MKJ 36°31'52" N, 106°48'55" W
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Measured Section 1: Puerto Chiquito. Measured by AM, MKJ
36° 31' 52" N, 106° 48' 55" W
Measured Section 2: Pounds Canyon. Measured by RWD, MK-J  36 33'52" N, 106 48'16" W
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**Measured Section 2: Pounds Canyon.** Measured by RWD, MK-J 36°33'52" N, 106°48'16" W
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Measured Section 2: Pounds Canyon. Measured by RWD, MK-J 36 33'52" N, 106 48'16" W
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Measured Section 2: Pounds Canyon. Measured by RWD, MK-J 36°33'52" N, 106°48'16" W
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Measured Section 2: Pounds Canyon. Measured by RWD, MK-J  36 33'52" N, 106 48'16" W
### Measured Section 3: Pounds Mesa North

Measured by KO, AM 36°35'8" N, 106°46'57" W

<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Bed sets</th>
<th>Sedimentary structures</th>
<th>Biologic</th>
<th>Notes</th>
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<tbody>
<tr>
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<td>SCS, low angle lams</td>
<td>1-3' bedsets</td>
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<td>8</td>
<td>8</td>
<td>@60'</td>
<td>SCS, low angle lams</td>
<td>Massive sand breaks up toward top</td>
<td></td>
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</tbody>
</table>

**Notes:**
- @60': Massive sand breaks up toward top
- @32': Very bioturbated sand, recessed notch 2.5" thick
- Scour surface: above = mud breaks below = sand that pinches out
- @3': Slope-forming sand, mostly covered
- Mudrips
- 1-3' ss bedsets w/ mud breaks
- Swales
- @3': Shale slope at below contact
Measured Section 3: Pounds Mesa North. Measured by KO, AM 36°35'8" N, 106°46'57" W
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Bed sets</th>
<th>Sedimentary structures</th>
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**Measured Section 3: Pounds Mesa North.** Measured by KO, AM 36 35°8' N, 106 46°57' W
### Thickness (feet)
- 240
- 230
- 220
- 210
- 200
- 190
- 180

### Grain Size (microns)
- Water: 150-350
- Windblown: 8-150
- Windblown: 0-25
- Water: 25-100
- Water: 100-400
- Water: 100-375
- Water: 175-325
- Water: 125-300
- Water: 175-275
- Water: 125-250
- Water: 89-150
- Water: 150-275
- Water: 125-177
- Water: 200-355

### Weathering profile and lithology
- Troughs
- X-beds / lamds
- Und low angle lamds

### Bed sets
- Sedimentary structures
- Biologic
- Notes

### Depositional environment
- FS?
- USF
- USF-MSF
- FS

---

**Measured Section 3: Pounds Mesa North.** Measured by KO, AM 36°35'8" N, 106°46'57" W

- **Troughs**: Laid back sand
  - @235°
- **Troughs**: 3 discontinuous mudbreaks, organics present
  - Scour into mud on low break
  - Slightly offset float block
  - @210°
  - Fe stained mud break-scoured, grades laterally to notch-sand on sand
  - Orange weathering sand
  - @195°
  - Minor mudrips
  - @187°: Translation south 100 m
- **Troughs**: Major mud/coal break, 0-1 m thick, scoured 10 cm deep. Some Fe concretions.
### Sedimentary structures

- **X-beds**: common
- **Troughs**: X-beds
- **Ripples**: troughs
- **Laminated structures**: organic laminae

### Biologic Notes

- **Covered**: Fe stained top
- **Scour surfaces**: at wavy, organic discontinuous mud breaks. Abundant 1-12 cm mudrods.
- **Organic laminae**: abundant wood
- **Coal**: "Chocolate milk" soil, scour-sand on sand. Coal bits in sand.
- **Coal break**: channel pinches out to south, major break, 1-4' dark coaly-mud. Sand appears churned, but no burrows seen.

