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# REVISED STRATIGRAPHIC RELATIONSHIPS OF THE DAKOTA GROUP IN THE TUCUMCARI BASIN, SAN MIGUEL COUNTY, NEW MEXICO, USA

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ABSTRACT — Recent stratigraphic studies in Colorado and northeastern New Mexico have provided a new detailed understanding of large-scale transgressive-regressive cycles in the Dakota Group, and their spatio-temporal impact on sediment distribution. In this region, the Dakota Group consists of the Mesa Rica Sandstone, Pajarito Formation, and Romeroville Sandstone, and the latest published stratigraphic framework has provided a further subdivision of the Mesa Rica Sandstone. Early studies established stratigraphic relationships of Jurassic to Lower Cretaceous strata at the northwestern rim of the Tucumcari Basin, in northeastern New Mexico (San Miguel County, USA). In order to apply the most recent stratigraphic framework, this area has been revisited. Six sedimentary logs and aerial imagery allow for analyses of facies association distribution, depositional architecture, and spatial extent of stratigraphic surfaces. These were then correlated to previously published log data to establish an integrated correlation panel, which stretches ~16 km along depositional dip and contains two main sandstone successions. The lower succession (6–10 m thick) is continuous throughout the study area and changes from fluvial to shallow-marine strata in a depositional down-dip direction. The upper succession (up to 6 m thick) is characterized by a discontinuous distribution of fluvial strata. Key stratal surfaces are correlated to the latest sequence stratigraphic framework and the two sandstone successions are identified as the lower and upper Mesa Rica Sandstone. This provides an update to previous interpretations, in which the Mesa Rica Sandstone was not subdivided and locally identified as the Pajarito Formation. Petrographic results reveal a high kaolin content, which is attributed to meteoric water diagenesis related to restricted accommodation at time of deposition. The Mesa Rica Sandstone units.

#### INTRODUCTION

Erosion of the Sevier Orogenic belt sourced several widespread river systems that transported sediment 100s of kilometers towards the north, east, southeast and southwest into the Western US continental interior (e.g., Turner and Peterson, 2004). Resulting deposits include the Upper Jurassic to Cretaceous sedimentary succession in Colorado, Oklahoma and New Mexico (e.g., Holbrook and Wright Dunbar, 1992; Scott et al., 2004). As part of this, the Cenomanian Dakota Group is subdivided into Mesa Rica Sandstone, Pajarito Formation, and Romeroville Sandstone in this region (Fig. 1A; Holbrook et al, 1987; Lucas and Kisucky, 1988; Holbrook and Wright Dunbar, 1992). Scott et al. (2004) divided the Mesa Rica Sandstone into three informal members (lower, middle, and upper Mesa Rica Sandstone) that are linked to higher order relative sea-level changes and are mappable in the Oklahoma panhandle and nearby outcrops in New Mexico. Holbrook et al. (1987) documented stratigraphic relationships at the Jurassic-Cretaceous boundary in east-central New Mexico. Subsequently, a transgression-related paralic middle Mesa Rica Sandstone was recognized (Scott et al., 2004). In this study, we present new data from northeastern New Mexico, collected between 2016 and 2018, and combine it with previous works. The key objectives for this paper are: i) to characterize and correlate key stratal surfaces between new and previously published stratigraphic data, ii) to apply the latest revised regional sequence stratigraphic framework (Scott et al., 2004) to the established correlation, and iii) to document petrographic characteristics of the Mesa Rica Sandstone.

# GEOLOGICAL SETTING

The study area is located at the northwestern rim of the Tucumcari Basin (northeastern New Mexico, Fig. 1A), which formed during the late Carboniferous and early Permian as a tectonic element of the Ancestral Rocky Mountains (Broadhead, 2004). The Sevier and Mogollon highlands form the main provenance area for the fluvial strata of the Jurassic Morrison Formation (e.g., Turner and Peterson, 2004). The Cretaceous Dakota Group sandstones contain different petrographic assemblages in the eastern and western interior, which suggest a source from pre-Cretaceous Cordilleran strata for the Dakota Group in the study area (Holbrook and Dunbar, 1992; Holbrook, 1996; MacKenzie and Poole, 1962; Scott et al., 2004). The Cordilleran orogeny resulted from back-arc compression in Late Jurassic, caused by subduction of the Farallon plate beneath the west coast of North America (DeCelles, 2004). Franklin and Tieh (1988) suggested a multicyclic origin for Dakota Group sediment, including eroded detritus from the underlying Morrison Formation. Other works also suggest that minor sediment volumes were sourced from local topographic highs (Kisucky, 1987; Holbrook and Wright Dunbar, 1992).

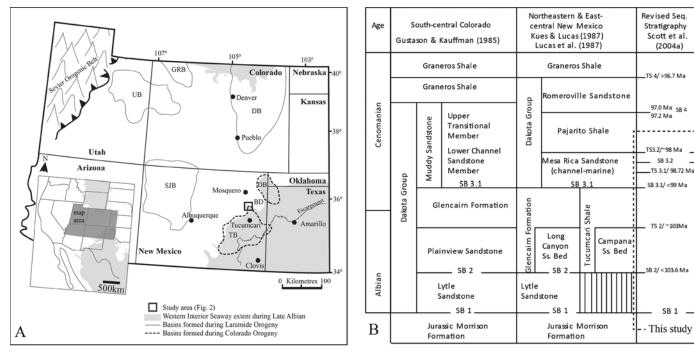


FIGURE 1. A) Map of the Western Interior during the Early–Late Cretaceous (Albian–Cenomanian) showing the approximate location of the Western Interior Seaway extent (light gray) and main basins that formed during Laramide and Colorado Orogeny (modified after Van Yperen et al., in press). GRB = Green River Basin; UB= Uinta Basin; DB (Colorado) = Denver Basin; SJB = San Juan Basin, TB = Tucumcari Basin; DB (New Mexico) = Dalhart Basin; BD = Bravo Dome; B) Stratigraphic column for the Aptian to Cenomanian succession in south-central Colorado and Northeastern and East-central New Mexico (modified after Oboh-Ikuenobe et al., 2008). Albian-Cenomanian boundary from Scott et al. (2018). SB = sequence boundary, TS = transgressive surface.

