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STRATIGRAPHIC ARCHITECTURE OF THE MESAVERDE GROUP IN THE SAN JUAN BASIN AREA

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Abstract— For more than 80 years, outcrop- and subsurface-based stratigraphic analyses of the San Juan Basin's Mesaverde Group have helped geologists establish relationships among sediment supply, accommodation, and stratigraphic architecture. Different types of depositional systems develop along regressive and transgressive coastlines. In typical regressive systems, shoreface sandstones gradationally overlie offshore shales with cm- to dm-scale interbeds of sandstone and shale representing a transition zone between those two depositional systems. Most outcrops of the Point Lookout Sandstone present some variant of this stratigraphic succession. Shoreface sandstones can be particularly thick if the shoreline trajectory included aspects of both progradation and aggradation. Sharp-based shorefaces indicate forced regression, a situation where a fall in sea level causes the shoreline to move basinward. In transgressive systems like that represented by the Cliff House Sandstone, sandstones deposited in barrier island complexes typically erosionally overlie nonmarine deposits. Those sandstones can be thin or even absent in purely transgressive systems. They can become thicker and interfinger laterally with nonmarine and offshore deposits when transgression slowed or paused while subsidence continued. The nonmarine Menefee Formation is heterolithic, with abundant fine-grained and carbonaceous deposits. These characteristics, along with the formation's wedge-shaped geometry, indicate that much of the deposition occurred in a rapidly subsiding foreland basin setting, landward of the time-equivalent Point Lookout and Cliff House shorelines.

INTRODUCTION

This paper illustrates and explains changes in stratigraphic architecture of shallow-marine and nonmarine deposits of the Campanian Mesaverde Group as exposed in outcrops around the margins of the San Juan Basin (Fig. 1). The Mesaverde Group and its stratigraphic equivalents in Colorado, Utah, and farther north were deposited along the western margin of the Cretaceous Western Interior Seaway (Fig. 2). Some of these outcrops, particularly those in the Book Cliffs area of eastern Utah, have been used for many decades as laboratories and classrooms for the development and instruction of siliciclastic sequence stratigraphy (e.g., Van Wagoner et al., 1990; Minor et al., 2022). Largely forgotten, and as discussed herein, is that several key concepts of sequence stratigraphy were developed and applied to the Mesaverde in the San Juan Basin more than 80 years ago. Hart (this volume) provided a high-level overview of the Cretaceous Western Interior Seaway that linked deposits from the San Juan Basin area with time-equivalent deposits elsewhere in the basin.

The Mesaverde Group in the San Juan Basin is a significant stratigraphic unit in many other respects. It has been a significant source of natural gas production since 1927 when the Blanco Mesaverde field was established. Decades later, that field would be recognized as one of the world's largest gas fields, although it has since lost that distinction. In the late 1970s, the Blanco Mesaverde field helped spawn the basin-centered gas concept, a name proposed to describe gas accumulations having production from large areas in the deepest part of the basin that are downdip from water-saturated rocks (Masters, 1979). Lessons from the Mesaverde also helped develop many of the concepts associated with naturally fractured reservoirs (Harstad et al., 1998; Lorenz and Cooper, 2003; Hart, 2006). These and other aspects of hydrocarbon production from the Mesaverde and other Cretaceous sandstones of the San Juan Basin were recently summarized by Hart (2021) and Hart and Cooper (2021).

STRATIGRAPHIC OVERVIEW

The Mesaverde Group forms a clastic wedge that thins and pinches to the northeast (Fig. 3). Molenaar et al. (2002) demonstrated that it can be >600 m thick in the southwest part of the basin. It is subdivided into three formations (from bottom to top): the Point Lookout Sandstone, the Menefee Formation, and the Cliff House Sandstone. The Point Lookout Sandstone consists of shelf, shoreface, and distributary-channel units deposited during the northeast progradation of the shoreline. The Cliff House Sandstone is the product of sandy coastal zone deposition during transgression and the formation's thickness varies considerably (Fig. 3). The intervening Menefee Formation consists of coastal-plain sediments (fluvial channels, swamps, etc.) deposited landward of the prograding Point Lookout shoreline and the transgressive Cliff House shoreline. The Mesaverde sits above and interfingers with the Mancos Shale, and it underlies and interfingers with the Lewis Shale.

The Mesaverde Group is variably exposed around the San Juan Basin margins. Relatively complete sections are present at various locations along the monoclines that rim the basin on the western, northern, and eastern margins (Fig. 4). The section is penetrated by many thousands of wells in the basin interior. Figure 5 shows an example of the Mesaverde Group as penetrated by a gas well in the north-central portion of the basin.

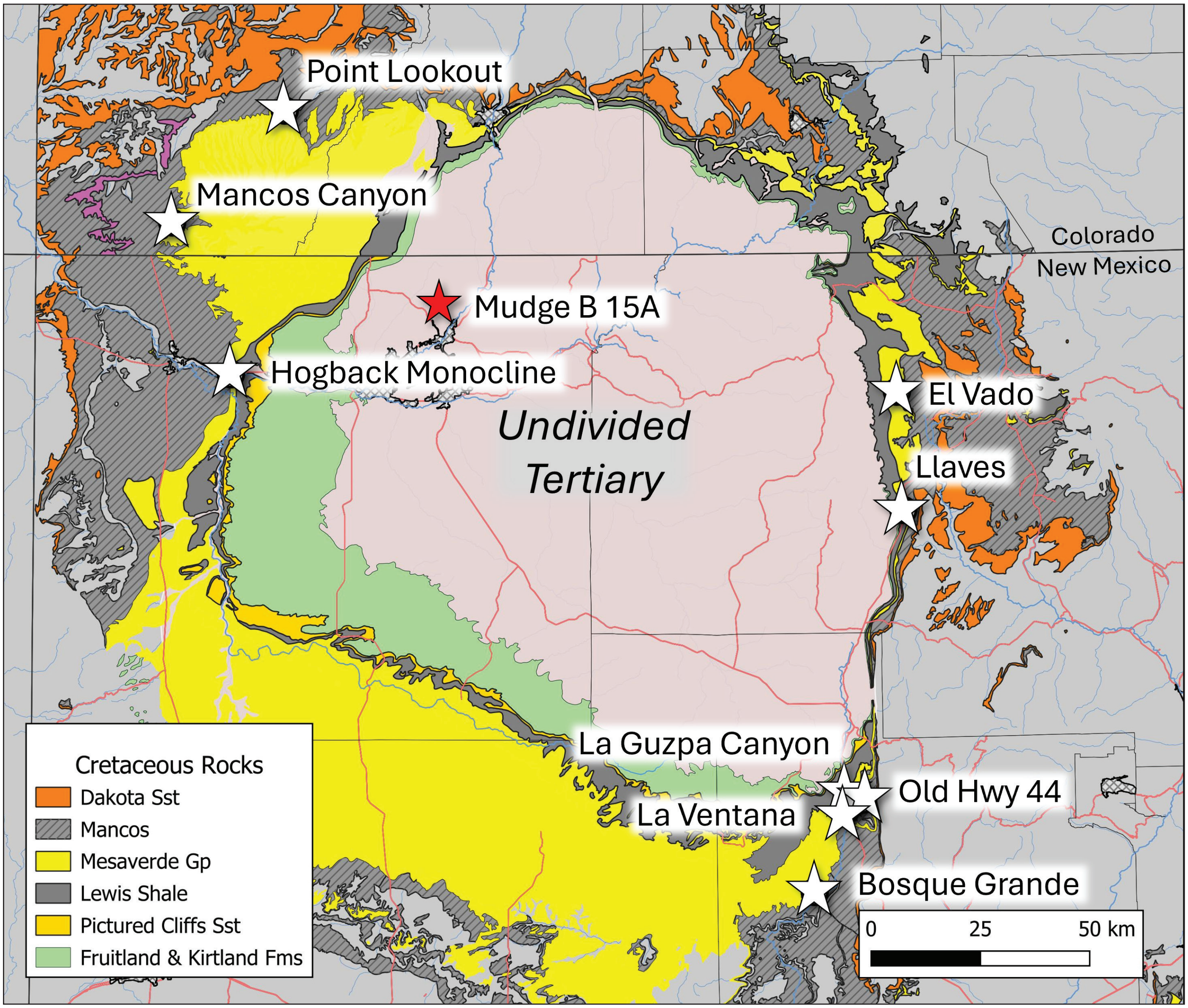

Figure 1. Location map showing simplified geology and locations of outcrops (white stars) shown elsewhere in this paper. Red star shows location of well shown in Figure 5.

SEQUENCE STRATIGRAPHIC CONCEPTS

Early Applications in the San Juan Basin

Many decades before the development of sequence stratigraphy as a formal concept, Sears et al. (1941) recognized shoreline sandstones of the Mesaverde Group as representing both shoreline regression (to the northeast) and transgression (to the southwest) along the margin of a broad, shallow Cretaceous seaway. Sandstones of the lowermost formation, the Point Lookout, formed in response to a relatively long-term regression. Sandstones of the uppermost formation, the Cliff House, formed in response to a relatively long-term transgression. The intervening Menefee Formation was deposited in a variety of floodplain settings landward of the Point Lookout and Cliff House shorelines.