### Measured Section 3: Pounds Mesa North

- **Measured by**: KO, AM 36 35'8" N, 106 46'57" W
<table>
<thead>
<tr>
<th>Thickness (foot)</th>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
<th>Grain Size (microns)</th>
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Measured Section 3: Pounds Mesa North. Measured by KO, AM 36 35'58" N, 106 46'57" W
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<td>80% burrow motiled thal.</td>
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<td>50</td>
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<td></td>
<td>▲ @ 50.5', gray shale</td>
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<td>40</td>
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<td></td>
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<td></td>
<td>Thinf bedded (&lt; 1&quot;) sandstone/shale</td>
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<td>30</td>
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<td></td>
<td>2-5&quot; sandstone beds</td>
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<td>15</td>
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<td></td>
<td>▲ @ 15', band of gray, silty mud (transgressive max?)</td>
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<td>▲ @ 5', gray shale</td>
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<td></td>
<td>Interbedded 1.5-10&quot; HCS sandstone and 1-2&quot; paper shales. Some ss up to 30&quot; thick. Strongly calcitic.</td>
<td></td>
</tr>
</tbody>
</table>

Measured Section 4: Apache Mesa South. Measured by RWD, KO, AM 36 37'9" N, 106 48'46" W
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts × 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Bed sets</th>
<th>Sedimentary structures</th>
<th>Biologic</th>
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<tbody>
<tr>
<td>120</td>
<td>13</td>
<td>22 24 28 30 32 34 36</td>
<td>Qul-100-200</td>
<td>Chon skol thal</td>
<td>SCS</td>
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<tr>
<td>110</td>
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<td>SCS</td>
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Measured Section 4: Apache Mesa South. Measured by RWD, KO, AM 36°37'9" N, 106°48'46" W
<table>
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<th>Thickness (feet)</th>
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Measured Section 4: Apache Mesa South. Measured by RWD, KO, AM 36°37'9" N, 106°48'46" W
## Measured Section 4: Apache Mesa South

Measured by RWD, KO, AM  36°37'9" N, 106°48'46" W  Page 4

<table>
<thead>
<tr>
<th>Thickness (feet)</th>
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<td></td>
<td>88-177-250</td>
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<td></td>
<td>88-177-250</td>
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</tr>
</tbody>
</table>

### Depositional environment
- **Kmf**: @236', gray shale, Scour with 1-2' relief, mudrips, Fe-stained
- **Kpl**: Fe-stained top

### Sedimentary Structures
- **troughs**
- **3:5 bedsets**
- **// lams**

### Biologic
- **oph**

### Notes
- **Current ripples**
- **Abundant organic grains**
- **Stinking Lake Beach**
- **POULOS MESA BEACH**

### Units
- **USF**: Sand-on-sand breaks
- **LSF-M3F**: Fe-cemented top
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
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**Measured Section 4: Apache Mesa South.** Measured by RWD, KO, AM 36°37'9" N, 106°48'46" W

- **Slope-weathering, non-resistant sandstone, obscure**
- **Fe-rind**
- **Flaggy, looks ripple weathered**
- **Fe-stained**
- **Variable bedding, scour**
- **Mudrills**
- **Mud breaks with rippled ss**
Measured Section 4: Apache Mesa South. Measured by RWD, KO, AM  36 37'9" N, 106 48'46" W
<table>
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<td>60</td>
<td>6</td>
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<td></td>
<td></td>
<td></td>
<td>@ 60° - translate section 10 yds Fe concretion layer minor mud breaks, mud clasts</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>// lams</td>
<td></td>
<td>Tool marks on sandstone base Interbedded sandstones and paper shales</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
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<td></td>
<td>SCS</td>
<td>thal</td>
<td>Abundant small Fe concretions (1/4&quot; - 1&quot;)</td>
</tr>
<tr>
<td>30</td>
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<td>@ 40° - translate section 50 yds</td>
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<tr>
<td>20</td>
<td>2</td>
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<td>HCS</td>
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<td>Discontinuous sandstone in shale slope</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>und // lams</td>
<td>thal oph</td>
<td>Scoured base, mostly covered, exposed below resistant cap</td>
</tr>
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Measured Section 5: Apache Mesa North. Measured by MK-J, SV 36 39°29" N, 106 49°13" W
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Sedimentary structures</th>
<th>Biologic</th>
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<tbody>
<tr>
<td>120</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
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<td>thal</td>
<td>Mostly covered shale/sand interbeds, abundant mud clasts in float</td>
</tr>
<tr>
<td>110</td>
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<td>Abundant mud clast layers</td>
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<tr>
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<td>discontinuous mud layers/muddy sand break, notch</td>
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<td>oph</td>
<td>Small mud clasts</td>
</tr>
<tr>
<td>60</td>
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<td>Fe concretions</td>
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<td>thal</td>
<td>Major translation of section, thickness approx. for 70'-85'</td>
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Measured Section 5: Apache Mesa North. Measured by MK-J, SV 36 39° 29' N, 106 49° 13' W
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</table>