## STRATIGRAPHIC FRAMEWORK

In the Tucumcari Basin, the open marine Cretaceous Tucumcari Shale separates the fluvial Jurassic Morrison Formation from the fluvio-deltaic, Cretaceous Dakota Group (Fig. 1B; e.g., Holbrook and Dunbar, 1992; Scott et al., 2004; Van Yperen et al., *in press*). The Tucumcari Shale is locally underlain by estuarine deposits of the informally-defined Cretaceous Campana Sandstone Bed (hereafter referred to as "Campana"; Holbrook et al., 1987; Holbrook and Wright Dunbar, 1992). These represent the sandy infill of local topographic lows, as the Late Jurassic landscape was inundated during relative sea-level rise (Holbrook et al., 1987).

An overall NW to SSE-directed depositional profile characterizes the sandstone and mudstone successions of the Dakota Group in southeastern Colorado and northeastern New Mexico. Three depositional transgression-regression (T-R) cycles record high-frequency relative sea-level fluctuations in the Western Interior Seaway (e.g., Holbrook and Wright Dunbar, 1992; Holbrook, 1996; Scott et al., 2004; Oboh-Ikuenobe et al., 2008). Late Albian–Early Cenomanian forced-regression caused widespread erosion and resulted in a regional sequence boundary (SB3.1, Fig. 1B), forming the basal surface of the Mesa Rica Sandstone (e.g., Holbrook and Wright Dunbar, 1992; Holbrook, 1996; Scott et al., 2004; Oboh-Ikuenobe et al., 2008). A following transgression (TS3.1) and regression (SB3.2) form the basis for the informal division of lower (fluvial, 8–12 m thick), middle (paralic, 3–4 m thick) and upper (fluvial, 1–7 m thick) members of the Mesa Rica Sandstone (Scott et al., 2004; Holbrook et al., 2006). The next transgression (TS3.2) resulted in brief connection of the southern Tethyan and northern Boreal seas (Oboh-Ikuenobe et al., 2008). This led to deposition of the paralic Pajarito Formation in New Mexico (Lucas and Kisucky, 1988), and the equivalent Dry Creek Canyon Formation in Colorado (Holbrook et al., 2006). Subsequent forced regression generated another sequence boundary (SB4) and caused deposition of the fluvial Romeroville Sandstone. Open marine and minor intervening coastal deposits of the Graneros Shale lapped onto the Romeroville Sandstone, reflecting a subsequent stable marine connection between northern Boreal and southern Tethyan seas (e.g., Oboh-Ikuenobe et al., 2008).

#### **METHODS**

Six sedimentary logs were measured at 1:100 cm scale within a 40 km² study area (log 1-6; Fig. 2). Sedimentary facies analysis was mainly based on lithology, structures, bioturbation assemblage and intensity. The latter was recorded using the 1–6 bioturbation index (BI) scheme of Taylor and Goldring (1993). UAV (unmanned aerial vehicle) imagery (taken with Phantom 4 Pro), photomontages, and field sketches were used to map sedimentary body geometries, lateral distributions, and extent of key stratigraphic surfaces. Facies associations were established from common facies assemblages in this dataset and matched with data (log A-D; Fig. 2) from previous work (Holbrook et al., 1987) to establish a depositional-dip oriented correlation panel.

Five samples from the Cenomanian Mesa Rica Sandstone and Jurassic Morrison Formation were selected for a prelimi-

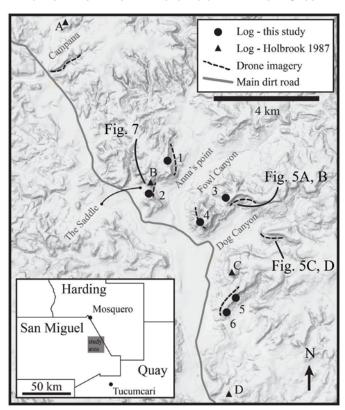


FIGURE 2. Map of study area showing locations of newly collected data (log 1-6) and previously published data (log A, B, C, D correspond to log Campana, Alamosa Canyon, Steve Trigg Windmill #1, Atarque, respectively, in Holbrook et al., 1987). Inset map shows counties and study area location.

nary petrographic investigation. They were powdered for X-ray diffraction (XRD) optical microscopy at the Department of Geosciences, University of Oslo (Norway). Consolidated sandstone samples were crushed in a mortar and later milled in a McCrone micronizer for 12 minutes, using 3 g of sample material liquidized in 9 ml ethanol. Each dried sample was loaded into a sample holder ensuring random particle orientation. A D8 Bruker Powder X-ray diffractometer collected data from 2 to 65°2θ with a step size of 0.01° and a count time of 0.3 seconds per step. Relative quantification of mineral phases from X-ray diffraction data was modelled and analyzed using Rietveld refinement through the software BGMN-Profex. We used a JEOL JSM-6460LV scanning electron microscope equipped with LINK INCA Energy 300 (EDS) and a standard Wolfram filament of 15 kV from Oxford Instruments to conduct scanning electron microscopy (SEM) on one Mesa Rica Sandstone sample.

#### FACIES ASSOCIATIONS

Five facies associations (Fig. 3, Table 1) are described, interpreted and ascribed to specific depositional environments, based on the combination of dominant sedimentary processes (facies), bioturbation intensity, and partly on lateral and vertical stacking relationships.

# FA1 - Prodelta deposits

**Description** — FA1 consists of gray, structureless muddy siltstone, with varying amounts of subordinate mudstone. Bioturbation indices (BI) are high (4–5), with *Thalassinoides*, *Phycosiphon*, *Planolites*, *Teichichnus*, *Chondrites*, and *Helminthopsis* (Fig. 3A). Macro-fauna were not observed. FA1 (max. 1.8 m thick) is sharply overlain by delta-front deposits (FA2) and pinches out in the northwest of the study area (log A).

