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JURASSIC STRATA IN EAST-CENTRAL NEW MEXICO AND THEIR REGIONAL SIGNIFICANCE

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Abstract.—The Jurassic section in east-central New Mexico is as much as 330 m thick and consists of Middle and Upper Jurassic strata of the San Rafael Group (Entrada, Todilto and Summerville formations) and overlying Morrison Formation. The Entrada Sandstone is as much as 53 m of eolianite sandstone assigned to the lower, Slick Rock Member and the upper, Exeter Member, which is an upper tongue of the Entrada that postdates Todilto deposition. The Todilto Formation is 2-7 m of organic-rich limestone of the Luciano Mesa Member that disconformably (J-3 unconformity?) overlies the Slick Rock Member of the Entrada. Summerville Formation strata are up to 40 m of repetitively-bedded sandstone and siltstone that disconformably overlie the Todilto and grade into/intertongue with the Exeter Member. The Morrison Formation disconformably (J-5 unconformity) overlies the Summerville and consists of a basal Salt Wash Member (up to 50 m of arkosic sandstone/conglomerate) and an upper, Brushy Basin Member (up to 150 m of smectitic claystone); locally, a 10-15-m-thick, trough-crossbedded sandstone at the top of the Morrison may be an equivalent of the Jackpile Member to the west.

The absence of the basal, Dewey Bridge Member of the Entrada Sandstone indicates that east-central New Mexico was landward of marine influence of the Carmel seaway during the Bajocian-early Callovian, and that the J-2 unconformity at the Entrada base represents a longer hiatus in east-central New Mexico than it does to the west. Todilto deposition took place in a paralic salina with little or no direct connection to the coeval Curtis-Sundance seaway. Summerville tidal flat facies extended across northern New Mexico, much of Colorado and Utah, northeastern Arizona and adjacent areas during the Callovian-Oxfordian transition, and graded southward and southeastward into eolian dunes. The J-5 unconformity at the base of the Salt Wash Member of the Morrison Formation represents a significant tectonic reorganization of the Jurassic depositional systems. Deposition of the Brushy Basin Member of the Morrison Formation did not take place in a single, large lake (Lake T'oo'dichi'), but instead on a vast floodplain dotted with smaller lakes.

Regional eastward-trending piercing lines between the Colorado Plateau and east-central New Mexico can be defined by stratigraphic truncations and depositional pinchouts in Jurassic strata. They only allow 5-20 km of right slip between the eastern margin of the Colorado Plateau and the craton in post-Jurassic time. Arguments that 60-170 km of right slip occurred here during the Laramide orogeny (Late Cretaceous-Paleogene) or Neogene thus are untenable.

INTRODUCTION

Jurassic strata in east-central New Mexico (Fig. 1) are mostly siliciclastic nonmarine sediments of Middle and Late Jurassic age. As much as 320 m thick, these strata have been much less studied than the economically-significant Jurassic section on the Colorado Plateau. Nevertheless, Jurassic strata in east-central New Mexico were deposited by the same depositional systems as rocks on the Colorado Plateau. Therefore, the Jurassic section in east-central New Mexico is critical to a broad understanding of regional Jurassic deposition in the Western Interior. It is also of significance to interpreting the post-Jurassic regional tectonic history between the Colorado Plateau and the Southern High Plains. Here, we summarize Jurassic stratigraphy in New Mexico and discuss its significance for regional depositional and tectonic history

STRATIGRAPHY

Marcou (1858) first identified Jurassic strata in east-central New Mexico, and their stratigraphic relationships and nomenclature have been studied since Lee (1902) (Fig. 2). Here, we summarize Jurassic stratigraphy in east-central New Mexico to further justify the nomenclature and correlations advocated by Lucas and Anderson (1998). Jurassic strata in east-central New Mexico are assigned to the San Rafael Group (Entrada, Todilto and Summerville formations) and overlying Morrison Formation.

SAN RAFAEL GROUP

Entrada Sandstone

The oldest Jurassic strata in east-central New Mexico belong to the Middle Jurassic (Callovian) Entrada Sandstone. As much as 53 m thick, the Entrada consists mostly of yellowish-gray, white and pale reddish-brown, fine-grained subarkosic sandstone (Mankin, 1958). Prevalent bedforms are large-scale trough crossbeds, although laminar bedding is locally common.

The Entrada Sandstone disconformably overlies Upper Triassic strata of the Chinle Group (Fig. 3). This unconformity encompasses a hiatus of about 40 million years and is the J-2 unconformity of Pipiringos and O'Sullivan (1978). In east-central New Mexico, the Entrada consists of two members, the lower, Slick Rock Member, which is mostly trough-crossbedded eolianites, and the upper, Exeter Member, which is an upper tongue of the Entrada that postdates deposition of the Todilto Formation (Lucas et al., 1985, 1987a, b) (Fig. 4). The Todilto Formation disconformably rests on the Slick Rock Member as far east as the Todilto pinchout near the Guadalupe-Quay County border (Lucas et al., 1985; Lucas and Kietzke, 1986). The Exeter Member intertongues with or grades into the overlying Summerville Formation elsewhere.