Sears et al. (1941) made two highly significant inferences about deposition of the Mesaverde Group and these two concepts are staples of modern sequence stratigraphy. The first was that basinward and landward fluctuations of the shoreline position developed in response to the interplay of (in present-day terminology) basin subsidence and sediment ("debris") supply. They argued that "[w]hen [subsidence] predominates, there is transgression; when sedimentation prevails, regression and regressive deposits are the result." This interpretation contrasted with the prevailing paradigm that regressions and transgressions were largely due to tectonic uplift/subsidence or global changes of sea level.

Sears et al. (1941) also suggested the simultaneous existence of four "zones of deposition": an offshore area where muds were deposited; a nearshore zone where sand was deposited; a coastal zone of swamps, lagoons, and estuaries; and finally (in the most landward position) floodplain deposits. Because these zones existed simultaneously, and because their

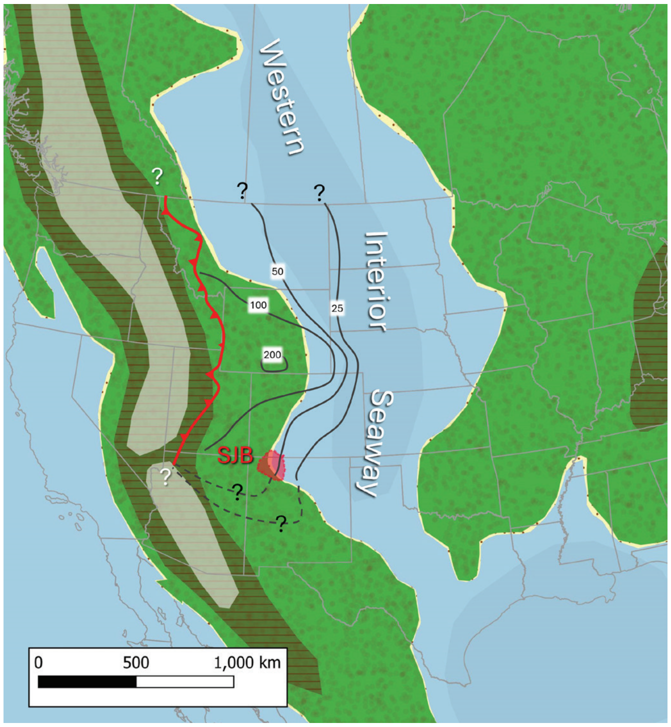

Figure 2. Schematic representation of Campanian paleogeography showing approximate extent of the Cretaceous Western Interior Seaway and the Tertiary San Juan Basin (SJB, red). Contour lines show deposition rates (m/My) for early Campanian strata and red line shows limit of active thrusting, both as defined by Yonkee and Weil (2015). Contours and thrust limit were not extended into Canada by those authors and their locations to the southwest of the San Juan Basin are not constrained by data. Modified from Hart (this volume).

locations shifted due to transgressions and regressions, depositional timelines crossed lithological boundaries.

Hollenshead and Pritchard (1961) later elaborated on these ideas and presented examples of their application to the Point Lookout and Cliff House sandstones. They related the thickness of Point Lookout and Cliff House sandstones to the rate of shoreline regression or transgression respectively. The Point Lookout is thinner where the shoreline was moving rapidly toward the basin center and thicker when the rate of progradation slowed. In the latter case, the shoreline sandstones built up vertically. Likewise, the Cliff House is thickest where the shoreline sandstones built up vertically and it is thin or even absent where the shoreline transgressed rapidly. These concepts are illustrated in Figures 6A, and Figure 6B shows a wireline log-based cross section that documents such stratigraphic architecture. Note the direction of shoreline movement (basinward, vertical, landward) is currently referred to as the shoreline trajectory.

Shallow-Marine and Nonmarine Depositional Systems

Depositional systems are the building blocks of stratigraphic sequences and a variety of shallow-marine and nonmarine depositional systems are represented in the Mesaverde Group. A fundamental distinction needs to be made between shoreline systems associated with transgressions and regressions. Those two conditions are associated with different coastal geomorphologic features, and hence, different types of stratigraphic features and stratigraphic successions that are preserved in the geologic record.

During shoreline regression (Fig. 7A), sand and mud are supplied (from a hinterland) to the shoreline by rivers that cut across a coastal plain. Whereas deltas (distinct shoreline protuberances) can form in some settings, more linear strandplains form where waves are able to quickly redistribute sediment alongshore from a river mouth. Sand is typically segregated to a shoreface, a wave-dominated zone that can be several meters thick and tens to hundreds of meters in width. Mud moves offshore with short-term variations in storminess, sediment supply, and sea level, causing sand and mud to interfinger between the shoreface and offshore areas. Channel sandstones, floodplain sands and muds, coals, and other lithologies can be deposited on the coastal plain.

During transgression, the shoreline is cut off from river-borne sand as the sea floods fluvial valleys. A common shoreline configuration is shown in Figure 7B. Morphological features include sandy barrier islands and associated tidal inlets, muddy back-barrier lagoons, and estuarine areas. Coal swamps, coastal-plain muds, and fluvial deposits can form landward of the salt-water intrusion limit.

Shoreline Movements and Vertical Stratigraphic Successions

As noted by Sears et al. (1941) and many other authors since, a shoreline will move basinward (regression) if the rate at which sediment is supplied exceeds the rate at which room is made available for that sediment to accumulate. Basinward movement of the shoreline is also referred to as progradation. In present-day terminology, the space available for sediment to accumulate is known as accommodation. As the shoreline progrades, Walther's Law dictates that shoreface sandstones will gradationally overlie offshore muds and that those sandstones will be overlain by coastal-plain deposits (e.g., the left side in Fig. 8A). During transgression, barrier-island sands are pushed landward where they come to abruptly overlie lagoonal, estuarine, or other nonmarine deposits. Barrier sands can be incompletely preserved so that, once the water becomes deep enough, marine shale may directly overlie nonmarine deposits

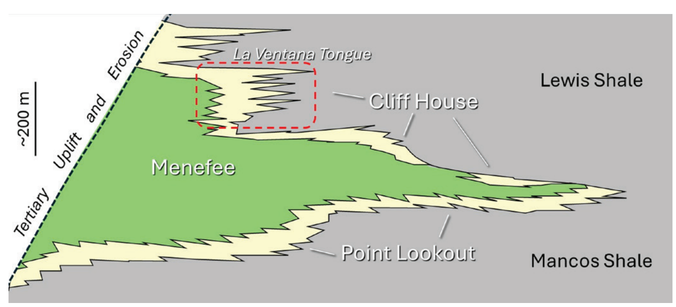

Figure 3. Schematic cross section through the Mesaverde Group showing the three constituent formations (Point Lookout, Menefee, and Cliff House) and interfingering relationships with the Mancos and Lewis shales. Red dashed area highlights the La Ventana Tongue of the Cliff House. Redrawn and simplified from Molenaar et al. (2002).

or be separated from them by barrier-island sandstones (e.g., the right side of Fig. 8B).

Relatively short-term transgressions and regressions can be superimposed on longer-term trends because of fluctuations in sediment supply, eustasy (global sea level), and/or subsidence. As a result, individual progradational successions (parasequences or sequences) can stack to form progradational, aggradational, or retrogradational geometries depending on the relative contribution of sediment supply and the rate at which accommodation is generated (Fig. 9).

OUTCROP EXAMPLES

Point Lookout Sandstone

For simplicity, I herein discuss the Point Lookout as being deposited as a prograding shoreface. Katzman and Wright-Dunbar (1992) and Wright-Dunbar et al. (1992) noted the depositional setting of the Point Lookout changes spatially, with well-developed shelf-shoreface successions developed in some areas but channelized successions being present elsewhere. The same type of variability is noted in the subsurface.

In many outcrops, the Point Lookout shows the type of facies stacking pattern associated with the type of Waltherian facies stacking expected for a prograding succession. Figure 10 shows two examples. In both cases, shoreface sandstones of the Point Lookout gradationally overlie the Mancos Shale. Spectacular as these outcrops might be, the interbedded sandstones and shales of the transition zone are not clearly visible. Figure 11 provides a closer view of the interbedded transition facies. The cm- to dm-scale sandstones of this facies were deposited during storms with interbedded shales representing fair-weather conditions.

A commonly overlooked aspect of shoreface successions in the Point Lookout or elsewhere is that their thicknesses should be similar to the water depth of modern shorefaces. Although that depth can vary between a few meters to more than 10 m, some shoreface sandstones are considerably thicker. In these thicker cases, the inference is that some component of aggradation (Figs. 6A and 9), associated with increased basinal subsidence and/or eustatic rise (concepts suggested by Sears et al., [1941] and Hollenshead and Pritchard, [1961]), is represented in the succession.