Interpretation — FA1 represents deposition below fair-weather wave base in a low-energy setting, at the most distal influence of a river effluent (e.g., Wright and Coleman, 1973; Gani et al., 2009). The stratigraphic position of FA1 is associated, farther downstream, with the open marine Tucumcari Shale, which contains abundant macro-fauna (e.g., Texigryphaea, Peilina levicostata) within the Tucumcari Basin (e.g., Scott, 1974; Holbrook and Wright Dunbar, 1992; Oboh-Ikuenobe et al., 2008). In the study area, a shallower setting for FA1 is indicated by the thin and silty appearance and lack of macro-fauna (e.g., Kisucky, 1987; Holbrook et al., 1987; Holbrook and Wright Dunbar, 1992; Holbrook and White, 1998). The trace fossil assemblage indicates brackish to normal marine conditions (MacEachern and Bann, 2008).

# FA2 – Delta front deposits

**Description** — A sharp tabular nature characterizes thin to thick (5-50 cm), very fine- to fine-grained sandstone beds of FA2 (Fig. 3B). Beds are structureless near the base of FA2 and progressively are more planar- and tangential cross-stratified upwards, with local pebbly sandstones and a lesser degree of a sharp basal contact. In places, interbedded ripple-laminated siltstone to very fine-grained sandstone, with common asymmetrical (current) and sparse symmetrical (wave) ripple lamination occur. Soft sediment deformation is common. Matrix- to clast-supported conglomerates occur in the southern part of the study area, and consist of poorly to moderately sorted sub-angular to sub-rounded clasts (average diameter 0.5-2 cm, outliers 4-6 cm). Sparse stringers of extrabasinal clasts are common. The bioturbation index varies (BI 0-4) and is characterized by a non-uniform but upwards-decreasing trend in the amount of bioturbation. Trace fossils include Ophiomorpha, Thalassinoides, Conichnus, Palaeophycus, Macaronichnus, Teichichnus, and Rosellia (Fig. 3C). Thick (0.3–2 m), thoroughly bioturbated (BI 5-6) sandstone beds with sharp bed boundaries are common at the base, and rare at the top of FA2. Bedsets form a continuous sheet (6–8 m thick) throughout the study area, except in the northwest. Locally, sandstone beds are arranged in low-angle accretionary strata, mainly dipping basinwards (SW to SE).

Interpretation — FA2 is associated with river-dominated deposition at the delta front, with episodic discharge events, inferred from the alternation of upper and lower flow regime bedforms, and the non-uniform bioturbation index. The latter is indicative of fluctuating colonization windows, which relates to variable frequencies and magnitude of depositional

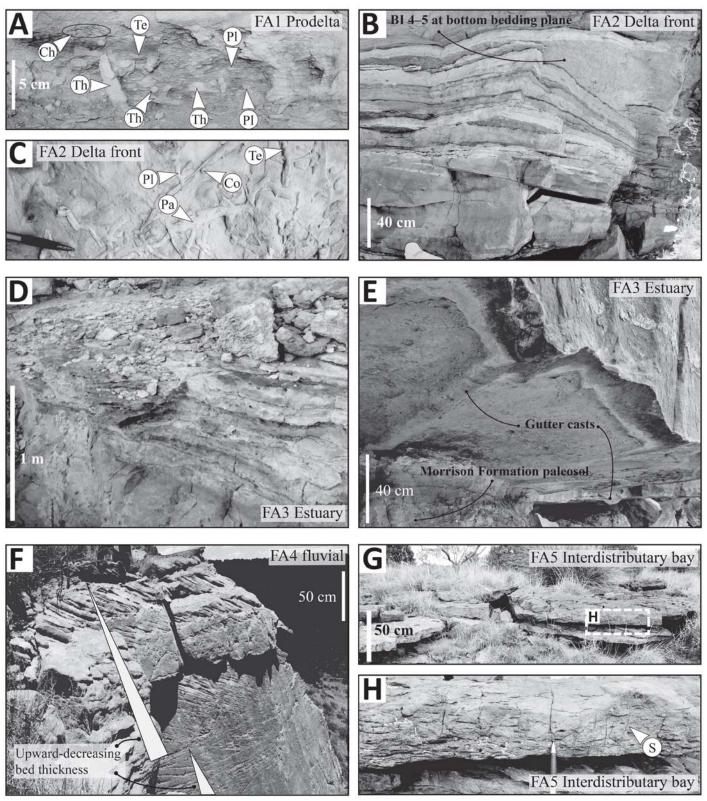


FIGURE 3. Photographs showing facies associations (Table 1) and selected ichnology. **A)** Muddy siltstone with thorough bioturbation (BI 4–5) in prodelta deposits (FA1); **B)** Tabular and sharp-bedded fine-grained sandstone beds in delta front deposits (FA2). Bioturbation index (BI) is non-uniform and especially bottom bedding planes are thoroughly bioturbated (BI 4–5); **C)** Basal surface of sharp-based fine-grained sandstone with moderate to high bioturbation (BI 4) in delta front deposits (FA2); **D)** Fining-upward, thoroughly bioturbated (BI 5–6) sandstone beds in estuary deposits (FA3); **E)** Gutter casts eroded into fine-grained Morrison Formation sediment with high degree of pedogenic modification. Infill of gutter casts with estuary deposits (FA3); **F)** Sets of tabular cross-stratified sandstone beds, in fluvial strata (FA4). Triangles indicate upward-decreasing bed thickness; **G)** Sharp-based, structureless and internally ripple-laminated sandstone beds with bioturbation (BI 0–3) in lower delta plain deposits (FA5). Dashed square shows location of figure 3H; **H)** Skolithos bioturbation (BI 3) in sharp-based, internally rippled, very fine-grained sandstone bed, in lower delta plain deposits (FA5). Te = Teichichnus, Pl = Planolites, Ch = Chondrites, Th = Thalassionoides, Pa = Palaeophycus, S = Skolithos. 15-cm pencil for scale.

