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LACUSTRINE DEPOSITIONAL ENVIRONMENTS OF THE UPPER TRIASSIC REDONDA FORMATION, EAST-CENTRAL NEW MEXICO

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Abstract.—The Redonda Formation of the Chinle Group represents deposition in lacustrine and lake margin depositional environments during the Late Triassic (Norian-Rhaetian?) in east-central New Mexico, but not in a single, large lake. Lake margin facies in the Redonda depositional basin correspond to basement highs that delineated the Paleozoic Tucumcari structural basin, indicating that older structures influenced deposition during the Late Triassic. Paleozoic structures were either topographically high, or a reactivation of the Tucumcari basin initiated changes in drainage systems. Coarse, terrigenous sediment was deposited in Gilbert deltas where fluvial systems flowed into the Redonda depositional system along its eastern edge. Delta progradation at the northern edge of the depositional system produced delta-front sheet sands that were deposited and reworked by waves or currents. Beach environments produced carbonate mud on shallow mudflats along some shorelines, whereas sand beaches prograded at other shorelines. In the deepest lake settings, deposition inevitably gave way to shallowing, and alternations of sandstone and mudstone recorded climatically induced changes in lake level and sediment influx throughout Redonda history. Evidence of Late Triassic climatically influenced lacustrine deposition at low paleolatitudes in the Southwest corresponds to other evidence for climate control of lacustrine deposits of similar age along the present East Coast. The frequency of the response in lakes of the Redonda depositional system is consistent with the interpretation that orbital forcing of climate influenced lacustrine sedimentation over a broad region of Pangea.

INTRODUCTION

Upper Triassic strata of the Chinle Group were deposited over a vast area in the western United States that extends from Nevada to Oklahoma, and from Texas to Wyoming (Lucas, 1993). Considerable sedimentological study of the Chinle Group has been undertaken on the Colorado Plateau (e.g., Stewart et al., 1972; Blakey and Gubitosa, 1983; Blodgett, 1984; Kraus and Middleton, 1987; Dubiel, 1989; Tanner, 2000) and in West Texas (McGowan et al., 1979, 1983; Granata, 1981). However, relatively little sedimentological study of the Upper Triassic strata in east-central New Mexico, between the Colorado Plateau and West Texas, has been attempted (a notable exception is Newell, 1993). Here, we present the results of a sedimentological study (Hester, 1988) of the Redonda Formation, which is the youngest Chinle Group stratigraphic unit in east-central New Mexico. This study concludes that Redonda deposition took place in an areally extensive lacustrine system of small lakes and lake margin facies, but not in a single, large lake, as had previously been concluded.

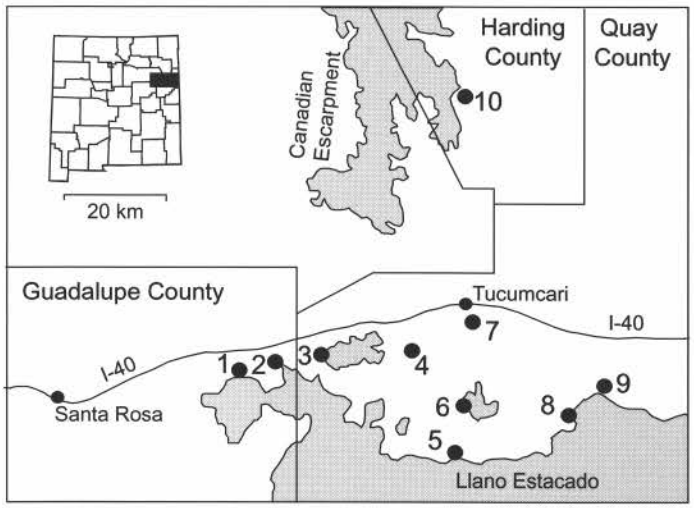


FIGURE 1. Map of part of east-central New Mexico showing location of sections of the Redonda Formation measured in this study. Sections are: 1 = Bull Canyon 1, 2 = Bull Canyon 2, 3 = Luciano Mesa, 4 = Pyramid Mountain, 5 = Ragland Hill, 6 = Mesa Redonda, 7 = Tucumcari Mountain, 8 = Apache Canyon, 9 = San Jon Hill, 10 = Gallegos.

PREVIOUS STUDIES

Dobrovolny et al. (1946) named, described and mapped the Redonda as a member of the Chinle Formation, documenting a variety of lithologies and thickness variations. From subsequent mapping (Wanek, 1962; Kelley, 1972), the Redonda is known to crop out over much of east-central New Mexico, including parts of San Miguel, Guadalupe, Quay and Harding Counties (Fig. 1). Fossils from the Redonda Formation include vertebrates, invertebrates and plants. Semionotid fishes and semiaquatic metoposaur and phytosaur fossils dominate the vertebrate fossil assemblages, and tracks represent rhynchocephalians, aetosaurs and dinosaurs (Gregory, 1972; Lucas et al., 1985; Hunt et al., 1989, 1993, 2000; Hunt, 1994; Lockley et al., 2000). Invertebrate fossils include abundant conchostracans and ostracods (Kietzke, 1987, 1989). Plant material is limited to pith casts of the calamitalean *Neocalamites* (Gregory, 1972; Lucas et al., 1985).

The tetrapod assemblage of the Redonda Formation is the basis of the Apachean land-vertebrate faunachron of Lucas and Hunt (1993), which is of late Norian and Rhaetian? age (Lucas, 1998). Magnetostratigraphy of the Redonda Formation is consistent with this age assignment, and indicates the Redonda Formation correlates to the Rock Point Formation of the Colorado Plateau (e.g., Steiner and Lucas, 2000).

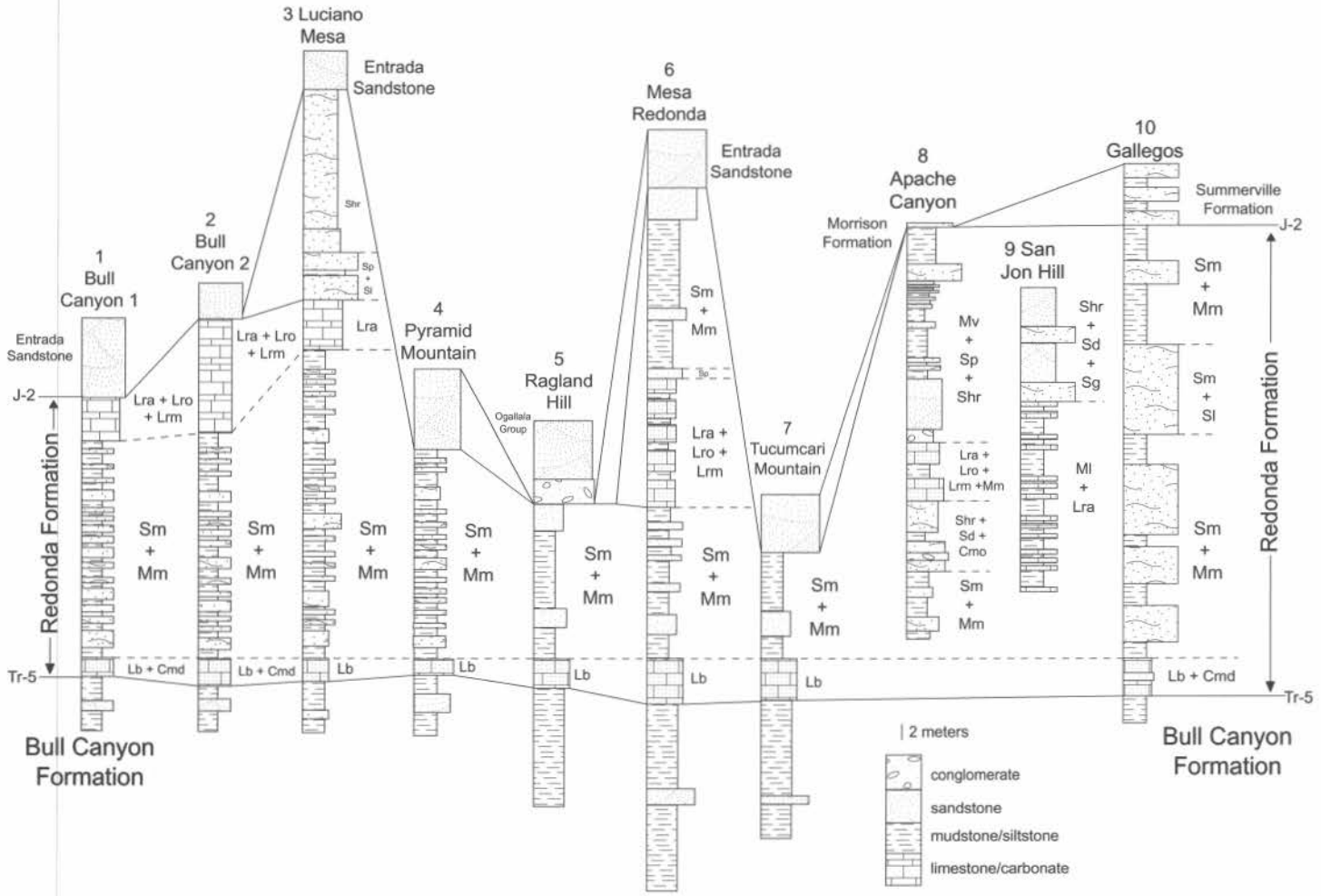


FIGURE 2. Measured stratigraphic sections and lithofacies of the Redonda Formation in east-central New Mexico. See Figure 1 for location of sections and text and Table 1 for lithofacies acronyms.