A much different type of inference is made when the transitional facies, which are cm- to dm-thick interbeds of sandstones and shales, are missing between shoreface sandstones and offshore shales. Gutter casts are commonly present at the base of the shoreface sandstone. This type of succession is known as a sharp-based shoreface and these geometries indicate shoreline progradation was driven by sea-level fall, a situation known

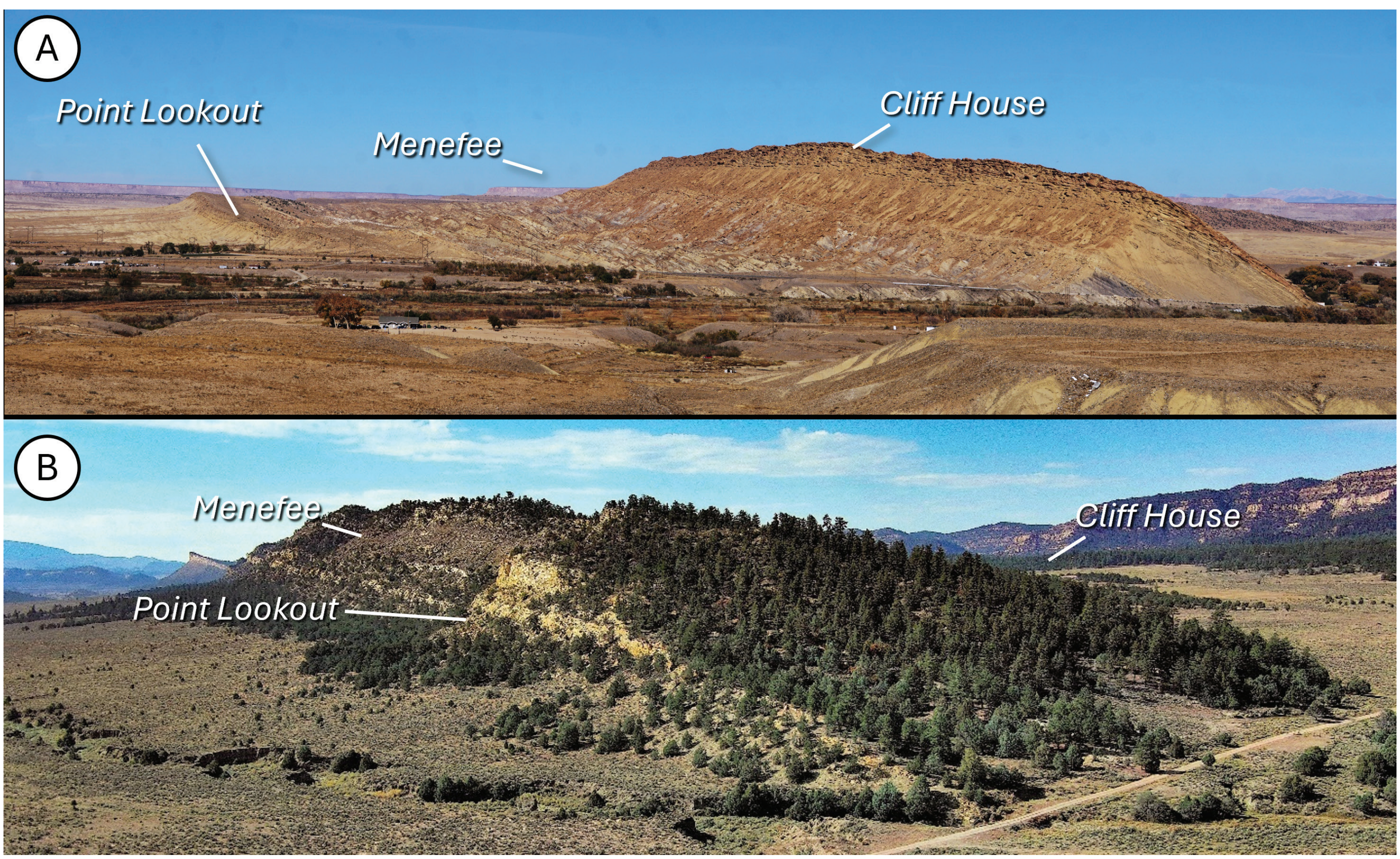

Figure 4. The Mesaverde Group in outcrop. A: At the Hogback monocline, western margin of the San Juan Basin. View to north. Shallow-marine sandstones of the Point Lookout Formation (left) are overlain by heterolithic deposits of the Menefee Formation. Resistant shallow-marine sandstones of the Cliff House Formation cap the succession. B: North of Llaves, NM. View to south. Point Lookout sandstones at the base of the cuesta are overlain by heterolithic nonmarine deposits of the Menefee Formation. Shallow-marine deposits of the Cliff House are thin and generally not visible along the western side of the cuesta. Locations of both outcrops shown in Figure 1.

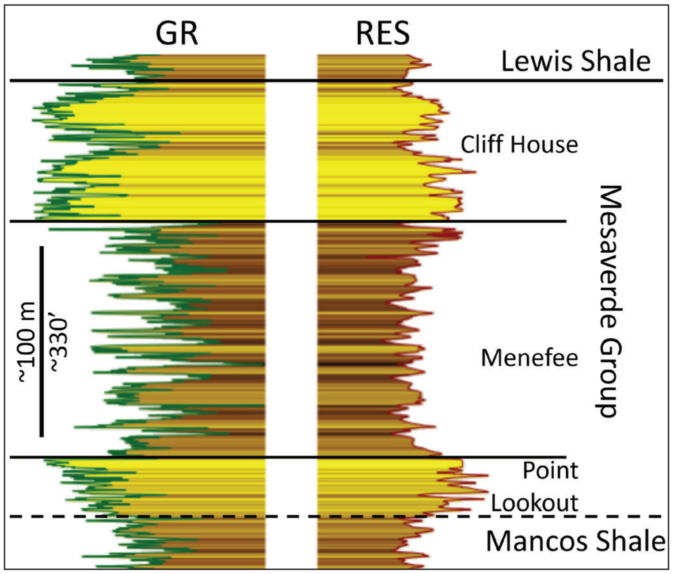

Figure 5. Wireline log expression of the Mesaverde Group in the north-central portion of the San Juan Basin (Mudge B 15A, P-08-31N-11W; see location in Fig. 1). Gamma-ray log (GR) at left and resistivity log (RES) at right are color coded to depict approximate lithology. Yellow: sandstone, brown: shale. The Point Lookout gradationally overlies the Mancos Shale. The contact between the sandy Point Lookout and heterolithic Menefee is sharp in this well, as is the contact between the Menefee and the Cliff House.

as forced regression (Plint, 1988; Plint and Nummedal, 2000). The Bosque Grande section described by Koning (2024) is an example of a sharp-based shoreface (Fig. 12).

Menefee Formation

The Menefee was deposited in a variety of nonmarine settings landward of the regressive Point Lookout shoreline and/or the transgressive Cliff House shoreline (Figs. 3, 6, and 7). Outcrops expose a variety of lithologies, including sandstones, shales, siltstones, carbonaceous shales, and coals. The contact between the Menefee and the underlying Point Lookout can be sharp or gradational. The latter is found where nonmarine deposits abruptly overlie shoreface and beachface sandstones (Fig. 13). In the subsurface, wireline logs show the shoreface sandstones can be locally incised and replaced by heterolithic fluvial and deltaic deposits. Outcrops of this type of succession are apparently not well preserved.

Outcrops of fine-grained units (paleosols, overbank deposits, etc.) in the Menefee tend to be easily weathered and recessive (Fig. 14). Channel fill deposits can be sandy (Fig. 15) or heterolithic (Fig. 16) but generally represent deposition in meandering fluvial systems.

The abundance and thickness of fine-grained (overbank) deposits in the Menefee indicate deposition in a high-accommodation setting. Whereas the concept of accommodation may