TABLE 1. Summary of facies assocations in Late Jurassic and Lower Cretaceous strata in the study area.

Facies Association & Interpretation	Description	Geometry and dimensions	Lateral and vertical relationships	Biogenic structures	Formation
FA1 Prodelta	Structureless, gray muddy siltstone. Mudstone content varies locally.	Continuously present throughout study area but pinches out towards the northwest. 0–1.8 m thick.	Sharply overlain by FA2.	BI 4–6: Phycosiphon, Thalassionoides, Planolites, Teichichnus, Chondrites, Helminthopsis	Tucumcari Shale
FA2 Delta front	Structureless, parallel-laminated, planar- and tangential cross-stratified, very fine- to fine-grained sandstone beds (5–50 cm). Locally interbedded with asymmetrical and symmetrical ripple lamination. Local occurence of clast stringers or matrix- to clast-supported conglomerate. Extrabasinal clasts average ø 0.5–2 cm, outliers ø 4–6 cm.*	Sheet-forming throughout study area, 6–14 m thick. Not observed in the northwest.	In erosional contact with FA4, or overlain by FA5.	Upwards decreasing BI 0–6: Thalassionoides, Conichnus, Ophiomorpha, Palaeophycus, Macaronichnus, Rosellia, Teichichnus, Diplocraterion. Top surface locally bioturbated (BI 0–5)	Mesa Rica Sandstone
FA3 Estuary	Fine-grained sandstone, primary sedimentary structures obliterated by bioturbation. In places fining-upwards to very-fine grained sandstone beds (5–20 cm). Where not bioturbated: parallel-laminated, planar- and tangential cross-stratification.	Localized throughout study area, 2–7 m thick.	Onlaps and incises into FA4, overlain by FA1.	BI 0–1 or BI 5–6: Thalassionoides, Ophiomorpha	Campana Ss. Bed
FA4 Fluvial	Parallel-laminated, planar-, tangential-, and trough-cross-stratified, very fine-to fine-to-medium-grained sandstone beds (5–70 cm). Locally, wood debris and mud rip-up clasts. Colored motling overprints top interval in places. Locally bioturbated top surface.	Single- or 2-story, bound by erosional concave- upward surfaces. 1–8 m thick.	Erodes into FA2 or FA5.	BI 0–2, top surface: Skolithos	Mesa Rica Sandstone Morrison Formation
FA5 Interdistributary bay	Gray-brown muddy siltstone with locally very fine-to fine-grained, sharp-based and ripple-topped sandstone beds (0.1–0.3 m thick), interbedded with ripple-laminated siltstone. Sandstone beds are predominantly structureless, locally cross-stratified.	Sheet sandstones, traceable for 100–200 m. Total thickness max. 1.5 m.	Overlais FA2.	BI 0–3: Skolithos, Arenicolites, Phycodes	Mesa Rica Sandstone

<sup>\*</sup>BI = Bioturbation Index (Taylor and Goldring 1993)

events (e.g., Gani et al., 2009). The upward-decreasing bioturbation index and upward-increasing pebble content indicate increasing energy conditions due to river mouth proximity (e.g., MacEachern and Bann, 2008; Bhattacharya, 2010). The laterally-extensive nature, low-angle accretion architectures, lack of channel-shaped scours, and the local near-absence of trace fossils, indicate axial and proximal mouth bar deposition. The thick, intensely bioturbated sandstone beds (BI 4–6) suggest a minimum of fresh-water induced stresses (e.g., MacEachern and Bann, 2008). These beds are found both at the base and top of the FA2 interval, and may reflect distal delta-front deposition or early delta lobe abandonment, respectively.

# FA3 – Estuary deposits

**Description** — FA3 consists of fine-grained sandstone with a high bioturbation index (BI 5–6, *Thalassinoides, Ophiomorpha*) that obliterates primary structures and bed boundaries. Parallel lamination, tabular and trough cross-stratification, and scour surfaces are discernible where bioturbation shows an upward-increasing trend (BI 0–6). FA3 fines upward to very fine-grained sandstone beds (5–20 cm) with interbedded siltstone in places (Fig. 3D). Dispersed quartz- and chert-dominated extrabasinal clasts (diameter <3 cm) are common. Extrabasinal clasts and mud rip-ups occur locally in lags (subangular-subrounded, diameter 2–4 cm) near the base (log B) and within the

<sup>\*</sup> ø = clast diameter

lower 1.5 m (logs B, 6). These are overlain by a thin (~5 cm) siltstone package. Gutter casts are sparsely present at the base (Fig. 3E). FA3 beds have limited lateral extent (max. 1 km) and they are commonly overlain by prodelta deposits (FA1). Bioturbated FA3 (2–4 m thick) onlaps onto fluvial strata (FA4, Morrison Formation), whereas the basal surface of non-bioturbated FA3 (6–7 m thick) is erosional.

Interpretation — FA3 is interpreted as estuarine deposits based on localized occurrence, marine influence and bioturbation (upward-increasing), and stratigraphic position below prodelta deposits (FA1; e.g., Holbrook et al., 1987). FA3 sediment infills scours that indicate originally-channelized flow conditions. These erosive currents also formed the gutter casts (e.g., Myrow, 1992), which were subsequently infilled. The high bioturbation index is indicative of conditions favoring trace makers such as wave-agitation (e.g., MacEachern and Bann, 2008). The stratigraphic position of FA3 relates to the Campana (Holbrook et al., 1987).