STRATIGRAPHY

The Redonda Formation is the youngest unit of the Chinle Group in east-central New Mexico, and overlies the Upper Triassic (Revueltian) Bull Canyon Formation (Lucas et al., 1985; Lucas and Hunt, 1989) (Fig. 2). In east-central New Mexico, the Bull Canyon Formation is as much as 110 m thick and is mostly grayish-red and moderate reddish-brown mudstone and lesser amounts of yellowish-gray to grayish-red, laminar to trough-crossbedded sandstone. Very minor lithologies are siltstone and intraformational conglomerate. Granata (1981) attributed both lacustrine and prodelta environments to the Bull Canyon Formation. However, the work of Newell (1993) and our own observations support a fluvial origin.

Dobrovolny et al. (1946) described the Redonda as ranging from 15 to 140 m in thickness and consisting of variegated shale, argillaceous limestone, siltstone and sandstone. Thickness of measured sections in this study ranges from 18 to 92 m (Fig. 2). Laterally continuous, interbedded fine sandstones and mudstones characterize the Redonda over most of the study area. This distinctive bedding makes the unit easily recognizable and prompted Griggs and Read (1959) to elevate the Redonda to formational rank (also see Lucas, 1993). The Redonda is unconformably overlain by Jurassic rocks (the Entrada, Summerville and Morrison formations) in nine of the ten measured sections. At one locality (Ragland Hill), the Redonda is unconformably overlain by the Neogene Ogallala Group.

The Bull Canyon/Redonda contact has been described as both unconformable (Granata, 1981; Kelley, 1972; Lucas, 1993) and conformable (Dobrovolny et al., 1946; Griggs and Read, 1959; Lucas et al., 1985). Granata (1981, p. 57) interpreted the contact as a paleosol, describing "variegated lavender and light green mudstone with possible root traces." Kelley (1972, p. 89) described fissures in the uppermost mudstone bed of the Bull Canyon Formation that are filled with Redonda sand in the upper meter of a "mottled greenish gray and lavender mudstone" and concluded that the contact is disconformable. Dobrovolny et al. (1946) defined the base of the Redonda as a variegated, purple calcareous siltstone. Lucas (1993) regarded the Redonda base as the Tr-5 unconformity correlative to the base of the Rock Point Formation on the Colorado Plateau.

We pick a distinctive pale red, laterally continuous, silty micrite as the Bull Canyon/Redonda contact in this study (Fig. 2). This unit is the variegated lavender and mottled green "mud-

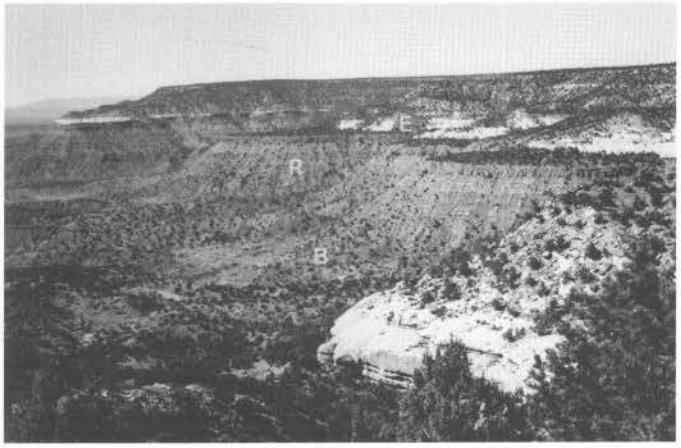


FIGURE 3. Outcrops of the Redonda Formation (R) at Bull Canyon form ribbed slopes above Bull Canyon Formation (B) mudstones and sandstones that floor the canyon and below bold, light-colored cliffs of the Entrada Sandstone (E).

stone" described by earlier workers (Dobrovolny et al., 1946; Kelley, 1972; Granata, 1981). The bed clearly marks a profound change from discontinuous, lenticular sandstones and mudstones of the Bull Canyon Formation to the distinctive, laterally continuous beds of sandstone and mudstone characteristic of the Redonda Formation (Figs. 3, 4a). Therefore, we identify the base of the Redonda Formation as a disconformity.

REDONDA LITHOFACIES

We describe Redonda lithofacies (Table 1) according to their dominant lithology—conglomerate, sandstone, carbonate and mudstone. Lithofacies were established based on grain size, sedimentary structures and ichnofossils. Because some variation in lithofacies exists between localities, the descriptions clarify the variation.

Matrix-supported Conglomerate (Facies Cm)

Poorly-sorted conglomerates contain very coarse sand-to-gravel-size clasts supported in a mud matrix. Clasts include intraformational sedimentary rock fragments of micrite and siltstone, vertebrate teeth and bone fragments, fish scales, clay rip-up clasts and conchostracan hash. We use the organization of the coarse fraction and geometry of the beds to separate matrix-supported conglomerates into two subfacies, organized (Cmo) and disorganized (Cmd) matrix-supported conglomerates.

Concentration of clasts in the middle portion of individual beds and lateral discontinuity of beds define organized matrix-supported conglomerates (Cmo). Abundant vertebrate teeth and bone hash, micrite rock fragments and clay rip-up clasts comprise the coarse fraction. Clay rip-up clasts are aligned parallel to flow. This lithofacies occurs in thin (10-50 cm thick), localized beds that taper before pinching out into mudstone within 2-3 m of outcrop. Individual beds have a low angle of depositional dip, generally 3-5°. Lower contacts are sharp, and stretched clay rip-ups occur within the basal portion of individual beds. Upper contacts rapidly grade to mudstone.

Organized conglomerates are interpreted as localized, subaqueous debris flows, though some may be subaerial alluvial fan deposits. Indeed, subaqueous and subaerial debris flows may be difficult to distinguish, but the presence of mudstone interbeds is more common in subaqueous flows (Nemac and Steel, 1984). Subaqueous debris flows characteristically concentrate coarse material in the middle of the bed, responding to shear stress along upper and lower surfaces of the flow (Middleton and Hampton, 1973). Stretched clay rip-up clasts may represent this zone of shearing. Alignment of clay rip-up clasts suggests laminar flow at the time of deposition (Fisher, 1971). Localized, subaqueous debris flows have been described from Gilbert delta fronts (e.g., Postma, 1985) and from submarine fans (Hein, 1983). The alternative hypothesis, that these organized conglomerates are alluvial fan deposits, is thus less well supported.

Poorly-sorted clasts distributed in a mud-rich matrix, and lateral continuity of beds, characterize disorganized matrix-supported conglomerates (Cmd). From visual field estimates, matrix comprises 60% to 70% of the bed, increases upward within the bed and consists of calcareous mud, terrigenous silt and clay. A trend of decreasing clast size upward is seen. This lithofacies occurs in laterally extensive beds and is not confined to a particular locality. The coarse fraction ranges from very coarse sand (Bull Canyon) to gravel (Gallegos) (Fig. 2). Clasts include micrite rock fragments and clay rip-ups. Fossil debris is not present, in contrast to organized matrix-supported conglomerates. Post-depositional burrows are abundant in Cmd lithofacies. Thickness of disorganized conglomerate beds ranges from 40 cm to 1 m. The beds are laterally extensive for hundreds of meters along outcrop. Cmd occurs in single beds or amalgamated beds, both with irregular basal contacts. Upper contacts are sharp in single beds and irregular in amalgamated units.

Poor sorting and matrix-supported clasts suggest sediment gravity flow processes (e.g., Fisher, 1971; Middleton and Hampton, 1976; Lowe, 1982). Irregular basal contacts and clay rip-up clasts suggest scouring of underlying units. However, lateral extent of the lithofacies rules out a localized process and requires a mechanism that could transport material over some distance. This lithofacies thus represents subaqueous gravity flow or cohesive debris flows that were not localized. During their development, flow was turbulent. Scouring into the underlying unit exemplifies erosion and turbulent flow. Textural inversion of a mud matrix with disseminated clasts, upward increase in matrix and presence of post-depositional bioturbation indicate a subaqueous setting (Nemac and Steel, 1985).

The disorganized fabric suggests Cmd may represent proximal flows. However, the decrease in clast size upward indicates some sorting took place. In Walker's (1979) fan model, debris flows may be associated with feeder channels, but no channels were documented in the present study. Matrix-supported conglomerates may also be associated with sublacustrine fans, where debris flows mix with lake mud and are deposited in flat-lying lobes (Nemac et al., 1984).