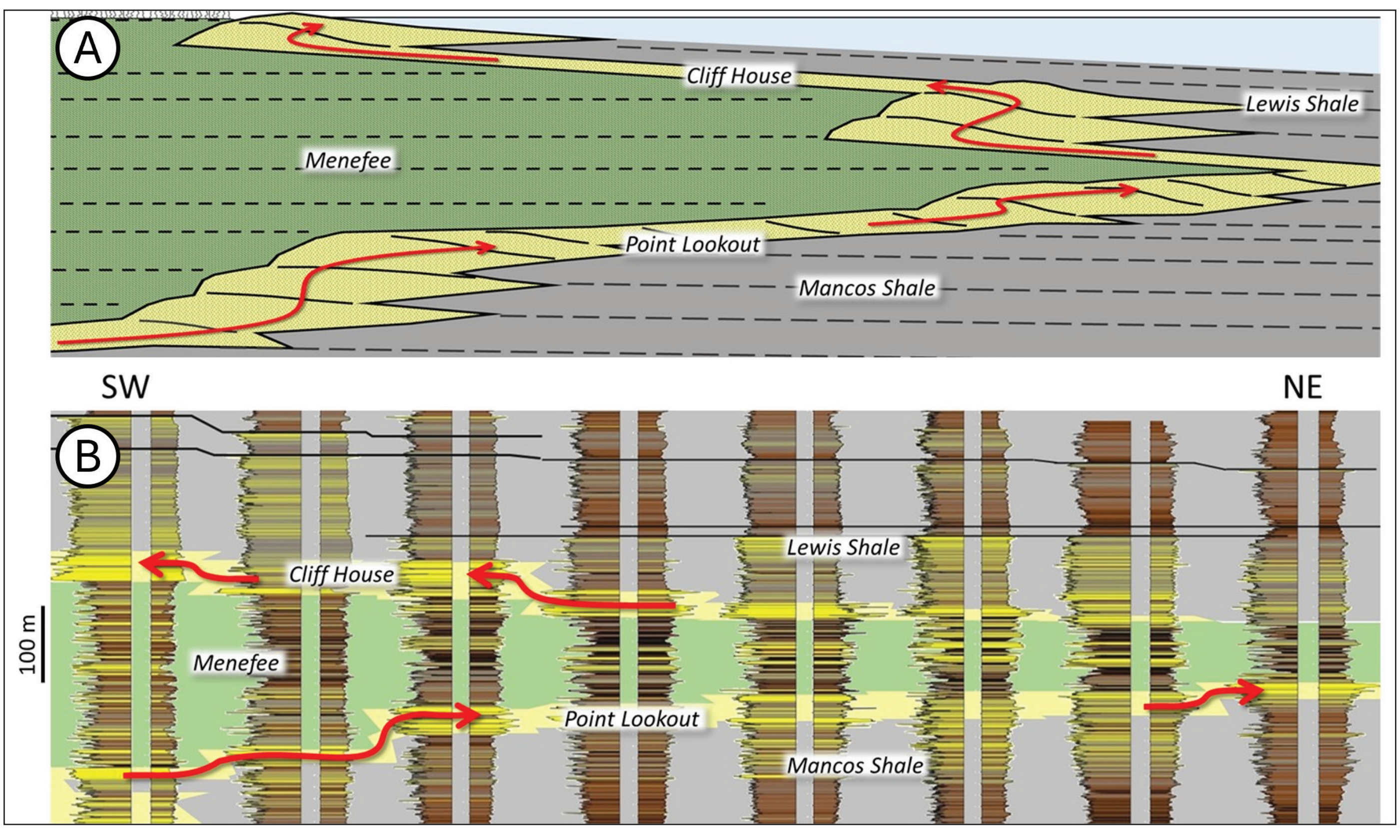

Figure 6. A: Schematic illustration below shows how thickness of the Point Lookout and Cliff House shoreline sandstones changed as a response to changes in shoreline trajectory (red arrows). Dashed lines represent depositional timelines (redrawn and modified from Hollenshead and Pritchard, 1961). B: Wireline log cross section illustrating changes in sandstone thickness (yellow) and inferred shoreline trajectory (red arrows) for the Point Lookout and Cliff House formations. Compare with part A. Logs shown for each well are gamma ray (left) and resistivity (right). Modified and used with permission from Hart (2021). See that publication for further information.

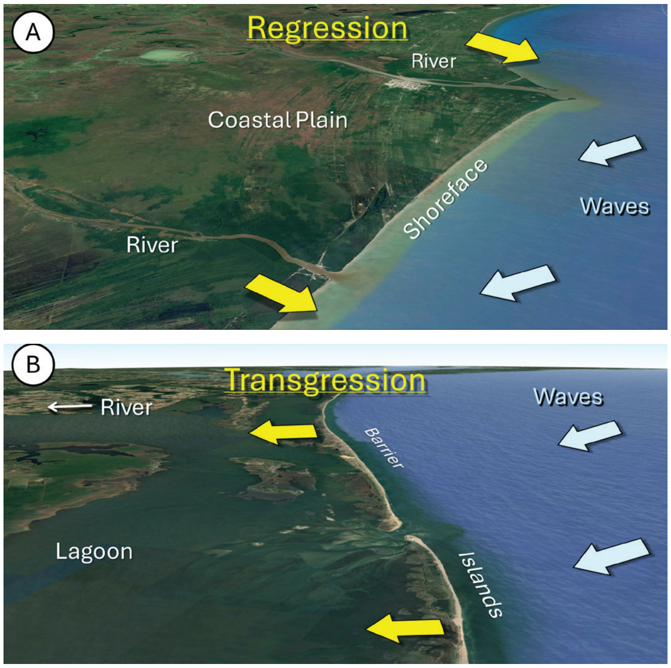

Figure 7. Satellite imagery of two different siliciclastic shoreline settings. A: Shoreline regression (direction shown by yellow arrows) is driven by the flow of river-borne sand to the shoreline. The sand is then redistributed by waves forming sandy shoreface. As the system progrades, shoreface sandstones gradationally overlie offshore deposits. B: In this transgressive setting, the shoreline (barrier islands) is separated from river-borne sediments by lagoons and estuaries. Waves push the barrier islands landward, causing barrier island sands to overlie back-barrier deposits.

be fairly easy to convey for marine settings (e.g., it approximates water depth), accommodation in nonmarine settings is somewhat more difficult to convey. Accommodation is the space available for sediment to accumulate, and basinal subsidence and sediment supply both change in nonmarine settings. The contribution of eustasy to generating accommodation in nonmarine settings is not always easy to establish, although Sears et al. (1941) and Hollenshead and Pritchard (1961) both noted that shoreline aggradation causes vertical aggradation of nonmarine deposits landward of the shoreline (Fig. 6).

In high-accommodation settings, fluvial systems (composed of channels and overbank deposits) aggrade. Channels tend to be isolated by relatively thick overbank deposits. There is little space available for overbank deposits to accumulate in low-accommodation systems. The stratigraphic architecture of these systems is dominated by amalgamated and laterally extensive fluvial sandstone bodies. If accommodation is zero or negative (e.g., the basin is being uplifted), sediment bypasses the basin completely.

Subsidence in a foreland basin increases toward the contemporaneous thrust belt, providing room for nonmarine sediment accumulation if the basin is not flooded by the sea. Thickening of the Menefee toward the southwest (Fig. 3) indicates active subsidence in that direction. Regional isopach maps of early Campanian strata have been used to document high westward-thickening subsidence rates in Utah and Wyoming at this time as part of the Sevier orogeny, and active thrusting in that area is likely to have been responsible for that subsidence (e.g.,

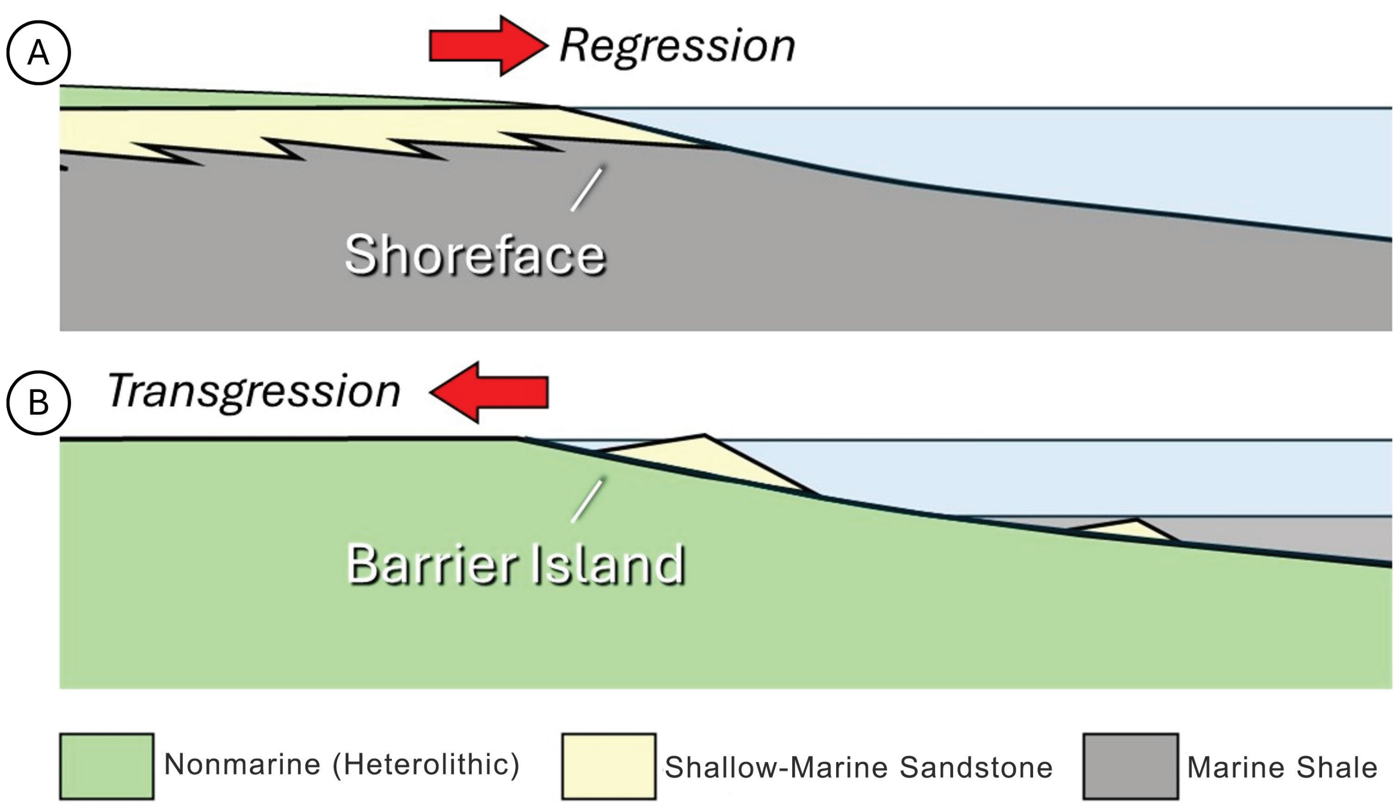

Figure 8. Schematic cross sections through regressive and transgressive siliciclastic shorelines. A: During regression, sandy shoreface deposits interfinger with and overlie (offshore) marine shale. B: During transgression, shallow-marine sandstones are pushed landward, often forming a discontinuous transgressive sandstone. Where present, the transgressive sandstones are overlain by marine shale. Otherwise, marine shale can directly overlie nonmarine deposits.