# FA4 - Fluvial deposits

**Description** — FA4 is characterized by 40–300 m wide, 1–8 m thick sandstone bodies composed of very fine- to medium-grained sandstone beds (5–70 cm thick), with parallel lamination and tabular and trough cross-stratification. Upward-thinning occurs locally (Fig. 3F). Erosional flat- and concave-upward surfaces, in places lined with wood debris and muddy rip-up clasts, bound one- or two-story channel-bodies. Varicolored mottling overprints the uppermost interval in places. Laterally continuous deposits of the Morrison Formation also fit with this facies association, but they are commonly whiter.

Interpretation — FA4 deposition resulted from the migration of two-dimensional and three-dimensional subaqueous dunes and ripples within subaqueous channels, and the formation of parallel laminations in upper flow regime conditions (e.g., Flemming, 2000). The absence of bioturbation, marine indicators, and mud-drapes suggests deposition by fully fluvial currents and the varicolored mottling indicates temporary subaerial exposure.

# FA5 – Interdistributary bay deposits

**Description** — FA5 deposits are predominantly composed of gray-brown muddy siltstone. They alternate with subordinate very fine- to fine-grained, sharp-based sandstone beds (0.1–0.3 m thick), with asymmetrically rippled bed tops, and are traceable for 100–200 m. Sandstone beds are generally structureless with rare cross stratification, and interbedded with rippled siltstone (Figs. 3G, H). Synerisis cracks are present and trace fossils (BI 0–3) include *Skolithos, Arenicolites*, and *Phycodes* (Fig. 3H). Isolated sandstone bodies of FA4 (fluvial) are embedded within FA5.

Interpretation — FA5 represents lower-delta-plain to interdistributary-bay deposits, based on its close relation to FA4 (fluvial) and absence of coal. The thin-bedded sheet-sandstone deposits represent crevasse-splays or overbank-flow deposits and the trace fossils assemblage indicates short-lived marine

incursions. The siltstone yields rare dinoflagellates and abundant spores and pollen (Oboh-Ikuenobe et al., 2008), which supports the interpretation of brackish conditions.

#### **PETROGRAPHY**

XRD results show extreme mineralogical maturity with variations in kaolin content in the sandstone samples (Fig. 4A). The Jurassic Morrison Formation contains the highest kaolin concentrations (15%). The Cenomanian Mesa Rica Sandstone has a 2–13% kaolin content in FA4 (fluvial), and 11% kaolin in FA2 (delta front). Quartz dominates the remaining bulk samples. In FA4 deposits, kaolin is distributed as patchy coatings around detrital quartz grains and as pore-fill trapped between framework grains (Fig. 4B). The most common grain contact is long. Quartz overgrowths were detected in the presence of dust rims and from sharp grain edges in backscatter SEM micrographs (Fig. 4C). Cement surfaces are clean and un-corroded, indicating an authigenic origin.

#### **FACIES DISTRIBUTION**

Campana estuarine deposits (FA3) unconformably overlie Morrison Formation fluvial strata (Figs. 5, 6) and represent the transgressive infill of topographic lows (Holbrook et al., 1987). The overlying prodelta deposits (FA1) of the Tucumcari Shale are present throughout the study area, except in the northwest (log A; Fig. 6), and separate Jurassic Morrison strata from Cenomanian Mesa Rica Sandstone deposits. This northwest pinch-out of FA1 is consistent with the inferred position of the upstream boundary of the Tucumcari Basin, and represents a close relationship between basin configuration and open-marine sediment deposition (e.g., Kisucky, 1987; Holbrook and Wright Dunbar, 1992; Holbrook and White, 1998). The overlying deposits consist of two main sandstone units (Figs. 5, 6); Succession 1 (S1) forms a continuous sandstone sheet (6–10 m thick) throughout the study area, whereas Succession 2 (S2) is discontinuous (0-6 m thick) and embedded within interdistributary fines (FA5).

S1 consists of laterally-extensive delta-front deposits (FA2), except in the NW corner of the study area, where fluvial strata (FA4) persist (log A; Fig. 6). The sheet-like nature of the delta-front deposits is interpreted to result from successive coalescence of mouth bars in low-accommodation conditions (e.g., Olariu and Bhattacharya, 2006; Van Yperen et al., in press). The change from fluvial to deltaic strata reflects the most proximal shallow-marine deposition within the Mesa Rica Sandstone, which took place at the rim of the Tucumcari Basin. S1.1 thickens down-dip, reflecting a basinward increase in accommodation. Succession S1.2 comprises laterally-discontinuous fluvial distributary channels (FA4) and sand- and mud-dominated interdistributary deposits (FA5; Figs. 5, 6). This represents a dynamic lower and upper-delta-plain setting, in which sedimentary patterns relate to the laterally varying influence of river and marine processes.

S2 consists of isolated composite fluvial bodies (FA4; Figs. 5C, D, 6), which amalgamate to form multilateral single or

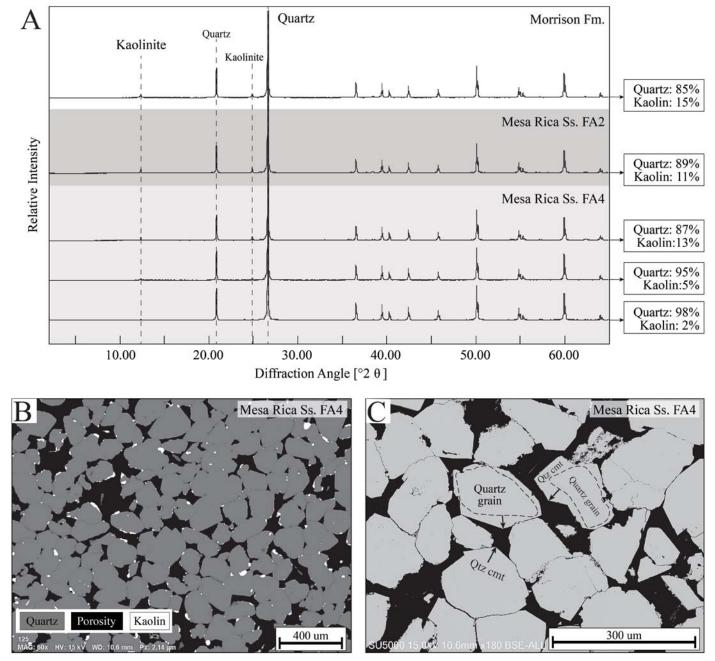


FIGURE 4. Petrography investigations show compositional maturity in both the Morrison Formation and Mesa Rica Sandstone. A) Quartz with varying kaolin concentrations were detected in the studied XRD diffractograms; B) SEM elemental phase maps show that quartz constitutes the dominant framework grain component, while kaolin is distributed as patchy grain coatings and occasional pore fill; C) Authigenic quartz overgrowths are detected by the presence of dust rims (dashed lines) and sharp grain edges (arrows). Long grain contacts are the result of in-situ cementation.