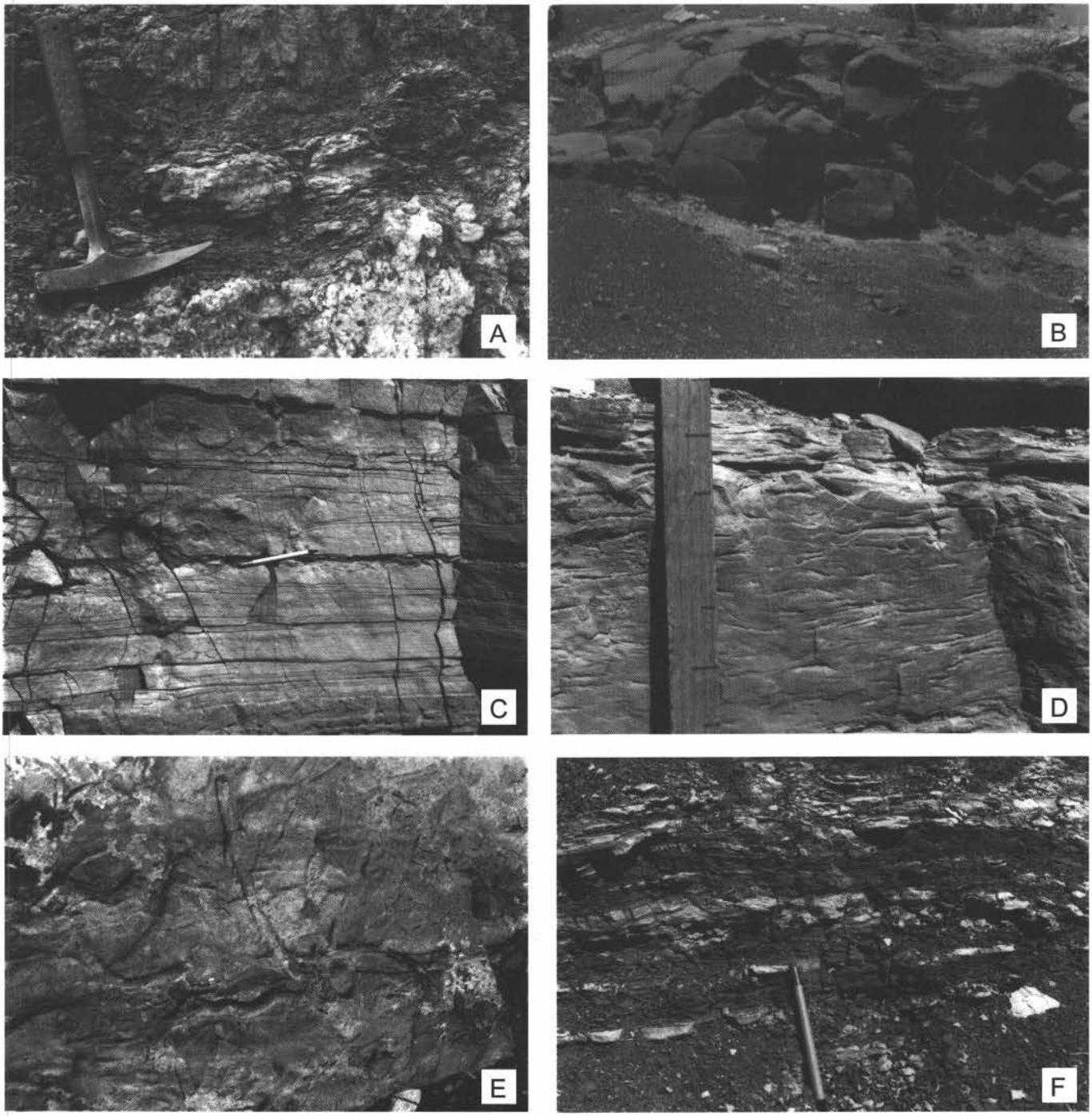


FIGURE 4. Selected examples of Redonda lithofacies. A. Basal marker bed of Redonda Formation at Mesa Redonda, lithofacies Lb. B. Lithofacies Sm at Bull Canyon. C. Lithofacies Sl at San Jon Hill. D. Lithofacies Shr at Apache Canyon. E. Lithofacies Lra at Bull Canyon. F. Lithofacies Ml at San Jon Hill.

Massive Sandstone (Facies Sm)

Massive sandstones are composed of very fine to medium, moderately sorted sand with minor amounts of coarse sand and occasional wood fragments. Vertical and sub-horizontal *Scoyenia* burrows occur throughout the otherwise structureless sandstones. Burrows contain meniscate backfill, accentuated by reduction halos along backfill and burrow walls. Intensity of bioturbation, thickness of individual sandstone beds and grain size vary by locality.

Sandstones occur as laterally continuous, 0.4-13 m thick, single bed units, although average thickness is 1.5 m. Thicker, medium-grained sandstones (Gallegos) contain fewer burrows. Some sandstone beds persist at the same stratigraphic level between localities for 24 km, attesting to their great lateral extent (Fig. 2). Indeed, persistent sandstone beds can be visually traced

TABLE 1. Redonda lithofacies.

Facies Code	Description	Geometry	Processes
Cmo	Organized, matrix-supported conglomerate; coarse fraction concentrated in center of bed; basal zone of shearing with "stretched" clay rip-ups.	Deposited in 10-50 cm thick, tapering wedges that pinch out into mudstone.	Sediment gravity flow, subaqueous debris flow.
Cmd	Disorganized, matrix-supported conglomerate; Clasts range from coarse sand to gravel; matrix increases upward in beds, comprises 60-70% of bed; post-depositional burrows.	Deposited in tabular, 0.4-1 m thick, single or amalgamated beds.	Sediment gravity flow, subaqueous, non-laminar debris flow.
Sm	Massive sandstone, very fine to medium; contains disseminated coarse sand and occasional wood; *Scoyenia* burrows; occasional sedimentary dikes. unconsolidated substrate.	Deposited in laterally continuous 0.4 to 13 m thick beds; beds continuous for km on strike.deposition on a weak,	Gravity settling of sand-sized grains ; bioturbation and sedimentation in equilibrium.
Sl	Laminated sandstone; fine, well-sorted sandstone; parallel and low-angle cross-stratification; minor ripple laminations	Laterally continuous beds from 20 to 60 cm thick.	Traction transport, high flow velocity, changing flow velocities.
Sp	Planar cross-stratified sandstone; fine to medium grained, moderately to well sorted sand; planar cross-stratification in sets from 10 to 30 cm thick. thickness 2-3.5 m.	Tabular, laterally continuous for hundreds of meters; thickness from 0.5 to 1.5 m; lenticular bodies pinch out into mudstone over 30 m;	Migration of two-dimensional mega-ripples under moderate flow velocity.
Sd	Disrupted sandstone; fine, moderately sorted sandstone; dish structures convolute bedding with parting lineations along bedding planes of exposed folds; ball-and-pillow structures rates.	Laterally discontinuous wedges; depositional dip 5-20 degrees; thickness 20-70 cm; wedges taper and pinch out into mudstone and sandstone lithofacies.	Destruction of primary bedforms by escaping pore fluid; deposition by high, unidirectional flow in beds that later slumped; deposition on weak substrate; high sedimentation
Sg	Normally graded sandstone; coarse to fine, poorly sorted sandstone; coarse tail grading; minor vertical and sub-horizontal burrows over 6 m of strike.	Laterally discontinuous wedges with depositional dip from 10 to 20 degrees; wedges range from 10 to 20 cm thick, taper and pinch out	Turbidity current deposition.
Shr	Horizontal and ripple-laminated sandstone; moderately well-sorted sandstone; asymmetrical ripples, horizontal laminations, parting lineations; climbing ripples	Laterally discontinuous wedges; thickness 20-70 cm; tabular, laterally continuous units up to 6 m thick composed of numerous, thin (5-10 cm) rippled beds; tabular, single beds are 0.1-1 m thick.	Traction transport; unidirectional high flow velocities; changing flow velocities; high sedimentation rates.
Lra	Asymmetrical, ripple-laminated micrite; calcareous mud with varying amounts of terrigenous silt and sand; wavy to lenticular bedding; ripple bedforms draped and interbedded with calcareous mud; or, ripple bedforms defined by terrigenous component of micrite; trace fossils (*Diplichnites*, *Cruziana*, *Pelecypodichnus*)	Laterally continuous for hundreds of meters along outcrop; thickness 0.1-3 m.	Precipitation of carbonate mud; occasional influx of terrigenous grains; unidirectional flow; diverse faunal activity.
Lro	Oscillation ripple-laminated micrite; calcareous mud with varying amounts of terrigenous silt and sand; symmetrical ripples; trace fossils as in Lra and tetrapod footprints.	Laterally continuous for hundreds of meters; thickness 0.1-3 m. grains;	Precipitation of carbonate mud; occasional influx of terrigenous bidirectional flow; diverse faunal activity; shallow to subaerial conditions.
Lrm	Mudcracked, ripple-laminated micrite; lithology as Lra and Lro; symmetrical and asymmetrical ripples; mudcracks; fauna as in Lro.	See Lra	Precipitation of carbonate mud with terrigenous influx; unidirectional and bidirectional flow; subaerial exposure.
Lb	Bioturbated, silty micrite; mottled to nodular; intensely bioturbated. of soupy, unconsolidated substrate.	Laterally continuous; thickness 1-1.5 m; traceable for km.	Precipitation of carbonate mud; settling of silt and clay; bioturbation
Mm	Massive mudstone; terrigenous silt and clay components; *Scoyenia* burrows.	Laterally continuous for hundreds of meters on strike; units are 1-9 m thick.	Suspension settling of silt and clay; quiet water; bioturbation.
Mv	Variegated mudstone; terrigenous silt and clay components; subtle color horizons; contains vertebrate bones, teeth, coprolites and fossil wood.	Laterally continuous units 0.1-3 m thick.	Settling from suspension in quiet water; diagenetic horizons; conditions for terrestrial flora and fauna.
Ml	Laminated mudstone; terrigenous silt and clay components; small, asymmetrical ripples.	Composite beds range from 0.1 to 1.5 m thick; composed of thin (1-4 cm) rippled beds; continuous for tens of meters.	Unidirectional flow.

along the Llano Estacado and Canadian escarpments between measured sections.

Lower contacts are irregular due to load casts, but spheroidal weathering accentuates the irregularity (Fig. 4B). Locally, small (2-3 cm wide, 10-100 cm long) sandstone structures taper downward and branch or are of consistent thickness as they project down into underlying mudstones. The longest of these structures appears slightly folded within a mudstone. Upper contacts are sharp. Burrows on the upper surface are filled with overlying mudstone.

Well-defined and preserved burrows, rather than a completely bioturbated fabric, imply continuous deposition with bioturbation and sedimentation at equilibrium (Ekdale et al., 1984). Fewer burrows in the thickest sandstones may indicate variability of sedimentation rates at the different localities. The lack of ichnofaunal diversity indicates some limiting conditions on organisms (Ekdale et al., 1984). *Scoyenia* burrows are attributed to soft-bodied animals whose oxygen requirement is less than that of hard-bodied organisms (Ekdale et al., 1984). Therefore, the dominance of bioturbation by soft-bodied organisms suggests that the oxygen content of the water could have been a limiting factor on the infauna during deposition of this lithofacies.