Todilto Formation

In east-central New Mexico, the Todilto Formation consists only of its lower, limestone member, the Luciano Mesa Member of Lucas

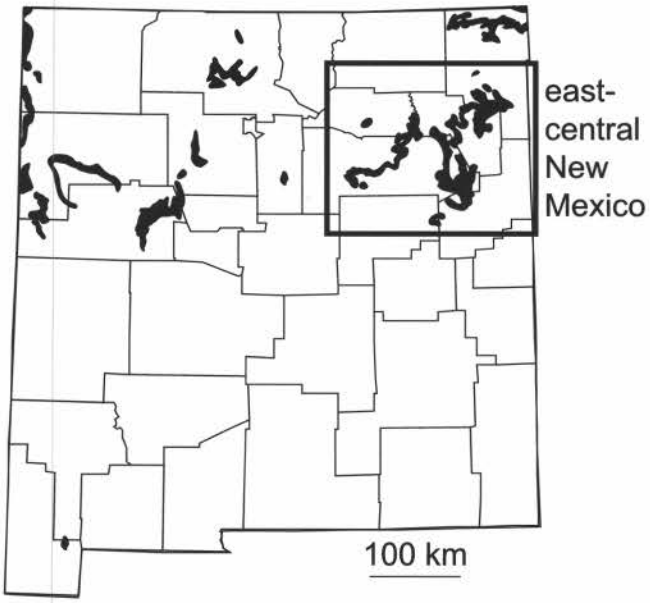

FIGURE 1. Distribution of Jurassic strata in New Mexico (after Dane and Bachman, 1965) and location of east-central New Mexico.

et al. (1995). The upper, gypsum member (Tonque Arroyo Member of Lucas et al., 1995) apparently was not deposited in east-central New Mexico. The Todilto Formation crops out in San Miguel, Guadalupe and western Quay County, where it is 2-7 m thick and is mostly organic-rich, varved limestone with minor intercalations of gritty, sapropelic shale and medium-grained sandstone (Figs. 3-4). The contact with the underlying Slick Rock Member of the Entrada Sandstone is a sharp surface of lithologic contrast with local reworking of Entrada sand into the basal Todilto Formation (Lucas et al., 1985; Lucas and Kietzke, 1986). As Lucas and Anderson (1998) suggested, the base of the Todilto is probably a regional unconformity correlative to the J-3 unconformity of Pipiringos and O'Sullivan (1978). Similarly, the Todilto Formation is sharply overlain by either the Summerville Formation or the Exeter Member of the Entrada Sandstone, and this too may be a regional unconformity.

Summerville Formation

Probably the most confusing Jurassic stratigraphic unit in east-central New Mexico is the interval here referred to the Summerville Formation (Figs. 2-3). These rocks have formerly been included in the Morrison Formation or termed Bell Ranch Formation, a parochial term introduced by Griggs and Read (1959). Furthermore, some workers have applied the terms Ralston Creek Formation or Wanakah Formation to these strata.

Summerville strata are as much as ~ 40 m thick and typically consist of repetitively bedded sandstone and siltstone. Individual beds are laterally continuous and vary in thickness from 0.1 to ~ 5 m. Colors range from very pale orange to light brown, and gypsum beds or nodules are common. At some localities, the Summerville can be divided into two units, a lower sandstone-dominated interval and an upper, red-bed siltstone and mudstone interval. The contact with the underlying Entrada or Todilto formations is sharp (disconformity?), and the Summerville intertongues/grades laterally into the Exeter Member of the Entrada Sandstone locally. The base of the overlying Morrison Formation is picked at either the base of a trough-crossbedded pebbly subarkosic sandstone or at the base of a green smectitic claystone.

Anderson and Lucas (1992) first justified use of the term Summerville Formation in east-central New Mexico by demonstrating the continuity and consistent lithologic character of Summerville strata from their type area in southeastern Utah across the Colorado Plateau, Rio Grande rift and onto the Southern High Plains (also see Anderson and Lucas, 1994, 1995, 1996, 1997, 2000; Lucas and Anderson, 1997; Lucas et al., 1995, 1999). The terms Bell Ranch, Ralston Creek and Wanakah are unnecessary synonyms of Summerville.

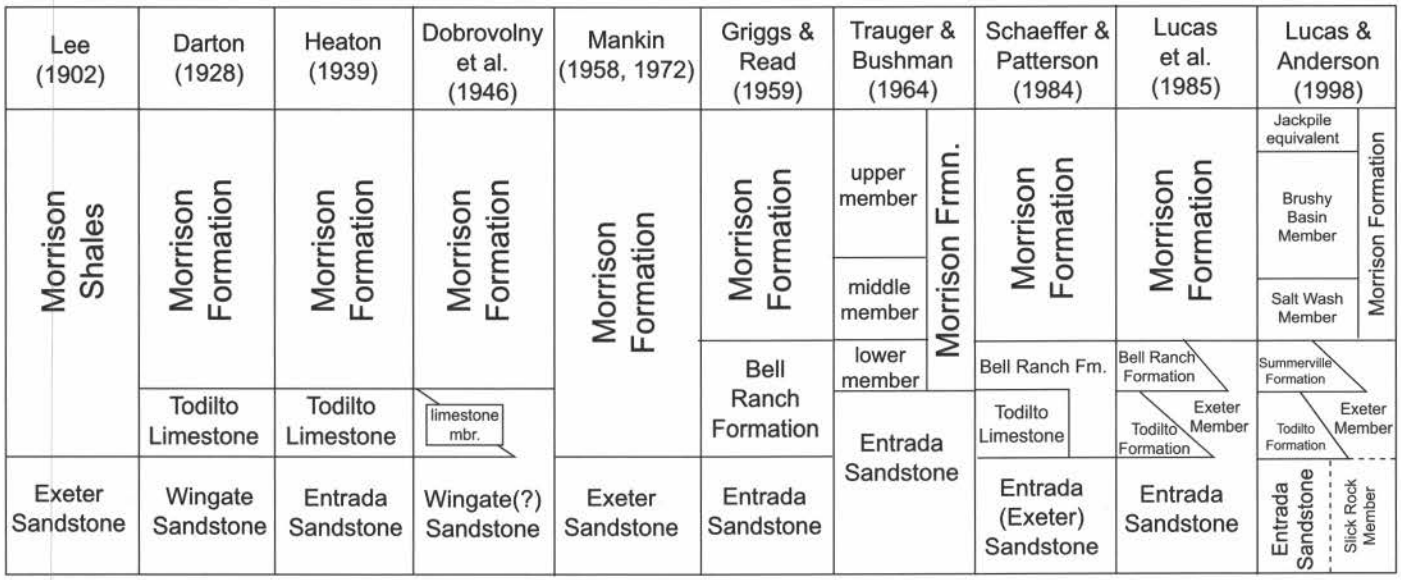

FIGURE 2. Development of Jurassic stratigraphic nomenclature in east-central New Mexico. The nomenclature advocated here is that of Lucas and Anderson (1998).