double stories. The isolated nature of these fluvial bodies suggests a higher A: S ratio (i.e., more accommodation or less sediment supply) than during S1 deposition.

# KEY STRATIGRAPHIC SURFACES

The basal surface of the Mesa Rica Sandstone is taken as a datum for correlation, as it highlights both the relief on the Campana and the upstream pinch out of the Tucumcari Shale (Fig. 6). The lithostratigraphic contact between the Mesa Rica Sandstone and Tucumcari Shale appears to have low diachroneity because it is nearly parallel to both the base of the Tucumcari Shale and top of the Mesa Rica Sandstone. The SB3.1 regional sequence boundary is placed as the basal surface of the fluvial Mesa Rica Sandstone further upstream (e.g., Holbrook and Wright Dunbar, 1992; Holbrook, 1996; Scott et al., 2004). However, the surface below the deltaic Mesa Rica Sandstone, in the study area, could represent a sequence boundary or a facies boundary (e.g., Bhattacharya et al., 2011) but further discussion is beyond the scope of this paper. The

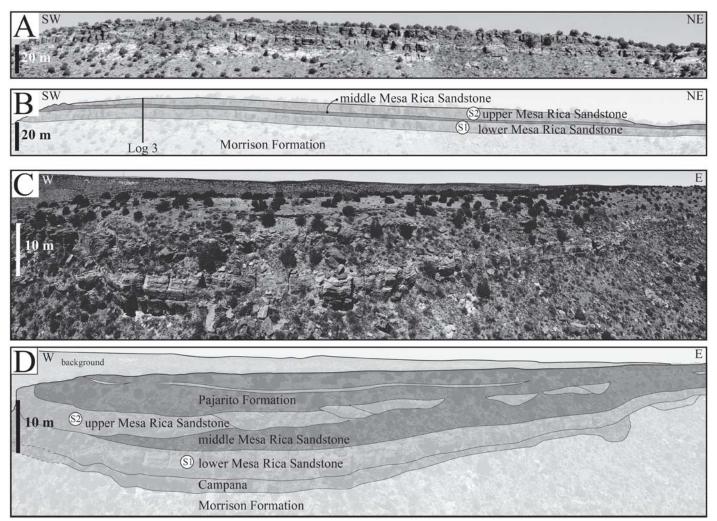


FIGURE 5. Pictures and corresponding schematic diagrams showing expressions of the S1 and S2 successions. A) Drone image showing S1 and S2 in Dog Canyon (location in Fig. 2); **B)** Diagrammatic section showing interpretation of A with log location indicated. S1 is continuous whereas S2 has a limited lateral extent; **C)** Drone image showing S1 and S2 in Dog Canyon (location in Fig. 2); **D)** Diagrammatic section showing interpretation of C. Note how S1 forms a continuous sheet, whereas S2 is discontinuous. Interdistributary bay deposits (FA5) of the Pajarito Formation are present. An irregular basal surface characterizes the Campana.

basal surface of the Campana (SB1-2-TS2) marks an abrupt facies shift from the underlying fluvial Morrison Formation to overlying estuarine (FA3) conditions. The Campana basal surface reflects onset of regional transgression, hence placement of TS2 at its base (Fig. 6). This makes the base of the Campana a combined surface, because the contact with the underlying Morrison Formation (Fig. 1B) also includes SB1 and SB2 (e.g., Holbrook and Wright Dunbar 1992). A low-energy infill of topographic lows is suggested by the onlapping relationship with the older Morrison Formation (Holbrook et al., 1987). Gutter casts can be interpreted to record erosion by rivers that deposited the Morrison Formation, with subsequent infill by Campana deposits. This would imply a break in time between formation and filling of the casts during the Jurassic and late Albian, respectively. However, although no tide-influenced Campana deposits have been documented, gutter cast formation and the local erosional contact between the Morrison Formation and Campana (log B, 2, 4) may also result from tidal

scouring. This process could be associated with the Campana transgression, and would offer an alternative hypothesis to the origin and infill of these gutter casts.

The top surface of the lower Mesa Rica Sandstone (S1, Figs. 6, 7C) is characterized by low (BI 0-2, *Skolithos, Ophiomorpha*) to intense (BI 5–6) bioturbation. It separates regressive strata below from overlying transgressive deposits and delineates a progradational to retrogradational stacking pattern, being therefore interpreted to represent a regional transgressive surface (TS3.1, Fig. 6). In the south, the top surface of S1.1 exhibits marine trace fossils and is interpreted as an internal flooding surface (FS, Fig. 6). The non-regional expression of this flooding surface is ascribed to autogenic processes intrinsic to the evolution and lateral variability of deltaic depositional systems (e.g., Amarosi et al., 2005; Olariu, 2014). This implies that the overlying S1.2 succession may represent reoccupation of the area after delta lobe abandonment, and the final regressive phase before a regional flooding (TS3.1, Fig.