Onset of deposition of sand-sized material took place on an unconsolidated, weak substrate, creating conditions for load structures to form (Allen, 1982). The sandstone structures along basal contacts are interpreted as sedimentary dikes injected into muds. Sedimentary dikes may occur in overlying or underlying beds, and gentle folding of the longest dike indicates that mud continued to dewater after injection of the dike (Miall, 1984). These structures are interpreted as dikes because no pattern of occurrence was observed, and injection structures tend to have extreme length compared to width (Allen, 1982). Cessation of sand deposition was rapidly followed by settling from suspension of silt and clay, allowing mud to accumulate in burrows along the upper surfaces of sandstones (Ekdale et al., 1984).

Lack of traction structures within these sandstones could be attributed to: (1) destruction of primary bedforms by organisms, (2) homogeneity of sand or (3) deposition where currents or waves did not affect sediments. The well-preserved, discrete character of the burrows, rather than a completely bioturbated fabric, rules out the first possiblity. Although not abundant, the presence of some coarser material indicates transport energy sufficent to carry coarse sand. Wood fragments might float until they became waterlogged and sank. Once deposition took place, this coarser material was not reworked into traction structures, suggesting that once deposited, massive sandstones were not influenced by moving water.

Coarse sediments can be carried into lake waters by river plumes, turbidity or slumping (Sly, 1978). If episodic turbidity currents deposited these sands, some traction structures would be expected. Slumps would generate structures indicative of rapid deposition such as dewatering structures, but homogeneity of the sand and fine grain size might obscure such bedforms. Density flows from rivers transport fine sand and silt into a basin on a continuous basis (Pharo and Carmack, 1979). The Sm lithofacies contains evidence of continuous deposition (bioturbation), but lack of other structures makes the process that transported these sands difficult to identify.

Laminated Sandstone (Facies Sl)

This facies consists of fine-to-medium, well-sorted, calcite-cemented sandstone that contains parallel, low-angle cross-stratification (Fig. 4C) and minor amounts of ripple cross-stratification. Sets are 4-10 cm thick and contain parallel laminations. The lithofacies occurs in beds 20-60 cm thick that are laterally continuous for hundreds of meters along outcrop. Lower contacts are sharp or gradational from other sandstone lithofacies. Upper contacts are sharp.

Traction transport under high flow velocities operates to form parallel and low angle cross-stratification (Harms et al., 1982). Ripples formed in the same grain size imply changing flow velocities and periods of lower energy conditions.

Planar-stratified Sandstone (Facies Sp)

Fine-to-medium, moderately to well-sorted, calcite-cemented sandstones contain planar cross-stratification. Cross-stratification is in sets 10-30 cm thick. The lithofacies occurs as laterally continuous or discontinuous beds. Tabular sandstone is continuous along outcrop for hundreds of meters and 1.5-2 m thick. The lower contact of tabular sandstones (Luciano Mesa) is sharp above a carbonate lithofacies. The upper contact is sharp and overlain by facies Sl. Tabular sandstone lacks any internal geometry to suggest amalgamation of channels. Discontinuous sandstones (Apache Canyon and Mesa Redonda) occur in convex bodies that pinch out within 30 m of outcrop. Thickness is 2-3.5 m. Lower contacts are sharp and may contain coarse sand grains.

Disrupted Sandstone (Facies Sd)

Fine, moderately sorted, calcite-cemented sandstones contain convolute bedding, dish structures and ball-and-pillow structures. Sandstones were deposited in laterally discontinuous, wedge-shaped bodies that dip from 5° to 20° and pinch out laterally into other lithofacies within meters of outcrop. Thickness of wedges varies from 20 to 70 cm, and ball-and-pillow structures form irregular basal contacts with underlying mudstone interbeds. Upper contacts are sharp.

During deposition or shortly after burial, soft-sediment deformation occurred in water-laid sediments. High sedimentation rates promote loose packing of sand (Allen, 1982), and sediments lose strength as liquefaction causes grains to separate temporarily and disperse in pore fluid, promoting development of soft-sediment deformation. Primary structures in sandstones were distorted after deposition, forming dish structures and convoluted bedding. Dish structures form as escaping pore water from sediment loading disrupts laminated sands (Miall, 1984). Folded primary structures and dish structures suggest that these beds were initially deposited by unidirectional currents. High sedimentation rates created conditions for disruption after deposition. Ball-and-pillow structures form as sand is deposited on weaker,

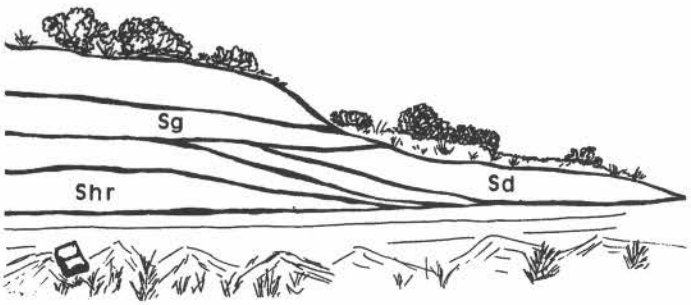


FIGURE 5. Drawing of the San Jon Hill locality, showing normally graded sandstone (Sg) in wedge-shaped bodies above disrupted (Sd) and horizontal and ripple-laminated sandstone (Shr). Sandstone interval is ~ 5 m thick.

unconsolidated mud (Miall, 1984). Unidirectional currents and high sedimentations rates operated in the formation of disrupted sandstones. Mudstone interbeds accumulated periodically as sand supply was cut off or flow energy reduced. When sand deposition resumed, muds were unconsolidated, allowing load structures to form. Environments compatible with development of these structures include deltas or river channels (Miall, 1984).

Normally Graded Sandstone (Facies Sg)

Coarse-to-fine, poorly sorted, calcite-cemented, normally graded sandstones contain fines throughout, with grading restricted to the coarse fraction (coarse-tail grading of Middleton, 1965). Minor vertical and sub-horizontal burrows are present. Grains include well-rounded, sedimentary rock fragments (micrite and siltstone), quartz, feldspar, oolites and fish scales.

This lithofacies occurs in laterally discontinuous beds that display wedge-shaped geometry along outcrop. Individual beds range in thickness from 10 to 30 cm and are generally separated by thin (1-2 cm) mudstone partings. Wedge-shaped bodies dip between 10° and 20°, taper and pinch out laterally within 6 m (Fig. 5).

Coarse-tail grading requires a range of available grain sizes and a sudden decrease in fluid competence, allowing grain settling in response to fluidal and gravitational forces (Middleton, 1965; Davis, 1983). Normally graded beds are associated with turbidite (underflow) deposition where denser river waters discharge into a lake (Hakanson and Jansson, 1983). The accumulation of packages of sandstone composed of normally graded beds implies sporadic discharge. Minor bioturbation indicates depositional processes dominated biogenic processes (Ekdale et al., 1984).

Horizontal and Ripple-laminated Sandstone (Facies Shr)

Fine, moderately well-sorted, calcite-cemented sandstones contain asymmetrical ripple cross-stratification and horizontal laminations. Surfaces of horizontally laminated beds contain parting lineations. Climbing ripples also occur with entire ripple form preserved (Fig. 4D). Lithofacies Shr occurs in both laterally continuous and discontinuous units. Discontinuous bodies are described in lithofacies Sg and Sd (Fig. 5). Climbing ripples are associated with these wedge-shaped beds.

Laterally continuous bodies (Luciano Mesa) may be as much as 6 m thick, but are composites of numerous, thin (5-10 cm) rippled beds. These laterally continuous units extend for hundreds of meters along outcrop. Small-scale scours (10 cm wide by 3 cm deep) are filled with thin (1-2 cm) rippled beds. Other laterally continuous units are thinner, ranging from 0.1 to 1 m thick and are single bed units (Apache Canyon).

Unidirectional flow, varying from high to low velocity, deposited these sandstones. In units having wedge geometry, direction of flow was at some angle to the dip of the beds. Climbing ripples associated with these units indicate periods of very rapid sediment supply from suspension combined with sufficient traction to produce and preserve entire ripple forms (Blatt et al., 1980). Horizontal stratification containing lineations indicates that in order to scour, flow must achieve a certain velocity for any given grain size (Blatt et al., 1980). Small scours in the tabular, composite interval suggest periods when flow velocity was increased to erode fine-grained sands. Increased flow velocity was sporadic, and once the scour developed, conditions of lower flow velocity returned.

Ripple-laminated Micrite (Facies Lr)

Ripple-laminated, calcareous mud containing varied amounts of terrigenous sand and silt comprises facies Lr. A diverse invertebrate ichnofauna occurs, including *Diplichnites*, *Cruziana* and *Pelecypodichnus* (Hester, 1988). Vertebrate tracks are abundant (Hunt et al., 1989, 1993, 2000; Lockley et al., 2000). Subfacies are defined by the presence of asymmetrical (Lra) and symmetrical (Lro) ripple laminations and mudcracks (Lrm). All three are in beds laterally continuous for hundreds of meters that range from 0.1 to 3 m thick.

Asymmetrical ripple-laminated micrites (Lra) may be composed of numerous, thin (1-2 cm) asymmetrical ripples with calcareous mudstone interbeds and drapes. Locally (Mesa Redonda), ripple-laminated micrites lack drapes or interbeds and contain the greatest amount of carbonate mud. The terrigenous component defines ripple cross-stratification that stands out in relief on outcrop. Upper contacts are sharp, but lower contacts may be sharp or gradational. The ichnofauna (Fig. 4E) includes numerous invertebrate trails and traces, similar to those described by Bromley and Asgard (1979) in Triassic lacustrine carbonates in Greenland.

Symmetrical, ripple-laminated silty/sandy micrite (Lro) contains symmetrical ripples, the amount of terrigenous material varies by locality (less abundant at Mesa Redonda), and reactivation surfaces can be seen. Mudcracked, ripple-laminated silty micrite (Lrm) gradationally overlies other micrite lithofacies. Tetrapod tracks of small rhynchocephalians and larger aetosaurs and dinosaurs are abundant in the micrites at Mesa Redonda. Lower contacts are gradational, whereas upper contacts are sharp.