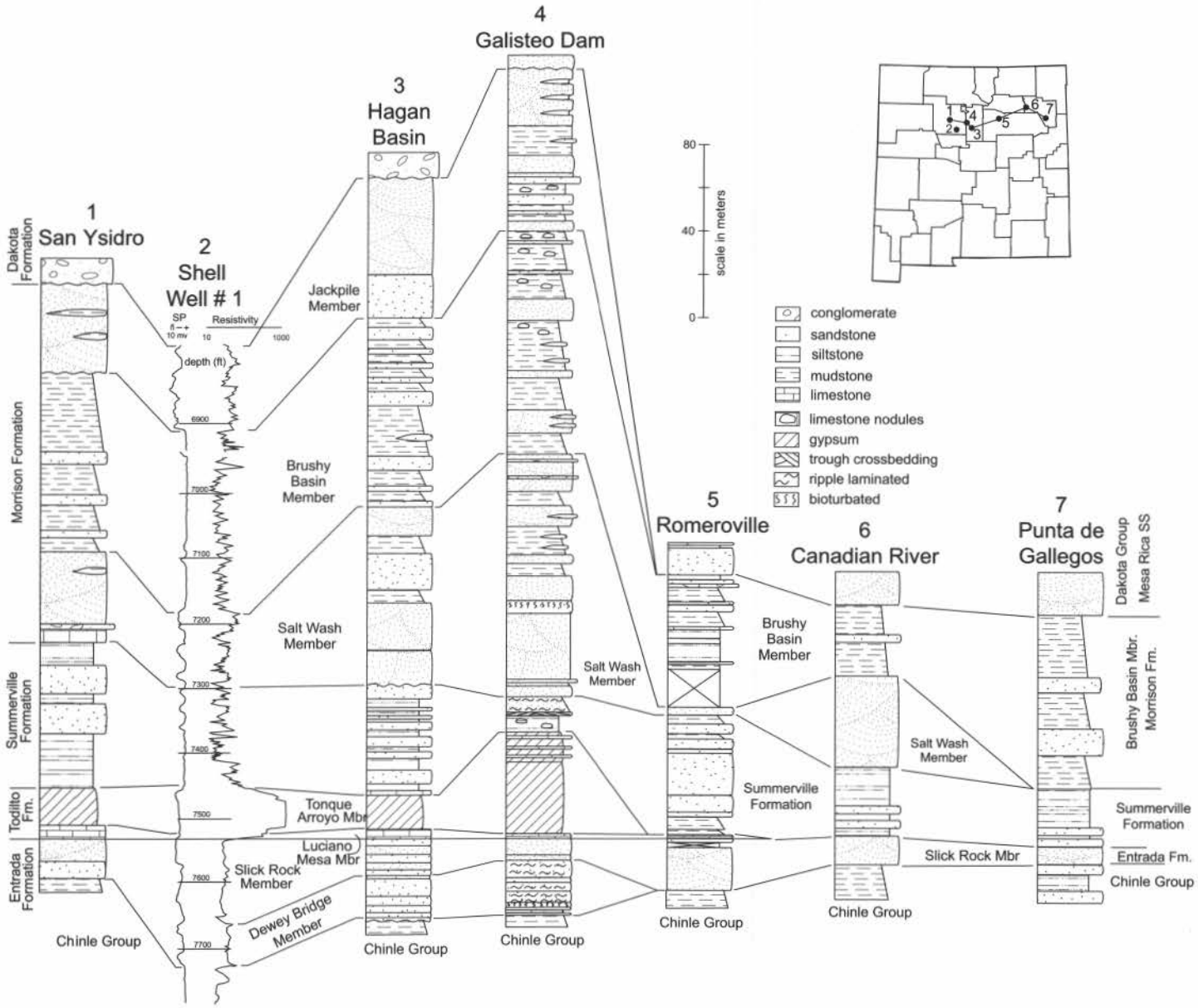

FIGURE 3. Correlation of Jurassic stratigraphic sections from the Colorado Plateau (San Ysidro) across the Rio Grande rift (Shell Well # 1, Hagan basin, Galisteo Dam) to east-central New Mexico (Romeroville Gap, Canadian River, Punta de Gallegos). Sections are from Lucas et al. (1999) except for sections at Canadian River (from Wanek, 1962) and Punta de Gallegos (from Lucas et al., 1985).

Morrison Formation

The Morrison Formation disconformably overlies the Summerville Formation in east-central New Mexico (Figs. 2-3). This is the J-5 unconformity of Pipiringos and O'Sullivan (1978). Lower Cretaceous strata (Tucumcari or Mesa Rica formations) disconformably overlie the Morrison Formation throughout this region; this is the K-0 unconformity of Pipiringos and O'Sulliuvan (1978).

The lower part of the Morrison Formation is as much as 50 m of subarkosic sandstone and conglomerate, the Salt Wash Member. The bulk of the formation is the overlying Brushy Basin Member, as much as 150 m of green and variegated, smectitic claystone and minor sandstone. Locally, the top of the Morrison Formation is a white, trough-crossbedded sandstone up to 15 m thick that may be a correlative of the Jackpile Member to the west (Holbrook et al., 1987).