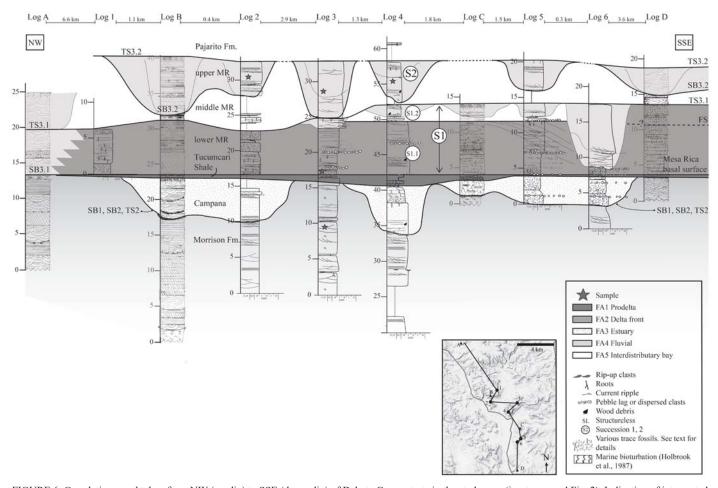


FIGURE 6. Correlation panel taken from NW (up-dip) to SSE (down-dip) of Dakota Group strata in the study area (inset map and Fig. 2). Indication of interpreted facies associations and key stratigraphic surfaces based on newly collected data (log 1-6) and previously published data (log A, B, C, D, in Holbrook et al., 1987). Base of the Mesa Rica Sandstone is used as datum. Note the continuous (S1) versus discontinuous nature (S2) of the main packages. Basinward-dipping (S) low-angle accretionary strata is present locally. MR = Mesa Rica Sandstone; TS = transgressive surface; FS = flooding surface; SB = sequence boundary

6). Above this, low bioturbation (BI 0–2, *Skolithos*) characterizes the top surface of S2 and is also interpreted as a regional transgressive surface (TS3.2, Fig. 6).

# DISCUSSION Provenance and burial diagenesis of the Mesa Rica Sandstone

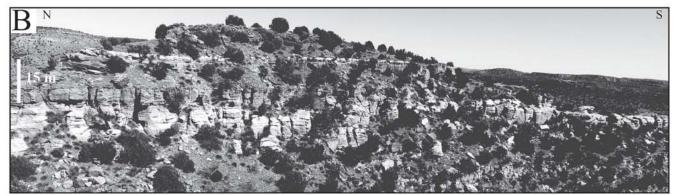
The Mesa Rica Sandstone mineral suite resembles that of the "western suite" after MacKenzie and Poole (1962), previously interpreted to originate from erosion of older sedimentary rocks (Franklin and Tieh, 1988). This accounts for the extreme mineralogical maturity documented in this study. Our analyses yield no significant petrographic distinction between the Jurassic Morrison Formation and the Cenomanian Mesa Rica Sandstone, which does not negate prior assertions of recycling of Jurassic detritus. A comparison of geochronological provenance data from both sandstones would further test this hypothesis.

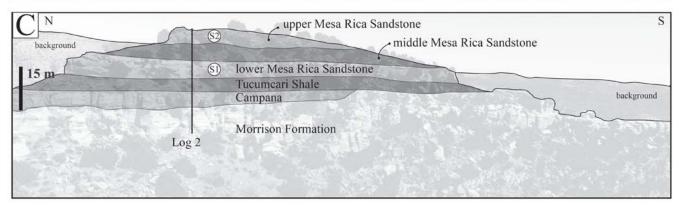
High kaolin contents (>10%) in the Morrison Formation and parts of the Mesa Rica Sandstone (Fig. 4A) could be attributed to meteoric water diagenesis related to the restricted accommodation at time of deposition. Deltaic and fluvial sediments are typi-

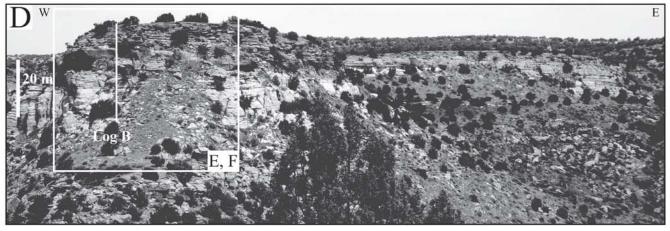
cally exposed to meteoric flushing because the sand bodies serve as groundwater aquifers (Bjørlykke, 2014). Extensive leaching of detrital feldspar and mica grains requires high groundwater recharge over long time periods (Bjørlykke and Aagaard, 1992). Such conditions are commonly inversely related to sedimentation rates, but low-accommodation settings limit burial depth and retain the available sediment in the leaching zone. However, the 13% kaolin in the Mesa Rica Sandstone (Fig. 4A) could originate from the reworking of the underlying Morrison Formation as well. SEM analyses of the kaolin crystal habit are required to further identify the origin of the kaolin material.

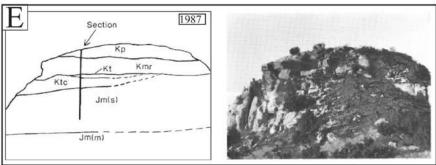
Quartz overgrowths detected in FA4 (fluvial) demonstrate that temperature-dependent diagenetic reactions have occurred in the Mesa Rica Sandstone. Sharp edges and un-corroded cement surfaces suggest that overgrowths formed in-situ. At temperatures exceeding 70°C, smectite-to-illite reactions precipitate excess silica as quartz cement (e.g., Walderhaug, 1994), implying that the Dakota Group experienced burial where temperatures exceeded 70°C. However, due to the unknown geothermal history of the basin, burial depth estimates of 1500–4000 meters are only approximate.