Carbonate mud precipitation and terrigenous silt and sand deposited by unidirectional currents operated during the formation of lithofacies Lra. Units composed of mud drapes and ripples indicate that coarser, terrigenous material was not always available to form ripples. Precipitation of carbonate mud dominated

during deposition of micrites that lack the wavy to lenticular bedding. When current energy was sufficient, terrigenous material was transported. A diverse and abundant ichnofauna indicates few limiting factors on organisms existed during deposition (Ekdale et al., 1984).

Symmetrical ripples (Lro) formed under oscillatory flow conditions produced by wave action (De Raff et al., 1977). Reactivation surfaces record a local and temporary shift of flow conditions (Allen, 1982). Wave-generated structures indicate that this lithofacies was deposited in shallow water. Local variation in the amount of terrigenous sediment suggests that Mesa Redonda was sediment starved relative to other locations during deposition of the micrite. Micrite and minor terrigenous silt and sand deposited by currents were subject to subaerial exposure when mudcracks formed (Lrm). Tetrapod tracks in this lithofacies further support identification of shallow to subaerial conditions.

Bioturbated Micrite (Facies Lb)

This lithofacies is only found at the base of the Redonda Formation. Massive, silty micrite displays an intensely bioturbated fabric that gives the facies a nodular or mottled appearance (Fig. 4A). Lithofacies Lb occurs as a laterally continuous unit, traceable for km. Thickness ranges from 1 to 1.5 m. The basal contact with underlying mudstone is gradational. Upper contacts are irregular when overlain by lithofacies Cmd or gradational where mudstones overlie the unit.

Precipitation of carbonate mud, bioturbation and deposition of terrigenous silt and clay are dominant processes contributing to this facies. Bioturbation was intense enough to destroy any primary structures. Mottled fabric can be produced by bioturbation of a very soft, highly liquified substrate (Ekdale et al., 1984) such as the bottom of a lake or pond. Pedogenic processes can also form calcareous nodules when K-soil horizons develop (Birkeland, 1974). Thus, facies Lb is interpreted here as primarily of lacustrine origin, though pedogenesis cannot be ruled out locally.

Massive Mudstone (Facies Mm)

Fine-grained rocks containing subequal parts of clay and silt are massive and contain silt-filled *Scoyenia* burrows. Lithofacies Mm occurs in laterally continuous beds from 1 to 9 m thick. Basal contacts with underlying units are sharp, and upper contacts appear irregular due to spheroidal weathering of overlying sandstone. Silt and clay settled from suspension in quiet water into an environment of faunal activity. Oxygen levels may have limited diversity, as in lithofacies Sm.

Variegated Mudstone (Facies Mv)

Fine-grained rocks that contain both clay and silt exhibit laterally continuous, subtle color banding (diagenetic?) that gives the lithofacies a stratified appearance. Vertebrate bones, teeth, coprolites and wood fragments occur scattered through the lithofacies. Thin, silty micrite lenses in the mudstones contain conchostracan molds.

Settling from suspension of clay and silt in quiet water formed this lithofacies. Carbonate precipitation in micrite beds containing fossils implies periods when standing bodies of water existed. Modern conchostracans live along the margins of large lakes and in small, temporary inland ponds ranging from fresh to brackish water (Webb, 1979). Color horizons in mudstones have been used as evidence of soil development (e.g., Kraus, 1987; Bown and Kraus, 1987). However, no root traces or other indications of pedogensis were identified.

Ripple-laminated Mudstone (Facies Ml)

Fine-grained rocks containing clay and silt display small, asymmetrical ripple laminations (Fig. 4F). Lithofacies Ml occurs as composite beds, composed of thin (1-4 cm thick) mudstone. Composite beds range in thickness from 0.1 to 1.5 m. Deposition of terrigenous clay and silt occurred under unidirectional flow. Fine grain size may indicate low flow velocities or reflect the size of sediment supply (Harms et al., 1982).

DEPOSITIONAL ENVIRONMENTS

Granata's (1981) interpretation of Redonda deposition as in a single, large lake cannot be confirmed. Instead, we interpret Redonda deposition as having taken place in a "lacustrine system" of small to moderate sized lakes (up to a few km? in diameter) and in lake margin and related environments. This is demonstrated by an analysis of the lateral occurrence and variation of lithofacies associations in the Redonda Formation, which identifies a large lacustrine depositional system with distal and proximal lake, shoreline, deltaic and fluvial environments.

Basal Marker Bed

The abrupt change from fluvial deposition of the Bull Canyon Formation to lacustrine deposition of the Redonda Formation occurs at the basal marker bed of the formation (Fig. 2). This marker bed is composed of silty, bioturbated micrite (Lb) and associated disorganized matrix-supported conglomerate (Lb + Cmd). Interpretation of this unit as a paleosol (Granata, 1981) that contains sandstone filled "fissures" (Kelley, 1972) supports a disconformable contact between the Bull Canyon and the Redonda formations.

Although detailed pedogenic analysis was outside the scope of the present study, an alternative interpretation of the basal marker bed is supported by field evidence. Lacustrine processes could account for the marker bed (Lb + Cmd and Lb). The change in depositional style from lenticular sandstones intercalated with mudstones of the Bull Canyon Formation into the laterally continuous, bioturbated, silty micrite (Lb) marks a profound change in stratigraphic architecture. Environments changed from variable to widespread consistency. One criterion used to delineate ancient lacustrine systems is lateral continuity of beds; intense bioturbation also is common (Picard and High, 1972).

Carbonate precipitation occurs in profundal and littoral lake environments (Dean, 1981; Picard and High, 1981), and terrig-

enous silt and clay, carried by rivers, can settle from suspension into deep lake environments. If these processes operated simultaneously, a mixture of silt, clay and carbonate mud would be deposited. Modern and ancient lakes show sediment distribution patterns that illustrate this combination (Picard and High, 1981, and references therein). In deep marine environments, this combination of sediments can result in a nodular texture (Jenkyns, 1978). Thus, the mottled and nodular appearance of Lb could represent a fabric developed by bioturbation of a soupy, unconsolidated substrate that existed on a lake bottom where carbonate mud and terrigenous silt and clay were accumulating.

The association of disorganized matrix-supported conglomerate with the silty micrite at Bull Canyon and Gallegos indicates that subaqueous sediment gravity flows influenced the environment during deposition of the marker bed. Matrix-supported conglomerates identified in Jurassic lake deposits in West Virginia occur in sublacustrine channels on lake slopes and on the non-channelized basin plain (Hentz, 1985). After deposition of the gravity flows, bioturbation continued, and burrows developed in the matrix-supported conglomerates. Matrix-supported conglomerates can be associated with sublacustrine fans (Nemac et al., 1984), where flows pick up mud from lake deposits. The lithologic similarity of Lb and the matrix of Cmd could be the result of such a process. Sediment gravity flows could be generated on unstable lake basin slopes or associated with oversteepening of delta slopes (Sly, 1978). Such flows can travel long distances on gentle slopes (Rodine, 1976). The occurrence of these conglomerates within the marker bed suggests that these processes were important early in the history of Redonda deposition.

The locality where Kelley (1972) described fissures was not located by us, but at Gallegos a structure interpreted as a sedimentary dike is associated with the marker bed. The structure originates from a massive sandstone, projects through a mudstone (where it appears contorted) and into the marker bed. If this structure represents a passively infilled fissure, then the fissure fill occurs between a mudstone and a massive sandstone and not within the marker bed. The slight folding of this structure suggests dewatering of the mudstone after emplacement of the sandstone, supporting the interpretation of a subaqueous, lake environment.

From evidence presented in this study, a lacustrine origin for the marker bed (Lb + Cmd) is reasonable. Field evidence is lacking for subaerial origin of the disorganized matrix-supported conglomerate. True root traces or bioturbation attributable to terrestrial fauna within this bed are absent, and this does not support a pedogenic origin.

Lacustrine Environments

Lacustrine environments recorded by parts of the Redonda Formation are represented by alternating massive mudstone and sandstone (Sm + Mm) (Fig. 2). A general trend in lacustrine systems is a decrease in grain size offshore (Picard and High, 1981), so we infer that Redonda mudstones represent distal environments, whereas sandstone deposition took place under more proximal conditions. The specific mechanisms that transported the sand and produced alternation of sand and mud are more difficult to identify.

The presence of disseminated coarse to medium grains within very fine to fine sandstone requires a physical mechanism capable of transporting these grain sizes. Physical processes that move coarse to medium sand into lakes include river plumes and turbidity currents. Rivers transport sediment into lakes, dispersing sediment as surface flows, interflows and underflows, depending on density contrasts (Hakanson and Jansson, 1983). Turbidity current underflows deposit a distinctive sequence (Strum and Matter, 1978). Pharo and Carmack (1979) distinguish turbidity processes from near bottom underflow by defining turbidity currents as episodic, and underflows as continuous. The massive sandstones (Sm) of the Redonda Formation contain no evidence of turbidite deposition such as graded bedding, so it is unlikely that turbidity currents carried sand into the environment. Continuous underflow could account for some of the features observed in the sandstones, because they can deposit chaotic, ungraded sand, silt and clay (Strum, 1979). The fabric of bioturbation developed in the massive sandstone (Sm) suggests an equilibrium between sedimentation and bioturbation (Ekdale et al., 1984), not episodic deposition. The area in a lake directly influenced by plumes is limited (Hakanson and Janson, 1983), and the wide exent of the sandstone is difficult to explain, even with multiple sources of sand (river plumes).

The widespread sandstones, however, probably represent transitional to shoreline lake environments rather than deeper water environments. Indeed, these sandstones are readily interpreted as the result of sheetflow in a subaerial and/or shallow, ephemeral lake setting. In modern lakes, sand-sized material occurs nearly exclusively in shallow shoreline or nearshore settings (Sly, 1978). Ancient lakes show similar sediment distribution patterns (Picard and High, 1981). Most sand-sized material is contributed by river inflows, and the remaining portion must be accounted for by shoreline processes, including current or wave activity (Sly, 1978).