Cross, 1986; Yonkee and Weil, 2015; Fig. 2). The continuation of time-equivalent (south)westward thickening in the Menefee implies active thrusting to the southwest of the current San Juan Basin although strata needed to constrain the location and rates of thrusting are not preserved.

Cliff House Sandstone

The Cliff House Sandstone overlies the Menefee. Locally, the contact between the two units is sharp, with shallow-marine sandstones abruptly overlying nonmarine deposits (including coal beds; Fig. 17). Elsewhere, defining the contact between the two formations can be difficult because the units can interfinger, a result of the vertical stacking of multiple relatively short-duration transgressive-regressive cycles. The interfingering, combined with the depositional complexity of barrier island settings (Fig. 18), can vertically juxtapose a wide variety of marine, marginal marine, and nonmarine facies.

As noted previously, the thickness of the Cliff House is highly variable. It can be thin to absent in some areas when

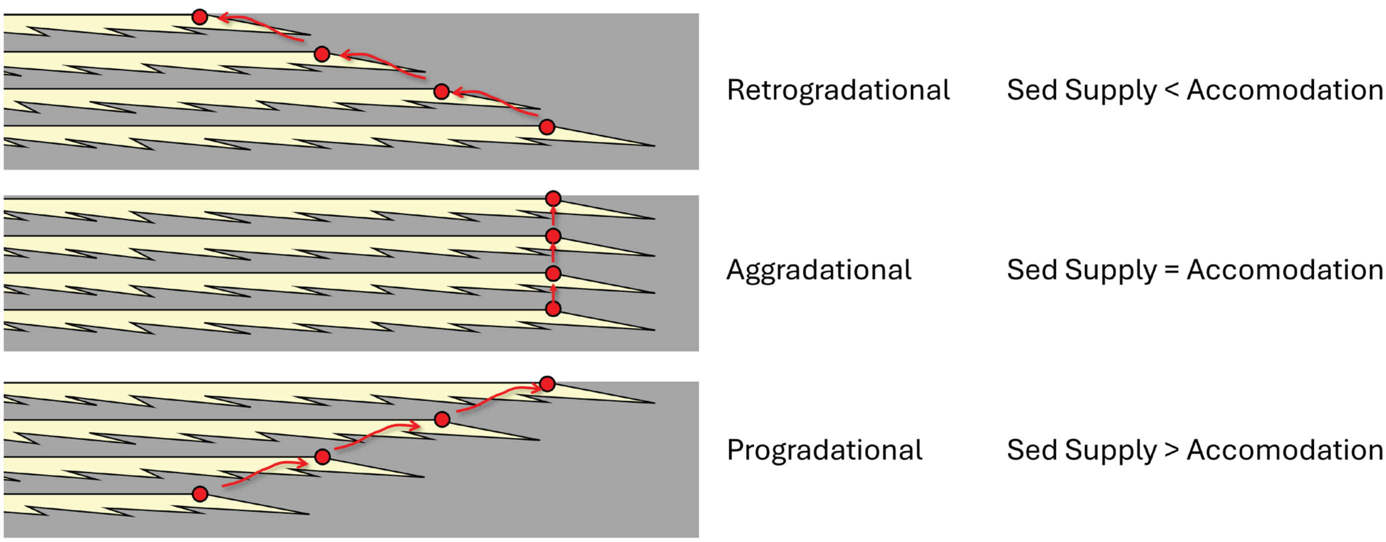

Figure 9. Three different parasequence and sequence stacking patterns. Red dots and arrows depict successive positions of the basinward limit of shoreline progradation. The paths defined by the arrows are analogous to the shoreline trajectories of Figure 6.

Figure 10. Outcrop examples of Point Lookout sandstones gradationally overlying the Mancos Shale. This type of conformable stratigraphic succession is produced by shoreface progradation. A: Entrance to Mancos Canyon, southwest Colorado. B: West of El Vado Reservoir in north-central New Mexico. Locations of both outcrops shown on Figure 1.

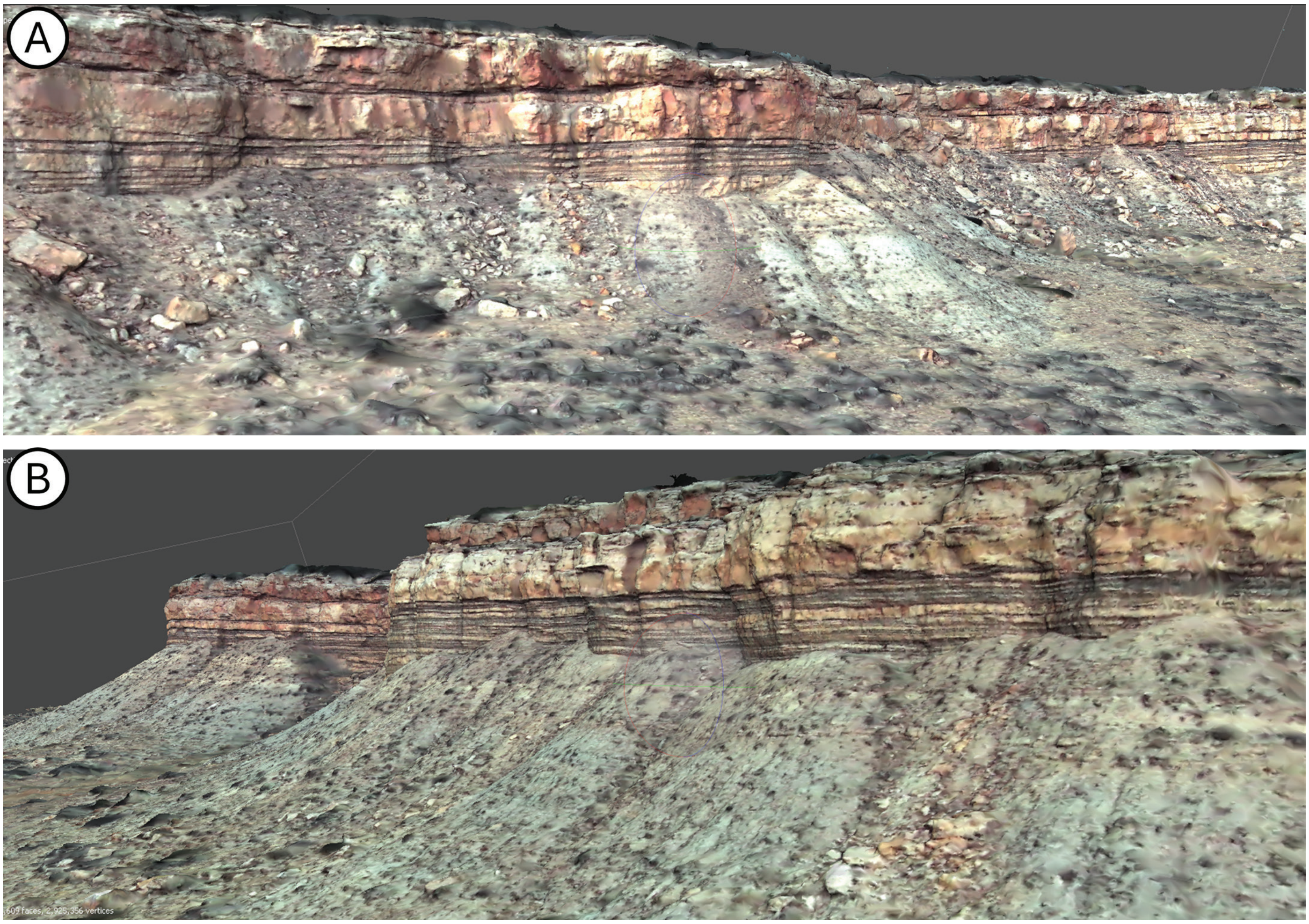

Figure 11. Two views of a drone-based 3D outcrop model showing a transitional facies of interbedded sandstones and shales beneath the thick Point Lookout Sandstone at the top of the cliff. Outcrop exposure is approximately 30 m high. Outcrop location shown on Figure 1.

transgression was rapid (Fig. 6A). Alternatively, it can be very thick if aggradation stacked multiple smaller transgressive-regressive cycles (Figs. 6A and 9). The La Ventana Tongue of the Cliff House (Fig. 3) is a thick, vertically stacked succession of shallow-marine sandstones (Fig. 19).

The Cliff House interfingers with the Lewis Shale (Fig. 3) because of the juxtaposition of short- and long-term transgressive regressive cycles, as suggested by Hollenshead and Pritchard (1961; Fig. 6A). In outcrop, the contact can appear sharp, but locally a transitional "fade-away" succession (parasequences becoming thinner and shalier upward) is present between the Cliff House and the overlying (and generally poorly exposed) Lewis Shale (Fig. 20).