REGIONAL SEDIMENTOLOGIC AND PALEOGEOGRAPHIC IMPLICATIONS

Jurassic strata in east-central New Mexico were deposited near or at the southeastern edge of the vast depositional basins that covered much of the Western Interior during the Middle and Late Jurassic. The older of these basins, here termed the San Rafael basin, is filled by the San Rafael Group, a westward thickening prism of sediments of mostly shallow marine, eolian and tidal flat origin. The San Rafael basin was a retroarc foreland basin that extended from Oklahoma-Nebraska on the east to Idaho-Nevada

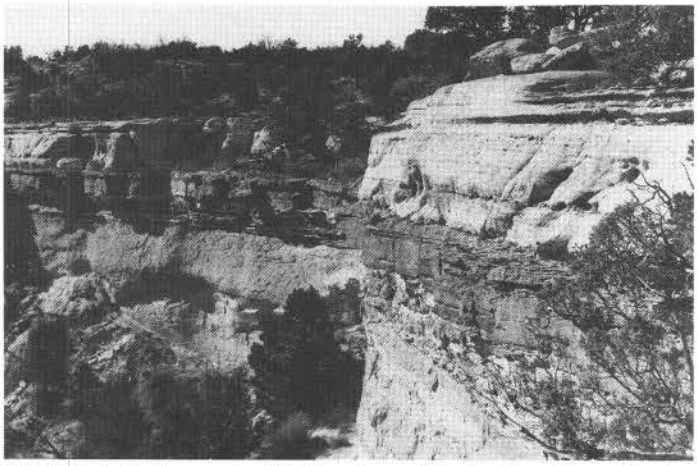

FIGURE 4. Dark, organic-rich limestone of the Luciano Mesa Member of the Todilto Formation above Slick Rock Member of Entrada Sandstone and beneath Exeter Member of Entrada; at Bull Canyon, T9N, R26E, Guadalupe County.

on the west (e.g., Kocurek and Dott, 1983; Lawton, 1994). The younger, Late Jurassic basin, the Morrison basin, had a similar geographic extent but was the site of fluvial deposition of the Morrison Formation by rivers derived principally from the uplifted and volcanically active arc terrane to the west.

Although most workers acknowledge that the Jurassic strata of east-central New Mexico were deposited as part of these vast depositional systems, the full implications of this have not always been appreciated. Here, we briefly review these implications with regard to the: (1) landward extent of the Middle Jurassic Carmel transgression; (2) Todilto salina deposition; (3) full extent of Summerville and related eolian facies; (4) tectonic reorganization of the depositional system at the beginning of Morrison time; and (5) deposition of the Brushy Basin Member of the Morrison Formation.

Carmel Transgression

During Bajocian time, a shallow sea transgressed into the San Rafael basin, and its southern tongue in Utah deposited the Carmel Formation (Fig. 5A). The Dewey Bridge Member of the Entrada Sandstone is laterally equivalent to the Carmel Formation and represents broad supratidal (sabkha) and coastal plain deposits of the Carmel seaway (e.g., Kocurek and Dott, 1983). The southeasternmost extent of the Dewey Bridge Member is in the Rio Grande valley of north-central New Mexico at Placitas, in the Hagan basin and at Galisteo Dam, about 450 km southeast of the Carmel shoreline near Moab, Utah.

The absence of the Dewey Bridge Member of the Entrada Sandstone in east-central New Mexico thus means that this region was landward of the marine influence (coastal plain environments) of the Carmel seaway. In east-central New Mexico, the base of the Entrada is the base of the Slick Rock Member, deposits of the vast early Callovian sand sea (erg) that covered much of the American Southwest after the retreat of the Carmel seaway (Blakey et al., 1988). This means that the J-2 unconfomity at the

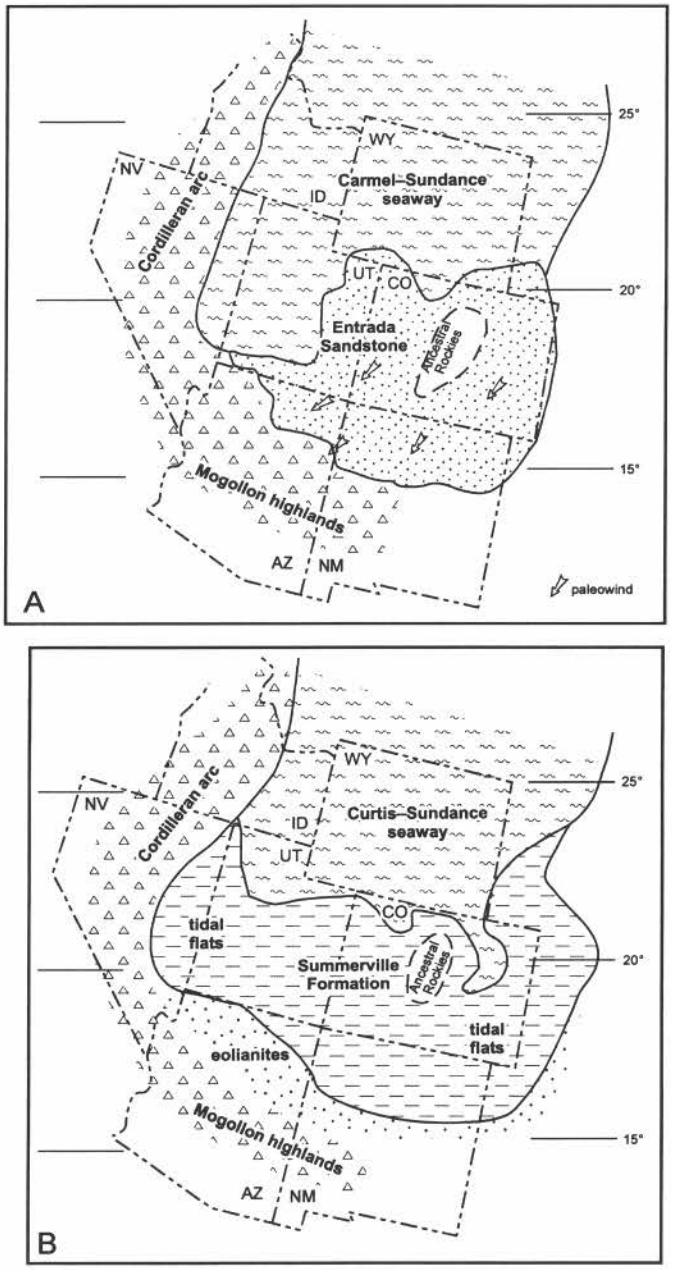

FIGURE 5. Simplified paleogeographic maps of part of San Rafael Group deposition (after Kocurek and Dott, 1983). A. Carmel-Entrada time (Bajocian-early Callovian). B. Summerville time (late Callovian-Oxfordian).

base of the Entrada represents a longer hiatus in east-central New Mexico than to the west in the Rio Grande rift and on the Colorado Plateau.