Measured Section 5: Apache Mesa North. Measured by MK-J, SV

63° 39' 29" N, 106° 49' 13" W

Page 3
**Measured Section 5: Apache Mesa North**

- **Unit**: Measured by MK-J, SV
- **Location**: 36° 39' 29" N, 106° 49' 13" W

### Column Headers
- **Thickness (feet)**
- **Unit**
- **Total gamma counts x 1,000**
- **Grain Size (microns)**
- **Weathering profile and lithology**
- **Bed sets**
- **Sedimentary structures**
- **Biologic**
- **Notes**
- **Depositional environment**

#### Sedimentary Structures
- **Trough ripples**
- **Obscure**
- **Trough**
- **Obscure SCS?**
- **Break w/ Fe concretions**
- **Massive, fractured sandstones, Fe-stained ripple breaks w/ mud clasts (discontinuous)**
- **Discontinuous ripple breaks w/in trough crossbedded ss**
- **Fe concretion layer**

#### Depositional Environment
- **Channel**
- **Subaqueous fan**
- **Stagnant lake basin**
- **Drop**

---

**Notes**

- Discontinuous ripple breaks w/in trough crossbedded ss
- Massive, fractured sandstones, Fe-stained ripple breaks w/ mud clasts (discontinuous)
- Break w/ Fe concretions
- Fe concretion layer
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
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**Measured Section 6: Horse Lake Mesa Southeast. Measured by DB, AM**

36 42'43" N, 106 50'18" W
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<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
<th>Grain Size (microns)</th>
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<th>Bed sets</th>
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Measured Section 6: Horse Lake Mesa Southeast. Measured by DB, AM 36 42'43" N, 106 50'18" W
<table>
<thead>
<tr>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Bed sets</th>
<th>Sedimentary structures</th>
<th>Biologic</th>
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</tbody>
</table>

- All slope-forming, isolated sand bodies
- Some terrestrial fossils leaves in float

Measured Section 6: Horse Lake Mesa Southeast. Measured by DB, AM

36 42'43" N, 106 50'18" W
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts × 1,000</th>
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</tbody>
</table>

**Notes:**
- Fe nodule ripups, wood lag, siltstone lag
- GAD = 45° shale break on top of ss. Some ripples at base of 1-1.5' sands.
- Interbedded low angle sands (10") and shales (1") w/ organic material. Bedding is undulatory. Shales thicken upward. Sand bodies pinch out laterally. X-beds prevalent laterally. @45° GAD in shale.
- DOWNLAP--Scour surface
- Slope-forming ss (more resistant laterally).
- Lichen cover; generally fining upward but all coarse
- Laterally discontinuous mud layer
- Minor organic lams, large scale troughs
- Notch @0° = sand/sand contact

Measured Section 7: Horse Lake Mesa NE. Measured by RWD, KO, DB, AM 36 43'29" N, 106 49'39" W
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts × 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Bed sets</th>
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<td>7</td>
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<td></td>
<td>burrow?</td>
<td></td>
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<td>6</td>
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Measured Section 7: Horse Lake Mesa NE. Measured by RWD, KO, DB, AM 36 43'29" N, 106 49'39" W Page 2
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Rotated blocks—out of place except for bits @136'.
Abundant mudrifs, very rubbly...burrowed?