A mixture of predominantly fine sand, silt and clay with minor medium sand can occur within transition zones of marine beaches where few inorganic primary structures are found (Reineck and Singh, 1973). Although lower energy conditions are found in lakes, shoreline processes differ little from marine counterparts (Collinson, 1978). Hence, the sandstones might represent widespread migration of a transitional facies. If so, the interbedded muds were deposited after lake expansion when coarser material was not being supplied to the middle of the basin, and suspension settling of only silt and clay occurred. Bioturbation is present in both sandstone and mudstone, suggesting that dissolved oxygen levels were sufficent to support burrowing organisms in both nearshore and profundal environments.

The interbedded pattern of sand and mud deposition suggests expansion and contraction of the lake. These changes occurred in a fairly regular pattern, and mud-filled burrows on the upper surfaces of sandstones suggest a rapid return to a quiet, mud-dominated environment.

Sheet sands have been interpreted as dune deposits in some other Late Triassic lakes (e.g., Stewart et al., 1972). Unlike the massive sandstone in the Redonda, such sandstones contain planar cross-stratification and developed during periods when the lake was dry. The fabric of the massive sandstone supports

an interpretation of subaqueous depostion, not migrating dunes. Although eolian processes could transport the sand-sized material (Allen, 1982), deposition apparently took place by suspension settling, because no traction structures developed.

Laminated sandstone is associated with massive sandstone (Sm + Sl) at Gallegos (Fig. 2), indicating the influence of waves. A high sandstone/mudstone ratio (1.2), medium sand size and inorganic primary structures support a proximal shoreline position for Gallegos in contrast to other locations where Sm + Mm occurs.

No clear evidence of a delta was found at Gallegos, but the evidence listed above suggests that it was near a sediment source. Axelsson (1967) described large deltas in lakes that lack Gilbert-style morphology and resemble marine lobate deltas. River plumes feeding into a lacustrine basin initially deposit the coarsest load in a lobate body at the river mouth and spread out laterally into the basin, where finer grains are deposited (Hakanson and Jansson, 1983). Massive sandstones at Gallegos may have accumulated as river plumes deposited fine-to-medium sand near a river mouth. Waves or currents in the lake could then generate the bedforms visible in the thickest sandstone.

Shoreline Environments

Shallowing upward or a change in lake chemistry occurs as offshore mudstone and sandstone (Sm + Mm) grade into silty, ripple-laminated micrites (Lr) at Bull Canyon, Luciano Mesa and Mesa Redonda. Environments dominated by terrigenous material are overlain by silty, sandy micrites (Lr) at Apache Canyon. Lithofacies associations present at these locations indicate considerable variability in local shoreline environments.

Carbonate Shorelines

At Bull Canyon, Mesa Redonda and Luciano Mesa, there is an upward gradation from offshore mudstone and shallow water sandstone into ripple-laminated micrites (Fig. 2). Shallowing upward is indicated as lithofacies lacking traction structures are overlain by carbonate units containing traction-generated bedforms. Rippled beds that contain a greater diversity of ichnofauna relative to underlying offshore environments also support a shallowing-upward model. Similar ichnofossils occur in Triassic calcareous lake deposits of Greenland (Bromley and Asgard, 1979), where they represent the shallowest lacustrine conditions (Clemmensen, 1979). These impure micrites were deposited as a lake became shallower, allowing waves to affect bottom sediments (Howard and Reineck, 1972). Wavy to lenticular bedding at Bull Canyon and Luciano Mesa suggest periods of still water when carbonate mud accumlated and coarser material (silt) was not supplied. Changing wave energy would be likely in a lake because winds might change periodically in both pattern and velocity. Periods of subaerial exposure created conditions for mudcracks to develop in ripple-laminated micrites. At Apache Canyon, wave energy was dissipated enough for fragile conchostracans to be preserved in mudcracked units.

At Mesa Redonda, sequences of asymmetrical and oscillation, ripple-laminated micrites (Lra + Lro + Lrm) containing mud cracks and separated by mudstone breaks represent depth or wave energy changes. The presence of ostracods (*Darwinula*) in these fluctuating shoreline facies (Kietzke, 1987, 1989) provides some constraint on maximum depth. Modern *Darwinula* are most abundant at a depth of 6 m and absent in depths greater than 9 m (McGregor, 1969). Based on this, deposition of mudstone interbeds took place in water probably no deeper than 6 m and possibly much shallower. Sparse, terrigenous grains were occasionally supplied to an environment dominated by carbonate mud precipitation. Tetrapod trackways indicate either subaerial conditions or water shallow enough for the animals to walk on the substrate.

The uppermost micrite at Mesa Redonda is capped by stratified sandstone, indicating that a carbonate mudflat was channelized by streams. Massive sandstone and mudstone (Sm + Mm) overlie the stratified sandstone, indicating a return to terrigenous deposition and a long term change in base level.

Nearshore carbonate precipitation implies that the shallow waters were well aerated and sufficiently hard to precipitate carbonate. High water temperatures also promote the precipitation of carbonate (Hakanson and Jansson, 1983). Shallow-water micrites deposited in the Redonda suggest that clastic supply decreased (Picard and High, 1981), and lake conditions changed to promote carbonate precipation. A change to drier climatic conditions might also account for such a decrease. Fluvial discharge would decrease and reduce the amount of terrigenous material to the depositional system, although some terrigenous material would be supplied during sporadic rainfall events (Bloom, 1978).

High and Low-energy Beaches

Planar, cross-stratified sandstones capped by laminated sandstones (Sp + Sl) overlie the ripple-laminated micrites at Luciano Mesa, and document a change from carbonate to terrigenous environments. Four beach sequences can be seen (Fig. 2), but the first sequence is the best developed and suggests that, at times, fairly high energy levels existed. The gradation from megaripple bedforms into parallel laminations suggests an increase in hydrodynamic energy upward during deposition of the first sequence (Fig. 2).

Along marine shorelines, prograding beaches can deposit a specific vertical sequence of bedforms that develop in response to waves approaching and breaking along the shoreline (Clifton et al., 1971). The sequence on a marine beach would include (from bottom up) asymmetrical ripples, megaripples, planar beds and parallel laminations. In the Redonda Formation at Luciano Mesa, only megaripple bedforms and parallel laminations occur in the first beach unit. The comparison to marine environments is legitimate because the processes and products of clastic lake shoreline environments differ only by size of bedforms, sorting and maturity, which are reflections of lower energy levels along lacustrine beaches (Collinson, 1978). The significance of this beach deposit is the presence of bedforms that indicate high-energy shoreline processes. Because small fluctuations of lake level can rapidly shift shoreline environments (Picard and High, 1981), the complete prograding beach sequence described from marine environments is not present in the beach sequences at Luciano Mesa. The megarippled interval is absent in the upper two beach sequences, and ripple laminations are dominant. Grain size varies



FIGURE 6. Panoramic drawing of the Gilbert delta at San Jon Hill. Sandstone interval is ~ 5 m thick. Units 1-3 are individual delta fronts, and unit 4 is the topset interval.

little between individual sequences, suggesting an upward trend of decreasing hydrodynamic energy or increasing depth during deposition of these beach sequences.

Ripple-laminated sandstones with small scours overlie the uppermost beach sequence at Luciano Mesa, indicating a long term base-level change. Unlike the base-level change at Mesa Redonda, the environment at Luciano Mesa continued to be influenced by hydrodynamic processes. At times, vigorous current action generated higher transport and erosional energy conditions. Unusually large storms could have created scours; when flow velocities returned to normal, scours were infilled and capped with ripple-laminated beds.

Deltaic Environments

Deltaic processes controlled or influenced deposition of the Redonda Formation at San Jon Hill and Apache Canyon, the most eastern localities. Like shoreline environments, variability in these deltaic environments demonstrate complexity within the Redonda depositional system.

Gilbert Delta

A well-developed Gilbert delta was exposed at San Jon Hill (Figs. 5-7) but has been destroyed by recent highway construction. Its structure is tripartite, consisting of topsets, foresets (delta front) and bottomsets. The vertical changes expected by progradation of this delta type include coarsening upward of grain size and variation in bed geometry (Gilbert, 1885; Barrell, 1912; Stanley and Surdam, 1978; Postma, 1985). At San Jon Hill, the Gilbert style delta clearly prograded into a lacustrine basin, although it deviates from an ideal profile.

The lowest interval at San Jon Hill consists of ripple-laminated mudstone and asymmetrical, ripple-laminated micrites (Ml + Lra) and represents the bottomset portion of the delta, which has been modified by unidirectional flow. Ripple-laminated mudstones have been described from lake deposits associated with delta building in modern lakes (Strum and Matter, 1978), from shallow water environments in Green Lake, New York (Ludlam, 1974) and from profundal lake-slope deposits in Virginia (Hentz, 1985). Because this interval grades vertically and laterally (landward) into coarser sediments, a deltaic interpretation of the deposits at San Jon Hill is supported. Because a thick (13 m) interval is present, some of the lower deposits may represent lake environments that were indirectly influenced by the prograding delta.

A lenticular bed of sandy micrite occurs high in the interval of mudstones (Fig. 6) and may represent the onset of deposition dominated by deltaic processes. This bed is interpreted as a channelizing and scouring event that occurred within bottomset beds. As flow spilled out over the channel, waning flow of the event created the vertical sequence.

Three progradational packages of foreset beds overlie the bottomset beds (Fig. 6). Very finely to finely disrupted, and horizontal and ripple-laminated sandstone makes up the first prograding foreset. Medium-to-coarse, normally graded and horizontal and ripple-laminated sandstone was deposited as the delta prograded. Normally graded sandstone developed in response to changing fluvial discharge, possibly due to seasonally higher discharge. High rates of deposition, unidirectional flow and turbidites are consistent with delta building in lakes.