THE MESAVERDE PETROLEUM SYSTEM

As noted in the introduction, the Mesaverde Group has been a significant source of natural gas in the San Juan Basin. Source rocks include some contribution from the Mancos and Lewis shales, but also a significant contribution from coals and carbonaceous deposits in the Menefee (e.g., Rice, 1983; Ridgely et al., 2013). Because current regulations permit comingling of gas production from the Mesaverde with production from other intervals (e.g., Dakota and overlying Pictured Cliffs), it is now problematic to define geologic controls on gas production from the Mesaverde alone. The best representation of that relationship is based on work by Whitehead (1993) who mapped average gas production per section (1 square mile) for the Mesaverde prior to the initiation of comingling. His work (Fig. 21) clearly established that thickness trends of the Point Lookout and Cliff House formations, defined by lateral and vertical movements of the shoreline (Fig. 6), controlled production. In essence, the thicker the sandstones, the greater the gas storage and the better the production from this basin-centered accumulation. Channels in the Menefee produce gas, but they are too randomly distributed to affect the trends shown in Figure 21.

SUMMARY

The Campanian Mesaverde Group forms a southwestward-thickening clastic wedge in the San Juan Basin. Outcrops of broadly time-equivalent rocks to the north (e.g., in the Book Cliffs of Utah) have been used to teach and develop sequence stratigraphic concepts for decades but exposures of the Mesaverde Group in New Mexico have been less frequently studied. Those New Mexico outcrops, and their subsurface continuation,

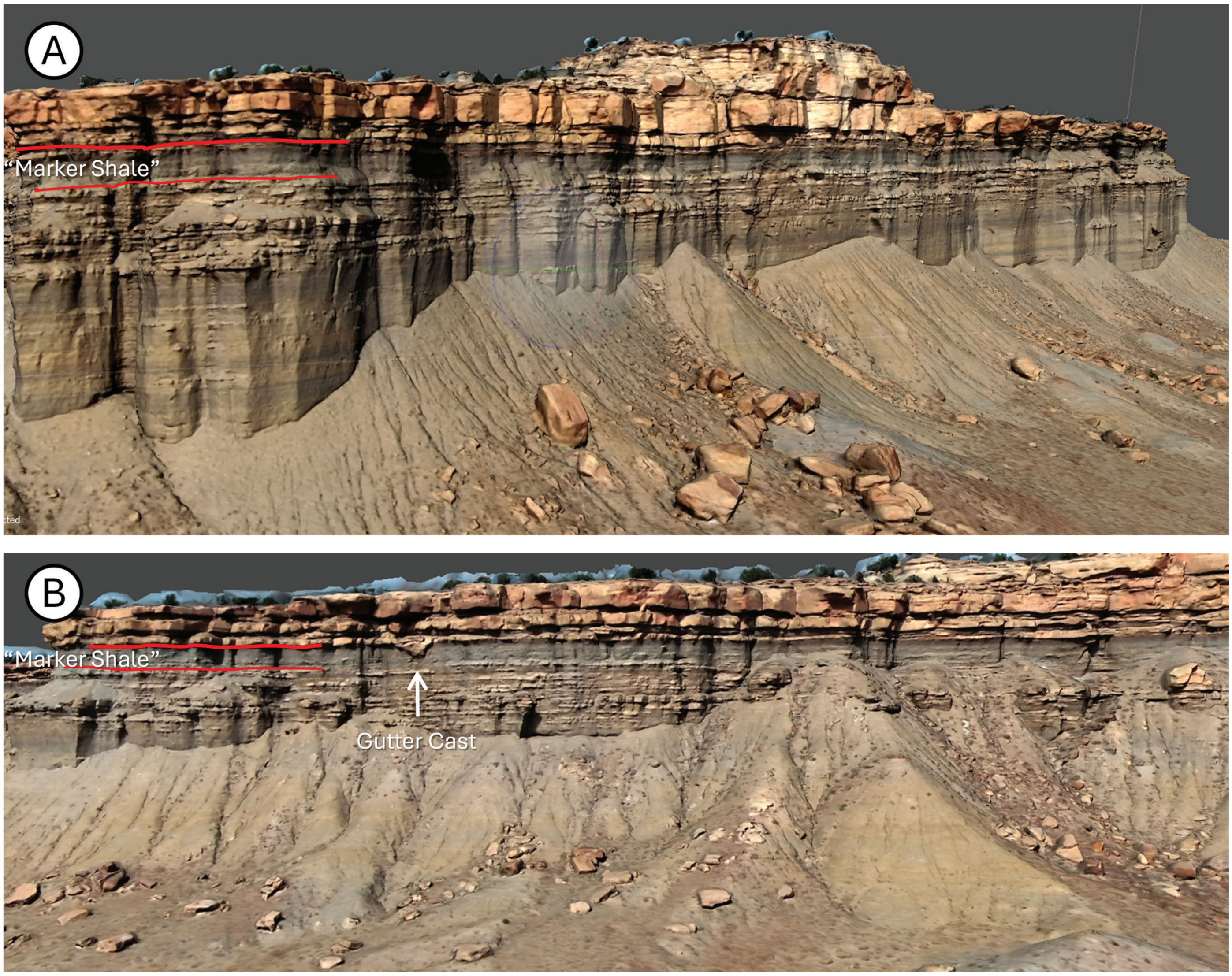

Figure 12. A stratigraphic succession indicating forced regression. Two views of a drone-based 3D outcrop model of the Point Lookout Sandstone and underlying Mancos Shale at Bosque Grande Mesa, NM. The "Marker Shale" is approximately 3.5 m thick and was deposited in an offshore setting. Shoreface sandstones of the Point Lookout (top of the cliff) abruptly overlie the Marker Shale and transitional facies are largely absent. Note gutter cast at the base of the Point Lookout in the lower image. See Koning (2024) for a more complete description of this outcrop.

Figure 13. Outcrop of the Mesaverde Group at the Hogback monocline north of U.S. Route 64 (approximate location shown in Fig. 1). Students (lower left) sit on the top of the Point Lookout. That formation is sharply overlain (right) by a heterolithic succession of nonmarine deposits. Ridge line at upper right formed by the Cliff House.

helped geologists define relationships among sedimentation, subsidence, and shoreline movements several decades before sequence stratigraphy became an established discipline.

The stratigraphic architecture of the Point Lookout, Menefee, and Cliff House formations needs to be understood in terms of the original depositional environments and how those environments shifted during regressions and transgressions of varying superimposed temporal durations. Shoreline sandbodies of the Point Lookout and Cliff House prograded, aggraded vertically, or were pushed landward depending on the interplay of sediment supply and the rate at which accommodation was generated through subsidence and eustatic fluctuations. Coastal plain deposits of the Menefee and offshore marine deposits of the Mancos and Lewis shales simultaneously shifted laterally and stacked vertically in response to shoreline movements. Accordingly, depositional timelines cross lithologic boundaries in those units with, for example, portions of the Menefee, Point Lookout, and Mancos Shale having been deposited simultaneously. The existence of these relationships was established over 80 years ago by San Juan Basin geologists.