FLUV

Measured Section 7: Horse Lake Mesa NE. Measured by RWD, KO, DB, AM 36 43'29" N, 106 49'39" W
Measured Section 8: Horse Lake Mesa North. Measured by RWD, MK-J, KO 36°46'39" N, 106°49'43" W
<table>
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<th>Thickness (feet)</th>
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Measured Section 8: Horse Lake Mesa North. Measured by RWD, MK-J, KO 36 46'39" N, 106 49'43" W
<table>
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<th>Thickness (feet)</th>
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Measured Section 8: Horse Lake Mesa North. Measured by RWD, MJ-K, KO 36 46°39' N, 106 49°43' W
Measured Section 9: Sulphur Canyon. Measured by RWD, MKJ.

36°47'32" N, 106°46'26" W

Covered slope—shale and mud at base, shale—mud grades upward into sandy mud. Resistant cap on top of bed. Bioturbated layer in massive sand. Resistant cap on top of bed. Several 1' massive ss outcrops.

Erosional contact, mud cracks at base. Sandy shale slope with small sandy outcrops. Bioturbated mud between 0.5-3' bedsets.

Depositional environment:

Cart are:

ot

LSF

OF

LSF

Deplorably structure

Sedimentary structures

Biologic structures

Erosional contact, mud cracks at base. Sandy shale slope with small sandy outcrops. Bioturbated mud between 0.5-3' bedsets.

Notes:

Erosional contact, mud cracks at base. Sandy shale slope with small sandy outcrops. Bioturbated mud between 0.5-3' bedsets.

Depositional environment:

Cart are:

ot

LSF

OF

LSF
Thicknes (feet)

Sedimentary structures

HCS

Laminating ripples

Notes

Prominent continuous notch
Fe concretions—meter scale or bigger

A @157.5'

Covered slope—massive v. fine sand

Minor mudbreak

Interbedded sand (0.1-1.5") and mud

Mudrip layers

Erosional scour surface

Discontinuous hummocks; interbedded sand (0.5-2") and organic shale lenses

Depositional environment

LSF

STRIKING LAKE BEACH

STONE LAKE BEACH

Measured Section 9: Sulphur Canyon. Measured by RWD, MKJ 36 47°32" N, 106 46°26" W
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts × 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Bed sets</th>
<th>Sedimentary structures</th>
<th>Biologic</th>
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**Notes**

- **△@239** Angular fine-gr. ss sits on channel ratty sands
  
  Smaller scale lenses upsection

- **△@220**
  
  Undulatory sand lenses
  Amplitude ~3
  
  Outcrop creates lens-shaped float = small channels?
  Lensed 2-4' scale. "Tidal" ss lenses bounded by mud

- **△@194**
  
  Ratty sands w/ gray shale breaks
  
  Resistant beds w/ coarse grains, recessed flakey muddy sands

- **△@188**
  
  Ratty sands w/ org. and gray shale mud breaks

**Depositional environment**

- EST
- LSF

**Measured Section 9: Sulphur Canyon. Measured by RWD, MKJ**

36°47'32" N, 106°46'26" W
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Measured Section 9: Sulphur Canyon. Measured by RWD, MKJ 36°47'32" N, 106°46'26" W
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<tr>
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Measured Section 9: Sulphur Canyon. Measured by RWD, MKJ 36 47°32' N, 106 46°26' W
Measured Section 9: Sulphur Canyon. Measured by RWD, MKJ 36°47'32" N, 106°46'26" W
## Weathering Bed and Sets Structures