Todilto Deposition

Anderson and Kirkland (1960) early recognized the continuity of deposition of the Todilto Formation from the Four Corners region to as far southeast as eastern Guadalupe County (Fig. 6). However, until the 1980s most workers regarded the Todilto as deposits of a marine embayment of the Curtis seaway (e.g.,

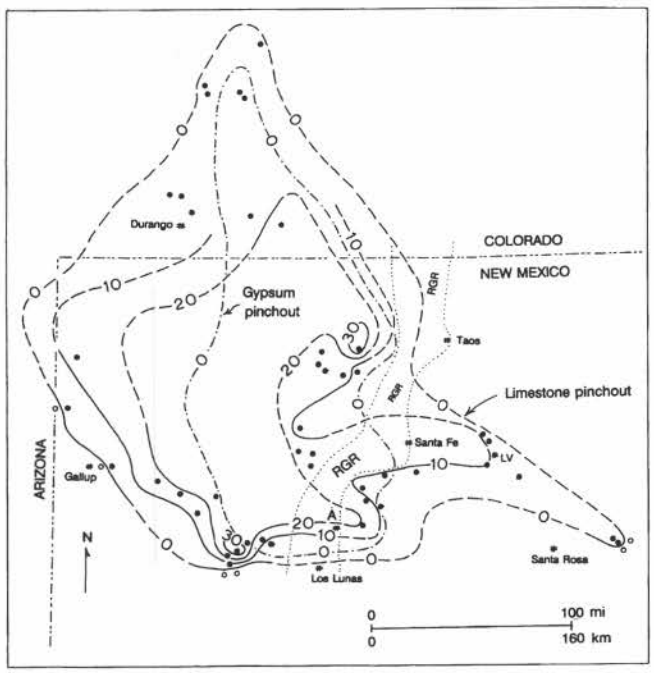

FIGURE 6. Approximate depositional limits of Jurassic Todilto limestone member (Luciano Mesa Member) and overlying Todilto gypsum member (modified from Ash, 1958; Kirkland et al., 1995). Dotted outline is Rio Grande rift (RGR). A = Albuquerque, LV = Las Vegas. Structure contours for Todilto limestone member are in feet.

Harshbarger et al., 1957; Anderson and Kirkland, 1960; Ridgley and Goldhaber, 1983). Nevertheless, several lines of evidence suggest that the Todilto depositional basin had little connection to the Jurassic seaway for most of its history and instead was a vast, paralic salina:

1. No direct stratigraphic continuity of Todilto strata and marine Jurassic strata exists, either on outcrop or in the subsurface. The Todilto evidently pinches out around its basin periphery into eolianites (Lucas et al., 1985; Anderson and Lucas, 1992).

2. No clearly marine fauna or flora are known from the Todilto Formation. Instead, a very low diversity fish fauna, as is characteristic of saline lakes, is known from the Todilto (Barbour and Brown, 1974; Lucas et al., 1985). Indeed, the low diversity fish and invertebrate fauna of the Todilto are strikingly similar to that of Quaternary salinas in Australia (e.g., Warren, 1982; Warren and Kendall, 1985). Armstrong (1995) claimed that the dasyclad algae found in the Todilto near Grants, New Mexico, indicate a marine environment, but today these blue green algae tolerate a wide range of salinity from fresh to hypersaline waters.

3. Carbon and sulphur isotope ratios calculated for Todilto limestones have a wide range of values compatible with a nonmarine, marine or mixed waterbody (Kirkland et al., 1995). However, strontium isotope ratios for the Todilto do not match those of sediments deposited from normal marine Callovian seawater (Kirkland et al., 1995).

Reconstructing the Todilto paleoenvironment as a salina is consistent with all data. Todilto deposition was initiated by marine flooding of an extensive area of low relief as the Curtis-Sundance transgression began (Fig. 5B). This supports the contention that the Todilto base, as far east as Guadalupe County, is the J-3 unconformity, which is the transgressive unconformity at the base of the Curtis Formation (Pipiringos and O'Sullivan, 1978). Following the flooding event, the Todilto basin was isolated from the seaway by coastal ergs. Freshwater stream runoff, influx of seawater by seepage through the erg, and possible short-lived overtopping of the erg replenished and maintained the Todilto salina. Increased aridity promoted evaporation, which eventually produced a smaller, evaporitic basin in which gypsum precipitated.

Summerville Deposition

During the Callovian-Oxfordian transgression and regression of the Curtis seaway, restricted marine and tidal flat deposits accumulated across much of Utah, Colorado and adjacent areas, including east-central New Mexico (Fig. 5B). The resulting broadly deposited lithosome merits one name, Summerville Formation, to express its continuity and lithologic integrity across this broad area. It has received numerous other names, including Wanakah, Beclabito, Bell Ranch and Ralston Creek, all of which should be abandoned.

Along the southern margin of Summerville deposition, and also immediately after Summerville deposition ended, eolian sediments accumulated. These eolianites were landward of the Summerville tidal flats, and in some areas encroached on them after Summerville deposition ceased. In east-central New Mexico, they are the Exeter Member of the Entrada Sandstone, strata homotaxial to the Bluff Sandstone and Acoma Tongue of the Zuni Sandstone in west-central New Mexico. The general similarity of depositional patrterns along the southern and southeastern edge of the Summerville tidal flat system is striking, though many details remain to be deciphered.

J-5 Unconformity

The onset of Morrison Formation deposition represents a significant tectonic reorganization of the Jurassic depositional system in the Western Interior. Prior to Morrison deposition, sedimentation in the San Rafael basin was by eolian, shallow marine and tidal flat systems in a relatively quiescent tectonic setting with source areas along the basin's western, southern and eastern perimeters. However, in Morrison time, deposition was primarily by easterly flowing rivers derived from the uplifted arc terrane to the west culminated by broad floodplains with a significant influx of altered volcanic ashes from the west (Fig. 7).