The geometry of the beds suggests prograding delta fronts building downflow into a lake basin. Slumping of a foreset bed occurred in unit 2 (Fig. 6), and horizontally laminated beds were folded. Similar traction structures on the delta front of lacustrine Gilbert deltas have been identified by other workers (e.g., Joplin and Walker, 1968; Stanley and Surdam, 1978). Accretion took place along inclined (10-20°) delta front surfaces. The geometry of these beds illustrates the expected inclined foreset surfaces of the ideal model, but dips from outcrop measurements do not represent the true angle, as exposure was at some angle to true dip.

The topset portion of the delta is unit 4 (Fig. 6). Lenticular bodies suggest stream channel influence characteristic of the ideal Gilbert delta model. No evidence of base-level changes can be seen. Thin mudstone interbeds within the graded portions may represent typical waning flow at the end of the depositional event. An estimate of water depth can be made from foreset thickness (Stanley and Surdam, 1978). At San Jon Hill, tracing one foreset bed to its bottomset suggests that water depth could have been as much as 6 m.

A number of Gilbert delta lobes prograded into the basin at San Jon Hill. A line drawing (Fig. 7) of a cliff exposure (just east of locality) illustrates a complex internal geometry with opposing dip directions. This geometry suggests that delta fronts prograded from various directions into the depositional system.

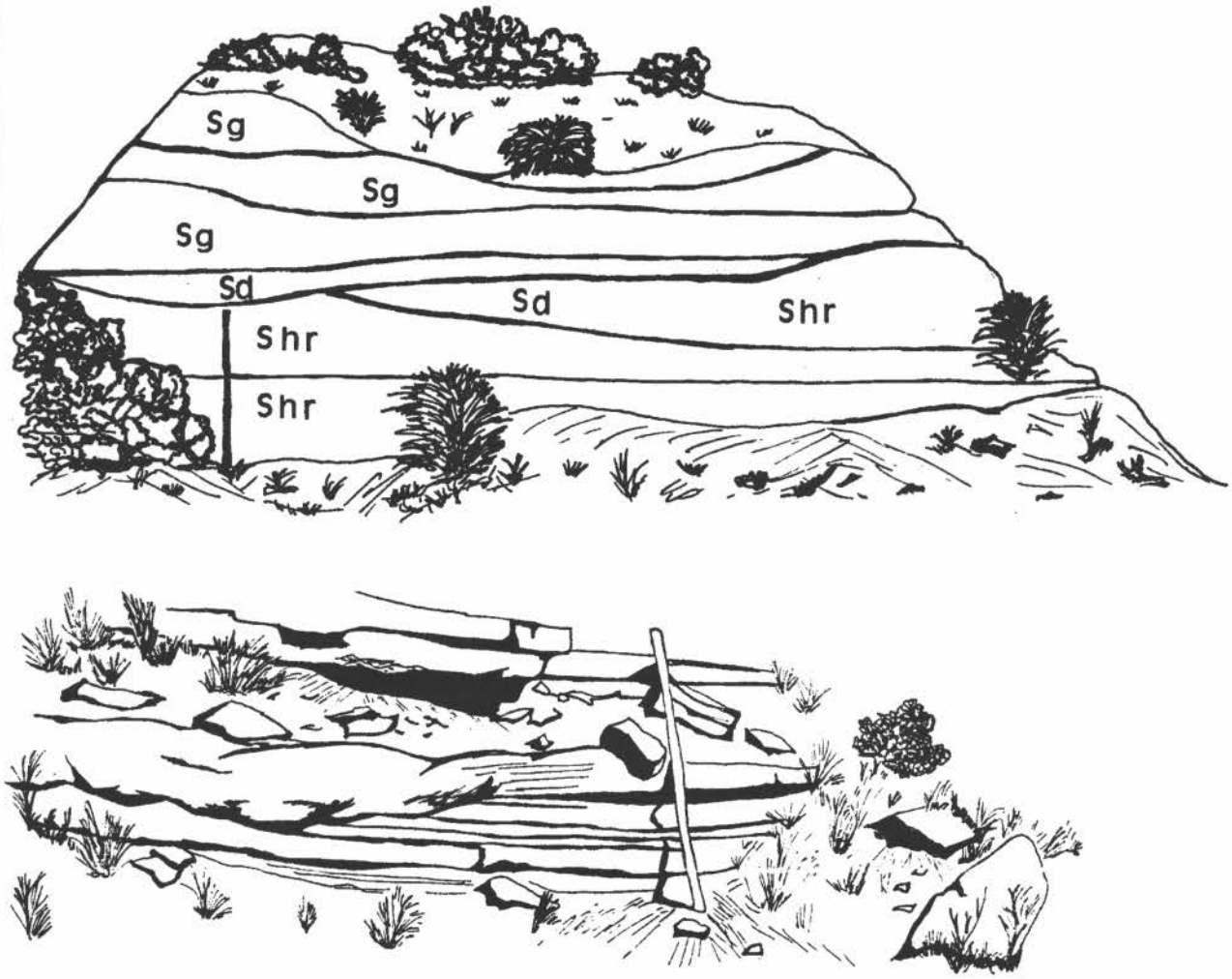


FIGURE 7. Top, the Gilbert delta front at San Jon Hill, illustrating the internal complexity of the prograding delta front. Bottom, drawing of the sublacustrine fan at Apache Canyon. Note small channel cutting into horizontally bedded units in sublacustrine fan system. Sticks are 1.5 m long.

Delta-front Fan

Sandstones and conglomerates interbedded with mudstones overlie the interval of massive sandstone and mudstone at Apache Canyon (Fig. 2). In contrast to San Jon Hill, deltaic processes are not clearly defined at Apache Canyon, but sedimentary processes are consistent with the environment of a delta-front fan. Alluvial fan deposition is also a possible source of these sediments, but delta-front fans can develop in lakes (Nelson, 1967; Strum, 1975), where sublacustrine fans are built predominantly by episodic high and low density turbidity currents (Rupke, 1978). Channel, levee and interchannel deposits of the fan system (Strum, 1975) produce interbedded sandstone and mudstone. No well-defined channels were identified within the interval at Apache Canyon. However, there are sandstones that truncate underlying interbedded sandstone and mudstone, suggesting channel deposits (Fig. 7). Localized debris flows carrying intraformational clasts deposited conglomerates on gently dipping (3-5°) fan surfaces. Deltaic processes ceased at the locality, and infilling of the basin continued with the deposition of silty and sandy micrites (Lr + Mm) in a carbonate-dominated shoreline. This change suggests that the supply of terrigenous sediment was cut off or at least slowed dramatically.

Fluvial Environments

Fluvial deposits overlie carbonate-dominated shoreline deposits at Apache Canyon (Fig. 2). Overbank fines and channel sands were deposited (Mv + Shr + Sp) after shorelines developed. Mud and fine sand accumulated in distal and proximal floodplain environments, and planar-stratified sandstone was deposited in channels by migrating bars. Carbonate mud accumulated, and conchostracans lived in floodplain lakes that were influenced by fluvial processes. Sand was occasionally deposited in small delta lobes within floodplain lakes as splays from channels developed during flood events. The sand component of these lobes and the channel sand are similar. Oolites deposited in mud were probably carried into the floodplain environment by eolian processes.

CONTROLS ON SEDIMENTATION

The offshore, shoreline, deltaic, fan and associated fluvial environments of the Redonda Formation comprise a complex, lacustrine depositional system (Fig. 8A). Interpretation of this system requires consideration of : (1) tectonic influences on basin

formation and the locus of deposition, (2) lacustrine and fluvial processes responsible for the variations observed in the lithofacies and (3) climatic controls on sedimentation.

Tectonic Controls

The change from fluvial and floodplain deposition of the Bull Canyon Formation to the lacustrine and lacustrine margin deposition of the Redonda Formation suggests that either climatic or tectonic events, or both, were responsible. Climatic change alone cannot account for the change from through-flowing fluvial to essentially impounded lacustrine deposition. Without a closed basin, if only rainfall increased, rivers would continue to flow down gradient. Reconstruction of Redonda lacustrine environments suggests a depositional system of small and moderate sized lakes and lake margin environments over an area of at least 5000 km^2 (Fig. 8A).

Tectonic change that involved the alteration of drainage patterns is the most plausible explanation of the Redonda lacustrine system. Localities where shoreline environments existed during most of Redonda deposition include San Jon Hill, Apache Canyon and Gallegos, indicating that these locations were near the margins of the Redonda depositional basin. These locations show some correspondence to the basement highs that define the Tucumcari basin (Fig. 8B), suggesting that highlands defining the basin may have been inherited from the Paleozoic basin.

The tectonic events that may have reactivated the Paleozoic basinal topography (and possibly triggered alteration of drainage patterns) are speculative, but possible mechanisms include large-scale tectonic warping associated with rifting along the Gulf Coast, as suggested by McGowen et al. (1979, 1983), and development of the Chinle back-arc basin (Dickinson, 1981; Lawton, 1994). A more local contributing mechanism could have been salt dissolution of Permian evaporites in the subsurface.

Controls on Lacustrine and Fluvial Lithofacies

Once Redonda deposition commenced, physical controls determined by the waterbodies themsleves affected sedimentation. The variablity of environments at specific geographic locations in the lacustrine system can be discussed with emphasis on some physical lake processes.

Proximal Redonda deposition occurred near the margins of the Tucumcari basin, suggesting that the Redonda lacustrine system may have been at least 80 km wide. Evidence of a high energy beach at Luciano Mesa suggests that a lake there was capable of producing waves that could generate megaripples and a swash zone. Wave- or current-generated bedforms in predominantly massive sandstone at Gallegos indicate that this locality was also positioned where these processes could not produce sedimentary structures. In contrast to northern and western localities, the easternmost localities at San Jon Hill and Apache Canyon were sites where river-dominated deltas and delta-fans were deposited. The existence of shorelines dominated by waves or currents in one part of the basin and fluvially dominated shorelines in another, suggests complex patterns of sediment influx.