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<th>Total gamma counts × 1,000</th>
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<tr>
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<td>22 24 28 32 34 38 38 40 40</td>
<td>180-450, 500</td>
<td>Fewer burrows</td>
<td>170-500</td>
<td>Troughs</td>
<td>Burrows</td>
<td>Sands more massive toward top</td>
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<tr>
<td>110</td>
<td>5</td>
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<td>177-500</td>
<td>Trough axis N76E</td>
<td>Low angle tams</td>
<td>Troughs</td>
<td>Low angle tams</td>
<td>Troughs</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td>177-350, 500</td>
<td>Major scour surface, abundant mudrips</td>
<td>Ripples</td>
<td>Org. lams</td>
<td>Org. lams</td>
<td>Many discontinuous mud breaks (101-120')</td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
<td>177-350</td>
<td>Break rises to north and loses notch;</td>
<td>Incl. beds</td>
<td>Troughs // lams / lams</td>
<td>Troughs // Lams</td>
<td>Break is sandy, ripped, churned notch</td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
<td>177-400</td>
<td>Break, churned up sand, no distinct burrows</td>
<td>Thal. oph.</td>
<td>Thal. oph.</td>
<td>Thal. oph.</td>
<td>Major downlap (92-120'), sands pinchout to north</td>
</tr>
<tr>
<td>70</td>
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<td></td>
<td>177-350</td>
<td>Scour surfaces, mudrips</td>
<td>Thal.</td>
<td>Major break, wavy contact</td>
<td>Major break</td>
<td>Scour surfaces, mudrips</td>
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<tr>
<td>60</td>
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<td>155-350</td>
<td>Break-sand on sand</td>
<td>Thal.</td>
<td>Major break, wavy contact</td>
<td>Break-sand on sand</td>
<td>Scour surfaces, up to 1'</td>
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<tr>
<td>50</td>
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<td>177-275</td>
<td>2' Scour surface, mud breaks</td>
<td>Thal.</td>
<td>Major break, slopes back</td>
<td>Discontinuous mud break, scour</td>
<td>2' Scour surface, mud breaks</td>
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<tr>
<td>40</td>
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<td></td>
<td>177-250, 200</td>
<td>3' thick muds @72'</td>
<td>Thal.</td>
<td>Major break, slopes back</td>
<td>Discontinuous mud break, scour</td>
<td>3' thick muds @72'</td>
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<tr>
<td>30</td>
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<td>177-260</td>
<td>Major break (sand on sand notch to north)</td>
<td>Thal.</td>
<td>Major break (sand on sand notch to north)</td>
<td>Major break-sand on sand</td>
<td>Major break-sand on sand, continuous in massive face</td>
</tr>
</tbody>
</table>

**Notes:**
- Sands more massive toward top
- Trough axis N76E
- Scour surfaces are Fe stained (100-120')
- Many discontinuous mud breaks (101-120')
- Break rises to north and loses notch; Break is sandy, ripped, churned notch
- Break, churned up sand, no distinct burrows
- Major downlap (92-120'), sands pinchout to north
- Scour surfaces, mudrips
- Major break, wavy contact
- Break-sand on sand
- Scour surfaces, up to 1'
- 2' Scour surface, mud breaks
- 3' thick muds @72'
- Major break; slopes back
- Discontinuous mud break, scour
- Mudrips
- Major break (sand on sand notch to north)
- Major break-sand on sand, continuous in massive face
- Discontinuous breaks-sand on sand

**Measured Section 10: Horse Lake Gap. Measured by KO, SV**

36° 51'13" N, 106° 46'29" W
<table>
<thead>
<tr>
<th>Thickness (feet)</th>
<th>Unit</th>
<th>Total gamma counts x 1,000</th>
<th>Grain Size (microns)</th>
<th>Weathering profile and lithology</th>
<th>Bed sets</th>
<th>Sedimentary structures</th>
<th>Biologic</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>17</td>
<td>24</td>
<td>100-300</td>
<td>250-500</td>
<td>250-500</td>
<td>leaf fossils in float</td>
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<td>130</td>
<td>16</td>
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<td>leaf fossils in float</td>
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<td>leaf fossils in float</td>
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Measured Section 10: Horse Lake Gap. Measured by KO, SV 36 51'13" N, 106 46'29" W
Measured Section 11: Monero Beach. Measured by RWD, MK-J, DB, AM, KO, SV 36°54'15" N, 106°51'4" W
<table>
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<th>Depositional environment</th>
<th>Mosses</th>
<th>Escarpage</th>
<th>Sedimentary structures</th>
<th>Bed size</th>
<th>Sedimentary facies</th>
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<th>Lithology</th>
<th>Paleosol</th>
<th>Trace fossils</th>
<th>Total 1000 x 10cm core</th>
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<td>Locally red</td>
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<tr>
<td>Channel</td>
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<td>Thickness (feet)</td>
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<td>Total gamma counts x 1,000</td>
<td>Grain Size (microns)</td>
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<td>Bed sets</td>
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Measured Section 12: Monero Beach North. Measured by RWD, MK-J, AM, KO, DB, SV  36 54°15" N, 106 51°14" W
Measured Section 12: Monero Beach North. Measured by RWD, MK-J, AM, KO, DB, SV  36 54'15" N, 106 51'4" W
<table>
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</table>