The J-5 unconformity at the base of the Salt Wash Member of the Morrison Formation thus is a tectonosequence boundary. It can be traced from the Salt Wash type section near Moab, Utah, across the Colorado Plateau and the Rio Grande rift onto the Southern High Plains of east-central New Mexico.

In east-central New Mexico, the thickness of the Salt Wash Member is highly variable, and at some localities it is absent, so the Brushy Basin Member rests directly on the Summerville Formation. We interpret this as a consequence of the hiatus associated with the J-5 unconformity. Thus, Salt Wash fluvial depos-

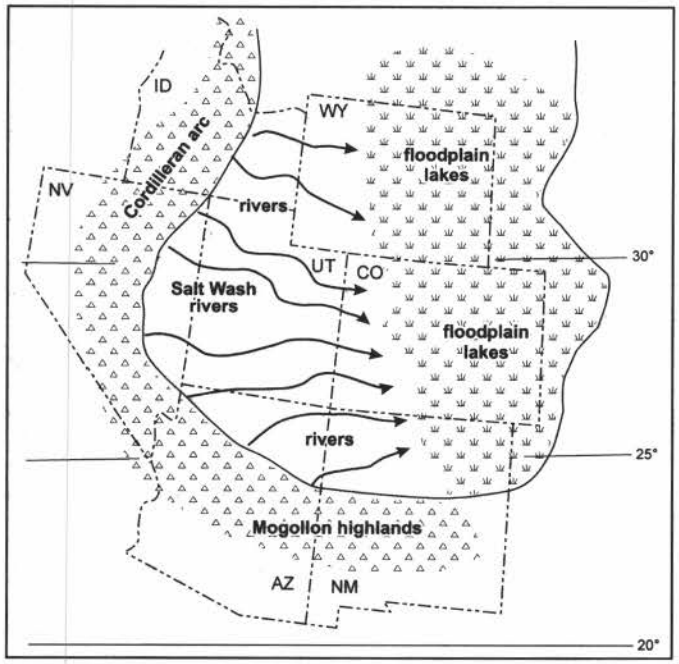

FIGURE 7. Simplified paleogeographic map of Late Jurassic Morrison Formation deposition.

its filled in topographic lows eroded into underlying San Rafael Group deposits during the J-5 hiatus. On the topographic highs, Morrison deposits did not accumulate until later, when Brushy Basin Member claystones blanketed the region.

Brushy Basin Member Deposition

Brushy Basin Member strata are the bulk of the Morrison Formation in east-central New Mexico. Indeed, the Brushy Basin Member is the most widely distributed interval of the Morrison, being found essentially across its entire depositional basin, from Utah to Nebraska and from New Mexico to Alberta (Peterson, 1972).

Significantly, Turner and Fishman (1991) argued that Brushy Basin Member deposition took place in a large lake in the Four Corners region, as much as 500 km in maximum dimension (NW-SE). This lake, termed Lake T'oo'dichi' (T'oo'dichi' is Navajo for "bitter water") was thought to be shallow, perhaps periodically drying up, with widely varying water chemistry, including high pH. However, most of the Brushy Basin outcrop belt lies outside of the margins of hypothesized Lake T'oo'dichi', and, indeed, the evidence presented to support the presence of the lake in the Four Corners region was seriously flawed (Anderson and Lucas, 1997).

Lacustrine deposits are present in the Brushy Basin Member throughout its outcrop belt, and these represent small, shallow, alkaline playa lakes surrounded by broad mudflats that laterally passed into adjacent alluvial environments (e.g., Dunagan, 2000). Brushy Basin Member facies in east-central New Mexico indicate this type of depositional setting (Lucas et al., 1985). The model of Lake T'oo'dichi' is not valid for Brushy Basin deposition in the Four Corners, nor does it explain Brushy Basin Member deposition across its vast outcrop area.

REGIONAL TECTONIC IMPLICATIONS

Jurassic stratigraphic data from east-central New Mexico have important implications for regional tectonic analyses concerning the timing and amount of movement of the Colorado Plateau during post-Jurassic time. It has been accepted since the 1950s (Kelley, 1955) that during the Laramide orogeny of Late Cretaceous and Paleogene age, the Colorado Plateau moved northeast with respect to the Rocky Mountain foreland to the north and the craton to the east (Fig. 8). The amount of resultant right slip on the eastern side of the plateau has been a topic of debate, with estimates ranging from 5 to 170 km.

Chapin and Cather (1981) estimated that the Colorado Plateau moved 60 to 120 km to the north-northeast relative to the crustal block to the east. They based their estimate largely on the presumed amount of crustal shortening across thrust and reverse faults to the north of the plateau in the Wyoming province (Fig. 8); the shortcoming of this approach was that it did not consider continuity of Mesozoic strata eastward from the plateau onto the craton (e.g., McKee et al., 1956; Hook et al., 1983). Chapin and Cather (1981) proposed that the decoupling occurred within a north-trending zone as wide as 100 km, marked by the Nacimiento fault system on the west, with most of the motion on