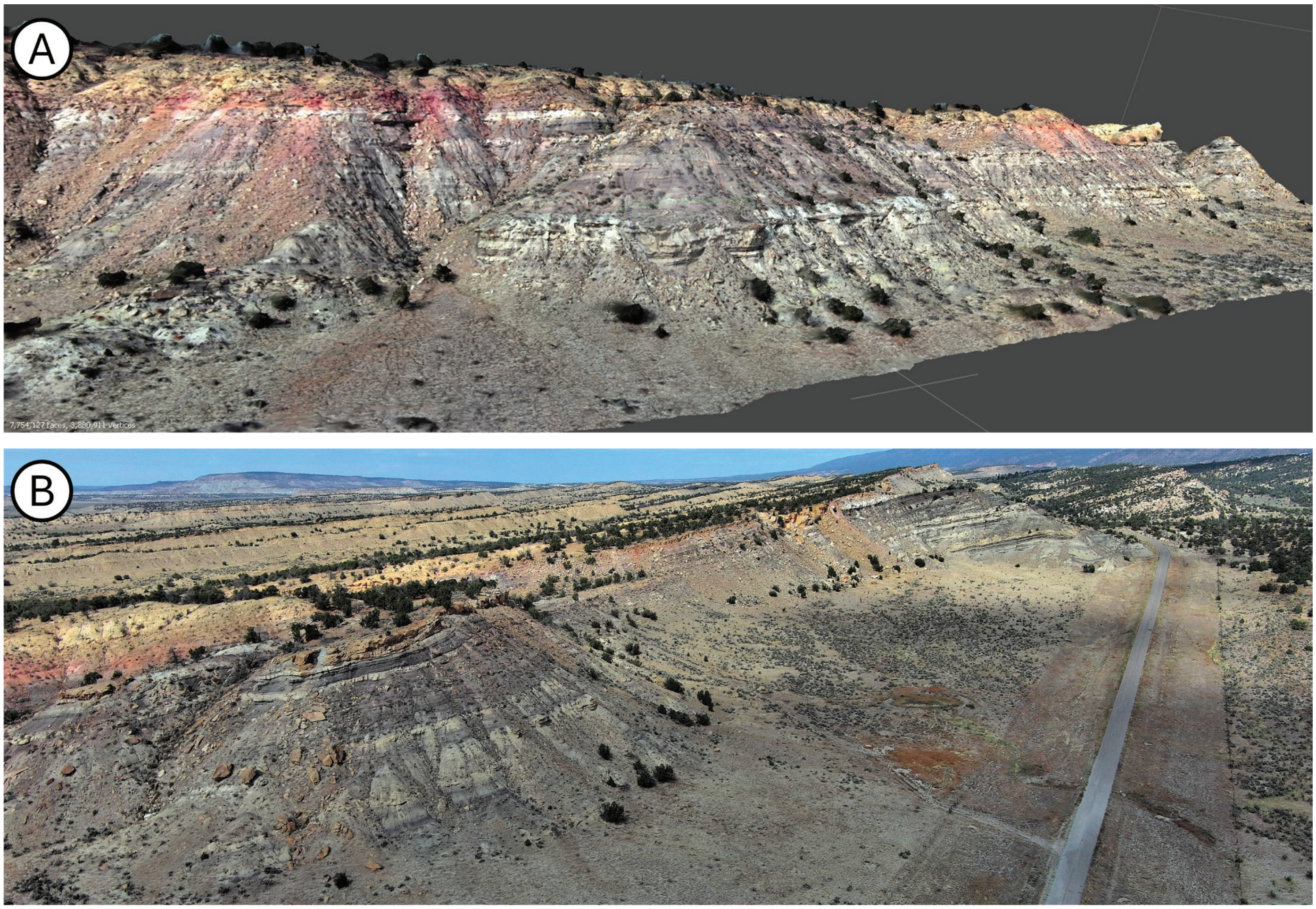

Figure 14. Aerial view of two Menefee outcrops along the Old State Road 44, south of Cuba, NM (location shown in Fig. 1). A: Drone-based 3D outcrop model of fine-grained deposits with few thin channel sandstones. Red-colored horizon at top of cliff is likely to be a paleosol horizon developed under well-drained conditions. B: Drone photo showing light gray mudstones interbedded with darker carbonaceous intervals.

Figure 15. Lateral accretion surfaces formed by point-bar migration a sandy fluvial channel in the Menefee Formation near La Ventana, NM (location shown in Fig. 1).

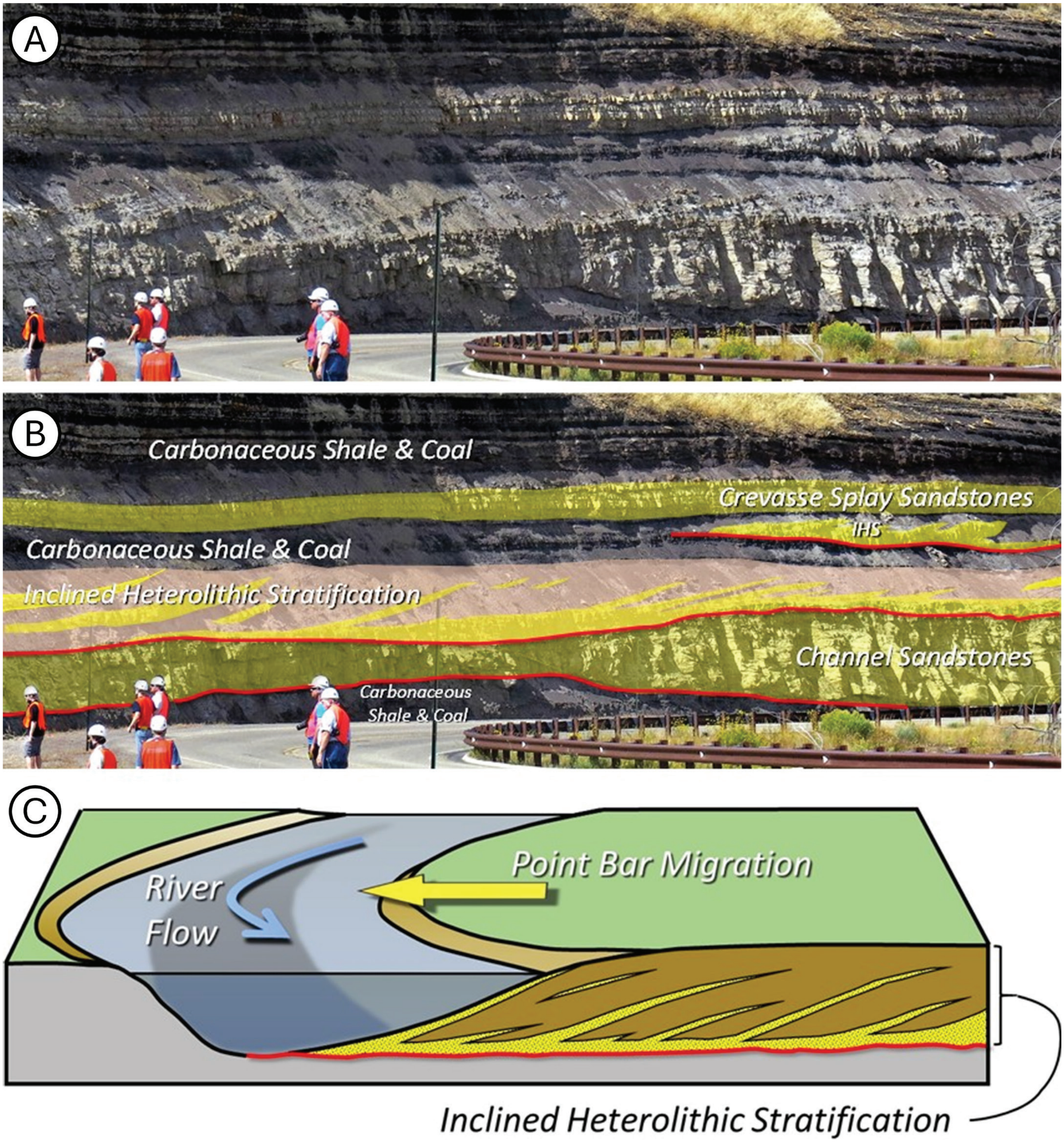

Figure 16. Heterolithic channel fill and associated floodplain deposits in the Menefee Formation near Point Lookout, CO (location shown in Fig. 1). A: Outcrop photo. B: Photo with annotation. Yellow: sandstone beds. Note dipping inclined heterolithic stratification (point bar deposits). C: Block diagram illustrating how inclined heterolithic stratification forms in response to point-bar migration.

Figure 17. Thick shallow-marine sandstones of the Cliff House sharply overlie nonmarine deposits of the Menefee at this location in Mancos Canyon, CO (location shown in Fig. 1). A dm-scale coal bed directly underlies the Cliff House at this location. People circled (red) for scale.