**SCS? und // lams**

- @ 48', paper shale break, major continuous
- @ 26', discontinuous break
- @ 19', 2' break with shale
- Fe concretions line burrows 1-3 inches
- Scoured, guttered base; fine organics in shales.
- Interbedded 1-3" ss and 1/2" paper shales; below and lateral are several 20-50" HCS sandstones.

Measured Section 13: Briggs Mesa-Martinez. Measured by RWD, KO, AM 36 54'12" N, 106 49'17" W
<table>
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<th>Unit</th>
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<th>Grain Size (microns)</th>
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Measured Section 13: Briggs Mesa-Martinez. Measured by RWD, KO, AM  36 54'12" N, 106 49'17" W
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Measured Section 13: Briggs Mesa-Martinez. Measured by RWD, KO, AM 36 54'12" N, 106 49'17" W
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Measured Section 13: Briggs Mesa-Martinez. Measured by RWD, KO, AM 36°54'12" N, 106°49'17" W Page 4
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Measured Section 13: Briggs Mesa-Martinez. Measured by RWD, KO, AM 36 54'12" N, 106 49'17" W Page 5
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Measured Section 13: Briggs Mesa-Martinez. Measured by RWD, KO, AM 36 54'12" N, 106 49'17" W
Measured Section 14: Briggs Mesa-East Rim. Measured by RWD, KO, AM, SV 36 54'38" N, 106 48'55" W
Measured Section 14: Briggs Mesa-East Rim. Measured by RWD, KO, AM, SV 36 54'38" N, 106 48'55" W
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| Measured Section 14: Briggs Mesa-East Rim. Measured by RWD, KO, AM, SV 36°54'38" N, 106°48'55" W   Page 5
### Measured Section 15: Willow Creek

**Measured by RWD, KO**

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<td>scs to / lams</td>
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<td>10 -190 grooves 30 -210</td>
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<td>40</td>
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<td>*Units M1, M2, etc., correspond to Muehlberger Section</td>
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Diatomaceous environment:
- **MSF**
- **OT**
- **LSF**
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Measured Section 15: Willow Creek. Measured by RWD, KO

36 54'30" N, 106 38'27" W

Page 2

Base of orange cliff

Very Fe. orange color--linear cemented zones with red color
Irregular Fe cemented scour?

Storm eroded base, grooves
Gray shale, burrowed siltstone
<table>
<thead>
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Measured Section 15: Willow Creek. Measured by RWD, KO  
36°54′30″ N, 106°38′27″ W
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Measured Section 15: Willow Creek. Measured by RWD, KO

36 54'30" N, 106 38'27" W  
Page 4

Top of section poorly described thanks to severe weather.
APPENDIX 2

Outcrop gamma ray data for selected measured sections (figure 1) described in this study. Data were collected using a U.S. Geological Survey GAD-6 gamma-ray spectrometer which simultaneously records total counts, potassium, uranium, and thorium. Data are reported as raw counts; count duration per sample was 90 seconds. Also shown for each section is the simplified lithology and depositional environments; ss, sandstone; org., organic; recalib., recalibrated.
Measured Section 2 - Pounds Canyon; see figure 1 for location.

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Measured Section 5 - Apache Mesa South; see figure 1 for location.

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