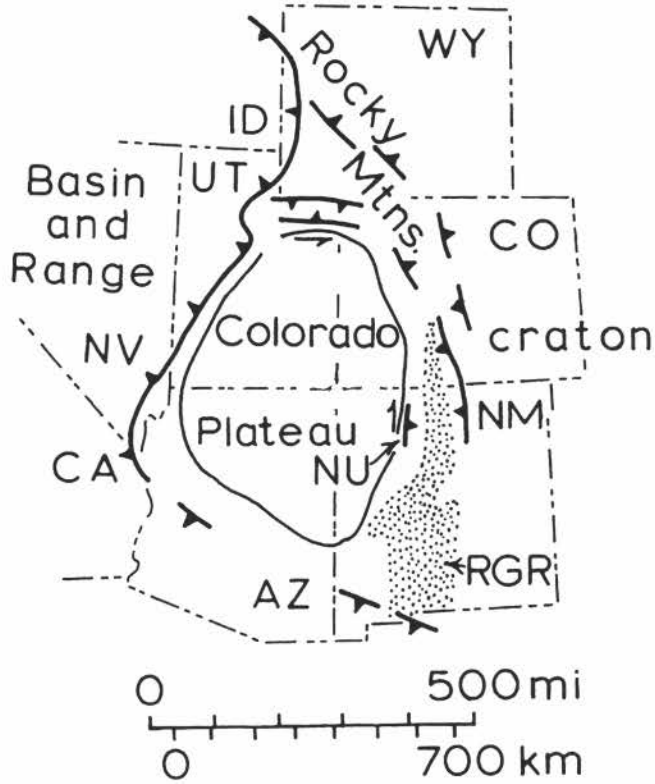

FIGURE 8. Location of Colorado Plateau and adjacent tectonic provinces. NU = Nacimiento uplift and RGR = Rio Grande rift (stippled).

faults that are now buried by the sedimentary fill of the Neogene Rio Grande rift. However, determining the amount of Laramide strike slip along the eastern margin of the Colorado Plateau and the Rio Grande rift region is complicated by the likelihood that strike-slip displacement may have occurred on some of the faults during the Precambrian, during the late Paleozoic, and again during the Neogene.

Following Chapin and Cather's (1981) model, Karlstrom and Daniel (1993) proposed that Proterozoic rocks demonstrated 100 to 170 km of Laramide right slip along several north-striking faults that they suggested were precursors of the Rio Grande rift. They proposed that the intersection of a regionally subhorizontal isobaric metamorphic surface with subvertical stratigraphic contacts and preexisting structures created piercing lines that could be used to indicate net displacement since about 1.4 Ga. Displacements of about 15 km across the Tusas-Picuris fault (Karlstrom and Daniel, 1993) and 37 km across the Pecos-Picuris fault (Miller et al., 1963) appear to be reasonable estimates, but these amounts of offset were constrained only as post-1.4 Ga. Miller et al. (1963) inferred that the right slip on the Pecos-Picuris fault probably occurred during the Precambrian.

Woodward et al. (1997) presented data from Jurassic isopach maps by McKee et al. (1956) that defined regional, east-trending piercing lines that permit 5 to 20 km of right slip between the eastern margin of the Colorado Plateau and the craton to the east (Fig. 9). However, Cather (1999) re-interpreted Jurassic and Cretaceous stratigraphic data that he felt were permissive or supportive of a minimum right slip of ~85 km on the eastern side of the Colorado Plateau. He included 13 km of well demonstrated right shift on the east side of the Defiance uplift in his estimate. The Defiance uplift, however, is within the Colorado Plateau, so it is irrelevant to the displacement on the eastern side of the Plateau.

Cather's (1999) paper was discussed by Ingersoll (2000), Lucas et al. (2000) and Woodward (2000). The thrust of Ingersoll's (2000) criticism was: (1) Cather's stratigraphic data were completely compatible with other models for Laramide deformation in this area, models not cited by Cather; (2) Cather's compilation does not provide a definitive choice among the various models; (3) interpretations of deflections of stratigraphic piercing lines were influenced by Cather's favored model; and (4) no lower limit on right slip was set by the stratigraphic data presented by Cather.

Lucas et al. (2000) noted that in Cather's (1999) paper the differences in depiction of data and analysis of previous workers stem primarily from: (1) selective use of part of, not the entire, database; (2) drawing trend lines on the basis of one data point; and (3) mistaken interpretation of data points. They presented precise examples to illustrate the problems in Cather's (1999) paper.

Woodward (2000) pointed out two major errors that caused Cather's (1999) estimate of a minimum of ~85 km of right slip to be highly questionable. A major problem concerns his failure to recognize that vertical surfaces as well as linear features can be used to determine lateral separation along major strike-slip faults. Also, his assumption that Phanerozoic pre-Laramide strike-slip motion on these faults was necessarily sinistral (Cather, 1999, p. 849) is not warranted (Ye et al., 1996; Woodward et al., 1999). In a paper dealing with phases of Laramide deformation in north-central New Mexico, Erslev (2001) concluded that the complexity of sedimentary patterns noted by Cather (1999) and the lack of consistent fault separations interpreted by Cather allow the possibility of no right lateral slip.

STRATIGRAPHIC DATA AND TECTONIC ANALYSIS

Lines that can provide piercing points where they meet fault surfaces include stratigraphic pinchouts and marker beds truncated beneath an angular unconformity (Crowell, 1959). In northern New Mexico, Jurassic strata are truncated southward by a regional, low-angle unconformity beneath overlying Cretaceous strata (e.g., Dobrovolny et al., 1946; Silver, 1948).

Paleotectonic maps of the Jurassic System by McKee et al. (1956) show zero isopach lines for three stratigraphic sequences (intervals B, C, and D of McKee et al., 1956) where the Entrada Sandstone, Todilto and Summerville formations, and the Morrison Formation are truncated by overlying Cretaceous strata. Although the precise placement of the zero isopach lines for the Entrada Sandstone (Fig. 9A) and the Morrison Formation (Fig. 9B) can be questioned, the overall patterns (Lucas et al., 1985) clearly indicate that 5 to 20 km of right slip can be accommodated along the Rio Grande rift, but certainly not 60 to 170 km. In a structural sense, isopach lines on maps represent surfaces of specific vertical dimensions that will show lateral separation if offset by strike-slip faulting. Isopach lines shown for Jurassic strata (Fig. 9) thus confirm a maximum of 5 to 20 km of right slip between the Colorado Plateau and the craton to the east.