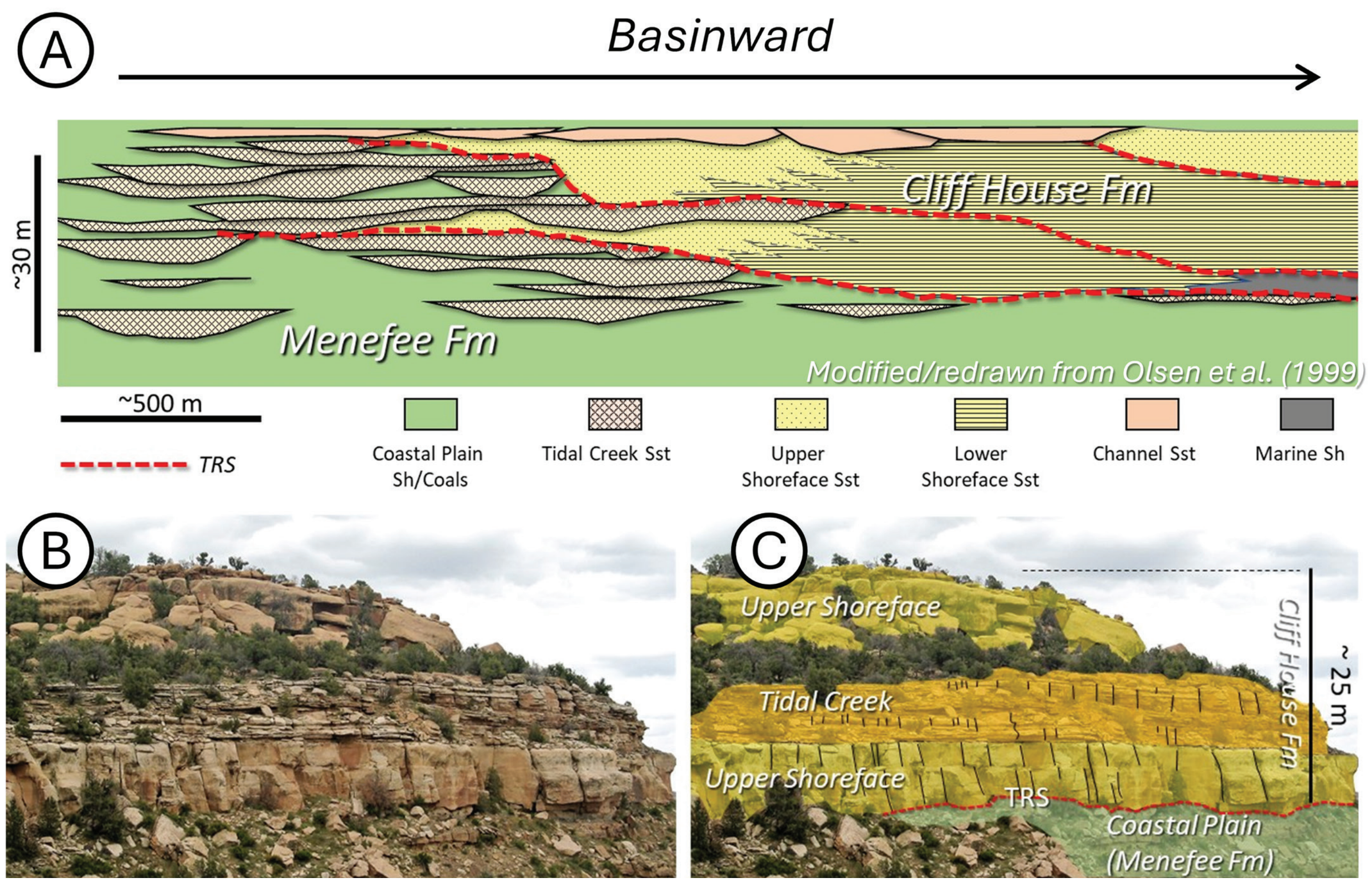

Figure 18. A: Stratigraphic heterogeneity associated with interfingering of Menefee and Cliff House deposits in Mancos Canyon (location shown in Fig. 1). Redrawn and simplified from Olsen et al. (1999). B: Outcrop of the Cliff House overlying the Menefee at Mancos Canyon. C: Annotated interpretation of the outcrop shown in B. Note differences in natural fracture development by facies in the Cliff House. Modified from Hart and Cooper (2021).

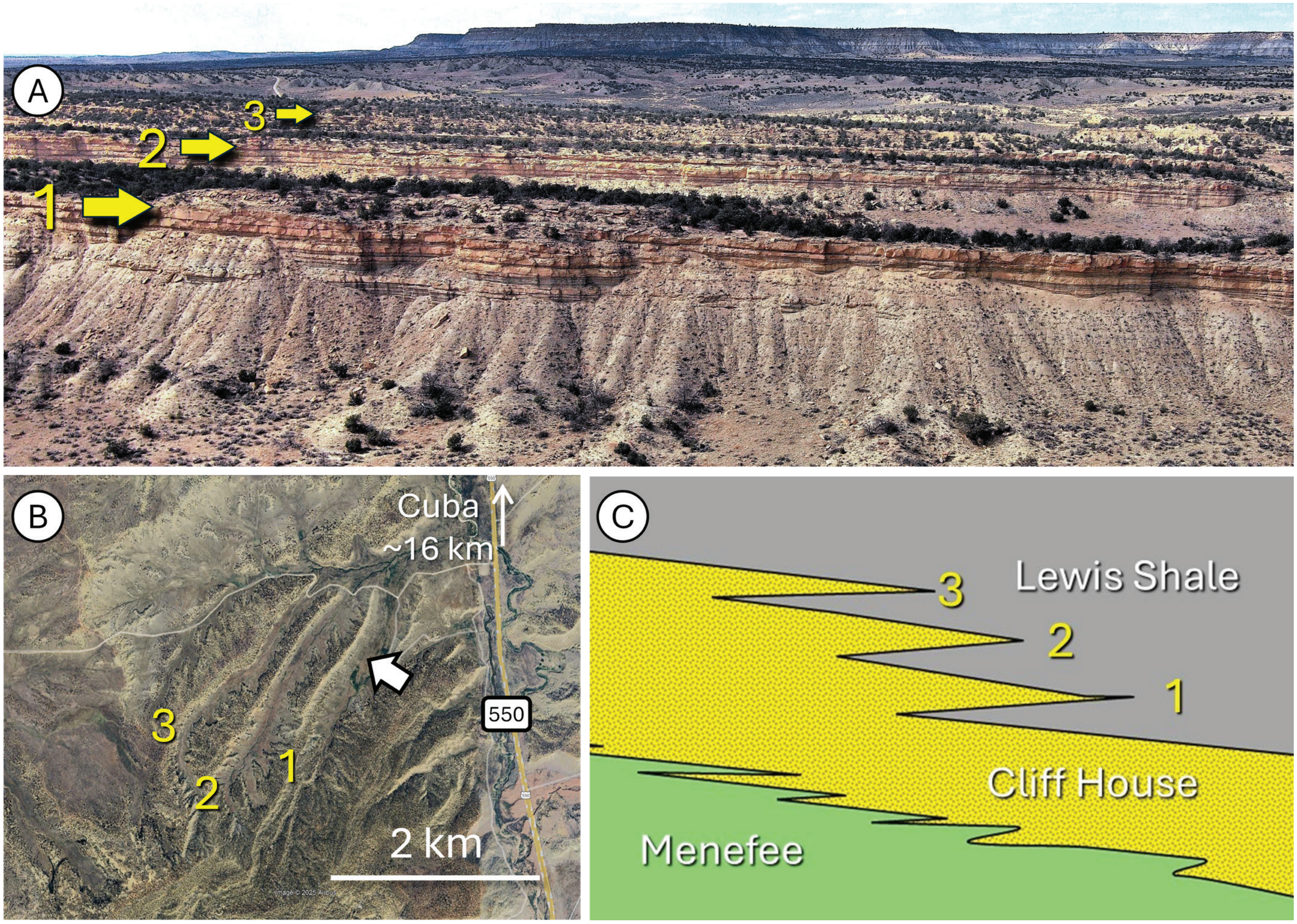

Figure 19. The La Ventana Tongue of the Cliff House represents an aggradational stacking of short-term transgressive-regressive cycles. A: Drone-based outcrop photo of three Cliff House "benches" (location shown in Fig. 1). B: Satellite view of the area highlighting the three ridges shown in A. C: Schematic representation of three stacked Cliff House sandstones (yellow) such as seen in the outcrop image.

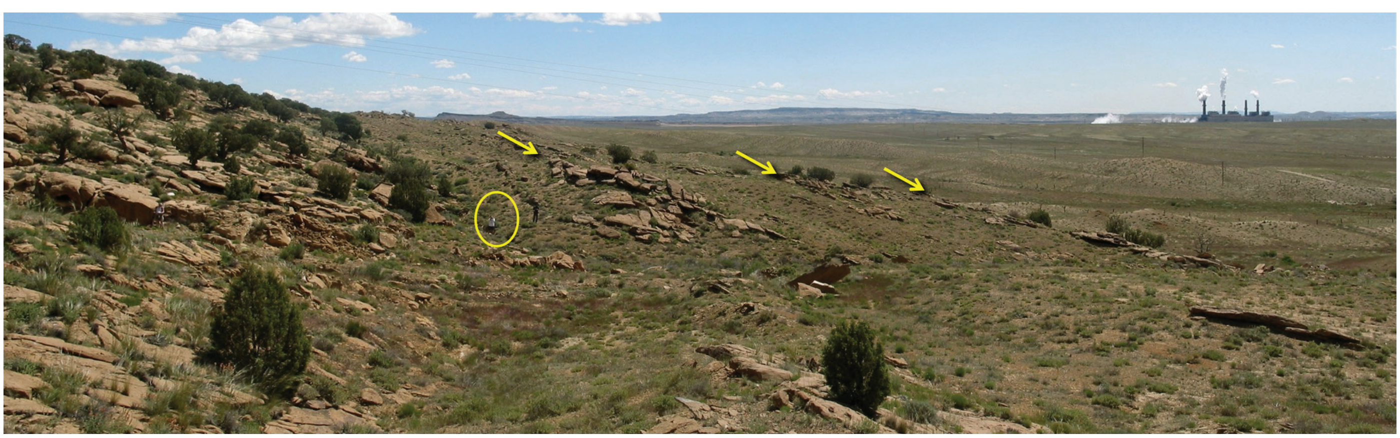

Figure 20. Retrogradational parasequence stacking at the contact between the resistant Cliff House (left) and the poorly exposed Lewis Shale (right) at the Hogback monocline (location shown in Fig. 1). Arrows point to thin sandstones capping parasequences, each of which becomes thinner and shalier upward. This type of succession indicates a retrogradational stacking pattern (Fig. 9).

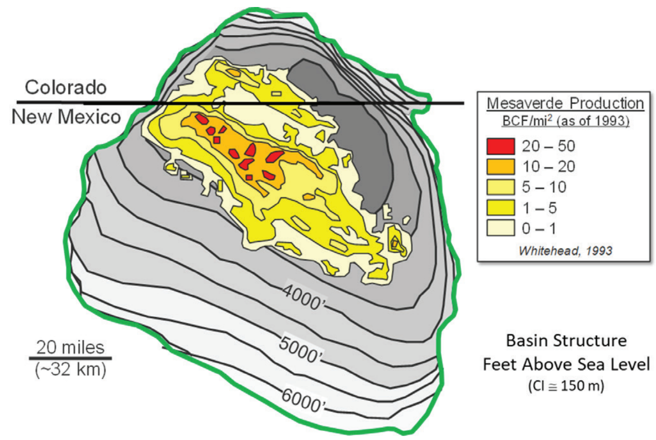

Figure 21. Average gas production (billion cubic feet/mi^2) from the Mesaverde Group as of 1993 superimposed on a structure map of the Pictured Cliffs Formation. Note the NW–SE production trends that correspond to the thickest portions of the Point Lookout and Cliff House sandstones; i.e., shoreline trends. Production contours drawn based on data compiled and presented by Whitehead (1993).

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