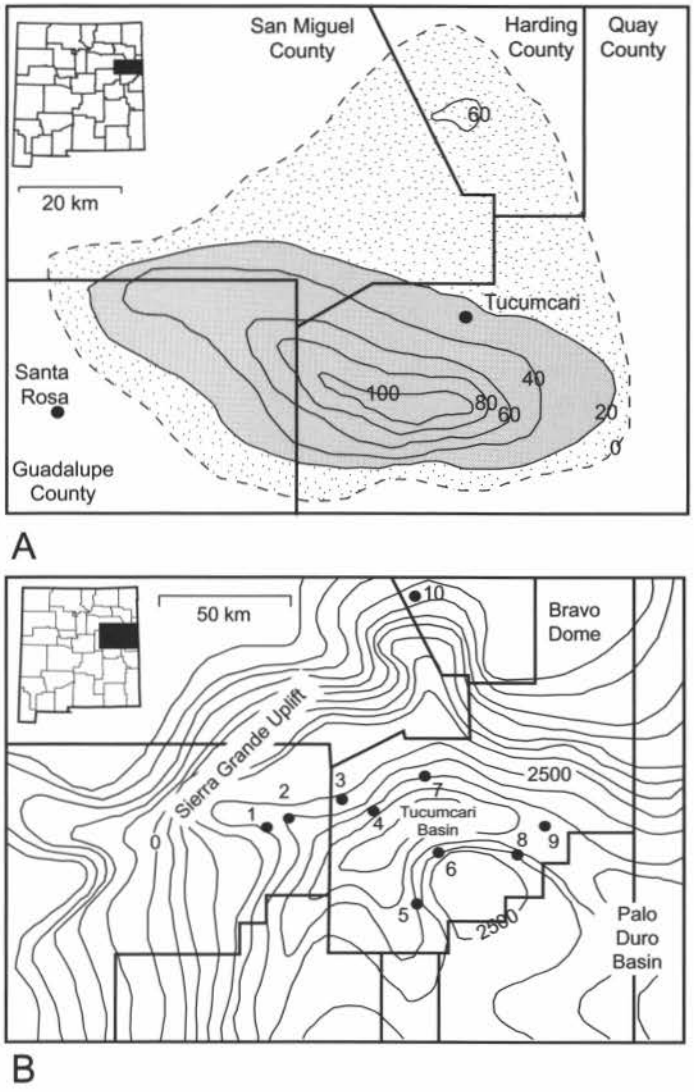


FIGURE 8. A. Isopach map of Redonda Formation (20 ft contour intervals) and outline of the minimum extent of the Redonda depositional system based largely on zero isopach line. B. Location of Redonda measured sections (Fig. 2) with respect to basement highs that define the late Paleozoic Tucumcari basin.

Orientation of the Redonda lacustrine system to prevailing wind patterns may have been an important factor in sedimentation (Sly, 1978; Fox and Davis, 1976), and Luciano Mesa may have been positioned along a shoreline that received much of the force of prevailing winds. The Redonda lake basin was situated between 9-11° north paleolatitude, which would place it in the zone of trade winds (Lamb, 1972). With prevailing winds blowing from the east-northeast, the eastern shorelines of lakes would have been sheltered.

Other shorelines would receive the effects of wind-generated waves within the lake. The sediments at Luciano Mesa preserve evidence of strong wave activity, but the location does not correspond to any basement high defining the Tucumcari basin. However, if basement highs controlled southern and western lake basin edges, it could represent an advancing southwestern or

western shoreline taking the force of easterly winds. Northern shorelines (Gallegos) would have received intermediate wave energy. Because wind patterns would have been more complex than presented here, the model is a simplification. However, a low-energy, eastern-basin edge where deltas were river-dominated and only low-energy beaches developed is consistent with a northeasterly-easterly wind model.

The Gallegos locality may have been similarly located with respect to prevailing winds. If the massive sandstone was wind-blown, thickest accumulations would be along northern and eastern shorelines, consistent for the Gallegos locality but not for San Jon Hill, where no massive sandstone occurs. This does not rule out an eolian origin, because some massive sand accumulated at Apache Canyon. However, most sands are carried into lake basins by rivers (Sly, 1978), and there may have been a sediment source (river mouth?) near Gallegos. Rivers dominated delta building along the eastern basin edge by forming Gilbert deltas at San Jon Hill and sublacustrine fans at Apache Canyon. This contrasts with Gallegos, where river plumes may have carried coarse material into the basin. Fluvial systems that supplied sediment to the depositional system were carrying grains derived from sedimentary sources. Abundant delta sediments at San Jon Hill and fluvial systems to the north (Gallegos) suggest greater fluvial input from the northeastern and eastern sides of the depositional system. The San Jon Hill deltas were river dominated and built by underflows depositing normally graded beds. In contrast, the massive sandstone at Gallegos may have accumulated as sand from a discharging river plume settled by suspension. Fluvial response to lake water differed at these localities, because river water density differed, or lake waters changed through time.

Climate Controls

Climate variables can influence a lacustrine depositional system in many ways, including lake level, chemistry and stratification (e.g., Sly, 1978; Collinson, 1978; Eugster and Hardie, 1978). Changes in rainfall could produce lake expansion and contraction, changing base level and bringing deeper water environments into a particular geographic position within a lake. The massive mudstones of the Redonda Formation probably represent periods when lake levels were relatively high at any given locality. Decreasing rainfall would cause contraction of the lake basins and bring transitional environments into a lake location that had previously been farther from shore. Hence, changes in precipitation could indirectly produce a series of interbedded mudstones and sandstones at a given location within a lake.

Climate factors may also have promoted the precipitation of carbonate at different times during a lake's history. Shorelines are dominated by carbonate precipitation at Mesa Redonda. The bulk of primary lacustrine carbonates are inorganic chemical precipitates that are directly controlled by the physical factors of temperature and evaporation concentration (Kelts and Hsü, 1978). Although shallow water favors carbonate precipitation (Picard and High, 1981), the occurrence of carbonate-dominated shorelines overlain by clastic-dominated shorelines at Luciano Mesa indicates periods of lake history when carbonate precipitation was favored, regardless of a shallow-water setting. At Mesa Redonda, terrigenous intervals occur above and below a carbonate-dominated interval, suggesting clastic and chemical cycles of lake deposition.

Van Houten (1964) proposed that detrital and chemical lake cycles within the Lockatong Formation (Newark Supergroup, eastern United States) were a manifestation of Milankovitch cyclicity. Detrital cycles were deposited when the lakes were at their maximum level and had outlets. Chemical cycles record periods of decreased precipitation, contraction of lake levels and changes in lake chemistry through evaportion and concentration of salts. More recent work using Fourier analysis (e.g., Olsen and Kent, 1996) documents periodicities of Newark lake cycles that correspond to those predicted by orbital forcing. In the Newark basin, the Lockatong and Passaic formations span late Carnian to earliest Jurassic time, overlapping the late Norian-Rhaetian? when Redonda sediments were accumulating. If orbital forcing mechanisms controlled sedimentation of the Newark Supergroup lakes, some record could be expected in other lakes existing within similar climatic belts, such as the lakes of the Redonda depositional system.

In the Redonda Formation, evidence of base-level changes or stratification changes, possibly related to climate, are best observed in the cyclic alternation of offshore mud and transitional sand. Changes in heating insensity of northern continental masses caused directly by the precession of the equinoxes (20,000 year cycle) alter the intensity of low pressure cells that drive monsoonal winds and control rainfall at any given locality (Rossignol-Strick, 1985). Alternatively, the cyclic pattern of sandstone and mudstone deposition could also be a reflection of changes in river input and density stratification within a lake. If sediment plumes transported the fine sand now found in the massive sandstones, then climatic forcing would directly regulate this pattern. Chemical changes occur in a lake by evaporation, influence lake stratification and therefore fluvial response to a basin (Wright, 1977; Collinson, 1978; Hakanson and Jansson, 1983).

A detailed analysis of cycles like that done for the Lockatong and Passaic formations, is not possible in the Redonda Formation because the lack of control on time and sedimentation rates prohibits the application of Fourier analysis. The Redonda is very thin compared to the many km thick lake sediments of the Newark Supergroup, which record all frequencies of cycles predicted by orbital forcing. However, it would not be unreasonable for the effects of 20,000 and possibly 100,000 year cycles to be recorded in 92 m of sediment in the Redonda Formation. In fact, two different frequencies represented by thin sandstone beds deposited between four massive sandstones are found at Luciano Mesa (Fig. 2)—a pattern similar to that found in the Lockatong Formation and in Milankovitch bedding cycles.

CONCLUSIONS

A large array of relatively shallow lakes and lake margin environments covered east-central New Mexico during part of the latest Triassic. At times, sedimentary terranes contributed terrigenous detritus to this lacustrine depositional system, while at other times the precipitation of calcareous mud was the domi-

nant sedimentary process. The northern and eastern margins of the depositional system were located near the Gallegos, Apache Canyon and San Jon Hill localities, which correspond to basement highs of the Paleozoic Tucumcari basin. This correspondence suggests that these structural features influenced sedimentation during Redonda deposition.

Variability of delta and shoreline lithofacies provides evidence for the distribution of wave energy and the effects of paleowinds. Higher wave energy existed along the northern and possibly southern or southwestern margins of the depositional system, where delta morphology and beach sediments were strongly influenced by lake processes. Deltas along the eastern edge of the basin were dominated by fluvial processes, suggesting lower wave energy. Terrigenous and carbonate cycles indicate periods in Redonda lake history when it was dominated by either physical or chemical processes under the strong influence of climatic change, especially chemical precipitation, but also changes in temperature and evaporation. Evidence for climatic control of deposition during the Late Triassic in New Mexico lends support to evidence of climatic forcing in the Newark basin to the east and suggests that orbital climatic forcing influenced Late Triassic lacustrine deposition over a broad geographic area.

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