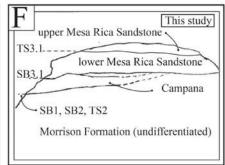












## Revision of Dakota Group stratigraphy

Latest insights into regional stratigraphy identified three transgressive surfaces within the Dakota Group (Fig. 1A); top lower Mesa Rica Sandstone (TS3.1), top upper Mesa Rica Sandstone (TS3.2) and the marine flooding related to deposition of the Graneros Shale (TS4; Scott et al., 2004; Oboh-Ikuenobe et al., 2008). These regionally-extensive transgressive surfaces are linked to changes in relative sea-level (Oboh-Ikuenobe et al., 2008). However, correlation shows that preservation of surfaces varies significantly throughout the study area (Fig. 6), which cautions against (sequence) stratigraphic interpretations based only on few data points. Prominent flooding surfaces TS3.1 and TS3.2 cap successions S1 and S2, respectively, and represent the down-dip extent of the transgressive surfaces mapped in the Oklahoma Panhandle and nearby outcrops in New Mexico (Scott et al., 2004). This implies that the lower continuous deltaic sandstone sheet (S1), the overlying lower-delta-plain / interdistributary deposits, and the discontinuous fluvial strata (S2) represent the lower, middle, and upper Mesa Rica Sandstone, respectively (Figs. 5, 7). Above S2, interdistributary-bay deposits were only recorded in log 4 (Fig. 6) and they correlate to the paralic Pajarito Formation (e.g., Holbrook and Wright Dunbar, 1992).

The results of this study show that the fluvial upper Mesa Rica Sandstone is mappable farther down-dip (Figs. 5, 7) than previously documented (Scott et al., 2004). This also contradicts Holbrook et al. (2006), who stated that the upper Mesa Rica Sandstone transitions from fluvial to marine, south of the Oklahoma Panhandle. Dobrovolny et al. (1946) named the Mesa Rica Sandstone, and Lucas and Kisucky (1988) defined type sections of both the Mesa Rica Sandstone and Pajarito Formation, ~40 km down-dip of the study area. Although some of their logs show potential for further subdivision of the Mesa Rica Sandstone, the package identified as Mesa Rica Sandstone could locally relate to the lower Mesa Rica Sandstone only. In that case, the lower part of the overlying Pajarito Formation would form the down-dip and paralic equivalent of the upper Mesa Rica Sandstone, as present in northeastern New Mexico and the Oklahoma Panhandle (Scott et al., 2004). Recent work by the present authors suggests that the upper Mesa Rica Sandstone extends down-dip into central-east New Mexico (Van Yperen et al., in press). Thus, the new interpretation of the Dakota Group in the study area differs from the interpretation by Holbrook et al. (1987), who based their correlation on a stratigraphic framework without subdividing the Mesa Rica Sandstone internally (Figs. 7E, F). The new

understanding of the local stratigraphy results in the identification of the middle and upper Mesa Rica in the study area and a 4–6 m thicker total Mesa Rica Sandstone than shown in previous models.

Finally, the 6–10 m thick lower Mesa Rica Sandstone recorded in the study area is thin compared to both its equivalent upstream fluvial (10–15 m, e.g., Holbrook et al., 2006) and downstream fully deltaic strata (12–20 m, Van Yperen et al., *in press*). This is consistent with deposition at the basin margin, close to base level, with vertical limits on aggradation and incision (e.g., Holbrook et al., 2006).

## **CONCLUSIONS**

Two main sandstone packages characterize the Dakota Group in the study area (San Miguel County, New Mexico); a continuous sandstone sheet (S1) consisting predominantly of delta-front deposits, and a discontinuous sheet (S2) consisting of fluvial strata. These correlate to the lower and upper Mesa Rica Sandstone, based on the revised established correlation panel, in which new and previously published data were integrated. This provides an update to previous interpretations in the study area, in which the Mesa Rica Sandstone was not subdivided internally and locally interpreted as the Pajarito Formation. Isolated occurrences of the estuarine Campana Sandstone Bed are more common than previously recognized. Their varying thickness and local erosive base possibly resulted from tidal-ravinement, in addition to the low-energy infill of topographic lows. The position of the study area at the rim of the Tucumcari Basin is reflected by a significant lateral facies change from fluvial to delta-front deposits, a thin lower Mesa Rica Sandstone compared to upstream fluvial strata and downstream fully deltaic strata, and the significant thickening of the succession down-dip (towards the southeast).

The Cenomanian Mesa Rica Sandstone contains recycled detritus eroded from older sedimentary strata (Jurassic Morrison Formation), based on the extreme mineralogical maturity and dominance of stable sedimentary and metasedimentary components. The high kaolin content (>10%) may be attributed to meteoric leaching of detrital feldspars and mica resulting from deposition in a low-accommodation setting, but could originate from the reworking of the underlying Morrison Formation as well. Finally, presence of quartz overgrowths indicates that the Mesa Rica Sandstone was exposed to temperatures >70°C. Depending on the geothermal history of the basin, this temperature corresponds to burial depths between 1.5–4 km.

FIGURE 7. Sequence of pictures and schematic diagrams illustrating the revised interpretation of Cretaceous stratigraphy. A) Photopanel providing overview and location of pictures B and D, on margins of 'The Saddle' (location in Fig. 2); B) Drone image showing Jurassic and Lower Cretaceous strata; C) Diagrammatic section showing interpretation of picture B. Note localized occurrence of the Campana and the vertical arrangement of the lower, middle, and upper Mesa Rica Sandstone; D) Photopanel showing Jurassic and Lower Cretaceous strata; E) Diagrammatic section showing interpretation of picture D, modified from Holbrook et al. (1987). The depicted section corresponds to log B in this study, Kp = Pajarito Formation, Kmr = Mesa Rica Sandstone, Kt = Tucumcari Shale, Ktc = Campana Sandstone Bed, Jm(s), Jm (m) = Morrison Formation Sandstone, Mudstone; F) Photopanels showing the revised interpretation of Cretaceous stratigraphy. The Mesa Rica Sandstone is subdivided into lower and upper. TS = transgressive surface; SB = sequence boundary. Sequence stratigraphic surfaces correspond to the regional stratigraphic framework (Scott et al., 2004; Oboh-Ikuenobe et al., 2008).

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