Near Carthage, New Mexico, about 88 km south of the regional wedge-edge of the Morrison Formation (Fig. 9B), ~1 to 3.3 m of possible Morrison strata lie above Triassic Chinle Group strata and below the Cretaceous Dakota Formation (Hunt and Lucas, 1987). There is no indication of any Morrison Formation strata between the regional wedge edge, shown in Figure 9B, and Carthage or south of Carthage. Hunt and Lucas (1987) suggested that the Morrison Formation was preserved from erosion either by being deposited in a topographic low or by a local downwarp before deposition of the overlying Dakota Formation. These limited, thin outcrops do not define a regional piercing line and therefore cannot be used to determine strike-slip movement. Cather (1999) mistakenly assumed that this outcrop defined the regional southern wedge-edge of the Morrison and used it to estimate an unwarranted large amount of right slip across the Rio Grande rift.

One of the most impressive piercing lines involving Jurassic strata is the wedge edge of the lower, limestone-dominated Luciano Mesa Member of the Todilto Formation (Fig. 6). This thin (mostly <6 m), highly distinctive unit represents deposition in a huge saline lake basin during the Callovian (see above). Isopachs of the Luciano Mesa Member reveal no offset of it or its southward depositional pinchout (zero isopach) across the Rio Grande rift. Restoration of 60 to 170 km of right slip within the Rio Grande rift creates a paleodepositional geometry for the Todilto basin that is very unlikely (Woodward et al., 1997, 1999).

In summary, regional eastward-trending piercing lines defined by stratigraphic truncations and depositional patterns in Jurassic

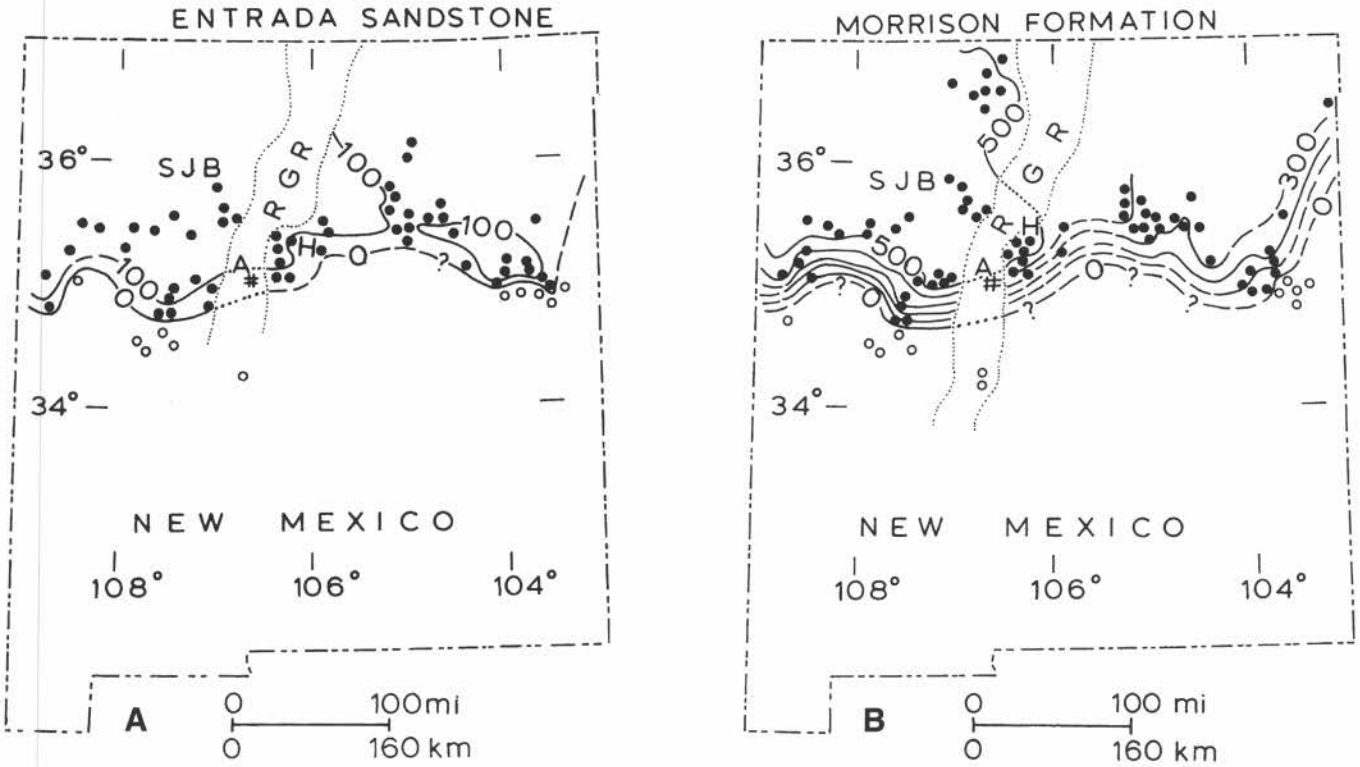

FIGURE 9. A. Thickness of Entrada Sandstone (interval B of McKee et al., 1956) showing wedge edge (zero isopach line). Contour interval is 100 ft (30 m). Solid circles show where Entrada Sandstone is present; open circles show where Entrada is absent, and older rocks are overlain by younger Jurassic or Cretaceous strata. B. Thickness of Morrison Formation and correlative strata (interval D of McKee et al., 1956) showing wedge edge (zero isopach line). Contour interval 100 ft (30 m). Solid circles show where Morrison is present; open circles show where Morrison is absent and older rocks are overlain by Cretaceous strata. A = Albuquerque, H = Hagan basin, RGR = Rio Grande rift (dotted outline), and SJB = San Juan basin. Modified from McKee et al. (1956).

strata in north-central New Mexico allow 5 to 20 km of right slip between the eastern margin of the Colorado Plateau and the craton to the east in Laramide (Late Cretaceous-Paleogene) and younger time. Estimates of 60-170 km of Laramide right slip by previous workers are not supported by Jurassic stratigraphic data. Restoration of 60-170 km of right slip creates lateral offset of the north-south extent of the Jurassic Todilto Formation, producing an untenable paleodepositional basin geometry.

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