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THE JURASSIC SYSTEM IN EAST-CENTRAL NEW MEXICO

SPENCER G. LUCAS, KENNETH K. KIETZKE and ADRIAN P. HUNT
Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131

INTRODUCTION

Jurassic sedimentary rocks are widely exposed in east-central New Mexico (Fig. 1). These rocks pertain to four rock-stratigraphic units (Entrada, Todilto, Bell Ranch and Morrison) and represent eolian, lacustrine and fluvial deposition during the middle to Late Jurassic.

Although Marcou (1855) first identified Jurassic strata in east-central New Mexico, no attempt, other than Mankin (1958a, 1972), has been made to analyze the stratigraphy, sedimentology and paleontology of the Jurassic in this part of the state. This paper presents such an analysis, based primarily on data reported by earlier workers or collected by ourselves from 86 control points in east-central and northeastern New Mexico (Fig. 2). Notes to the text of this paper are indicated by numbers in brackets (e.g., **[1]**) and are in Appendix 1. Rock colors follow the classification of Goddard et al. (1979), and UNM refers to the Department of Geology, University of New Mexico.

ENTRADA SANDSTONE

Introduction

Gilluly and Reeside (1928) originally named the Entrada Sandstone for exposures at Entrada Point in the northern part of the San Rafael Swell, east-central Utah. The Entrada is now well known as a sandy unit, predominantly of eolian origin, present in parts of Utah, Arizona, Colorado and New Mexico (Imlay, 1980).

Heaton (1939) first applied the name Entrada to the oldest Jurassic rocks in east-central New Mexico (Fig. 3). Prior to his work, and even after it, some stratigraphers of the U.S. Geological Survey used the name "Wingate Sandstone" for rocks in east-central New Mexico now recognized as Entrada (Fig. 3). In addition, Lee (1902) proposed the term Exeter Sandstone for the oldest Jurassic strata near Battleship Mountain in the Dry Cimarron Valley of northeastern New Mexico.

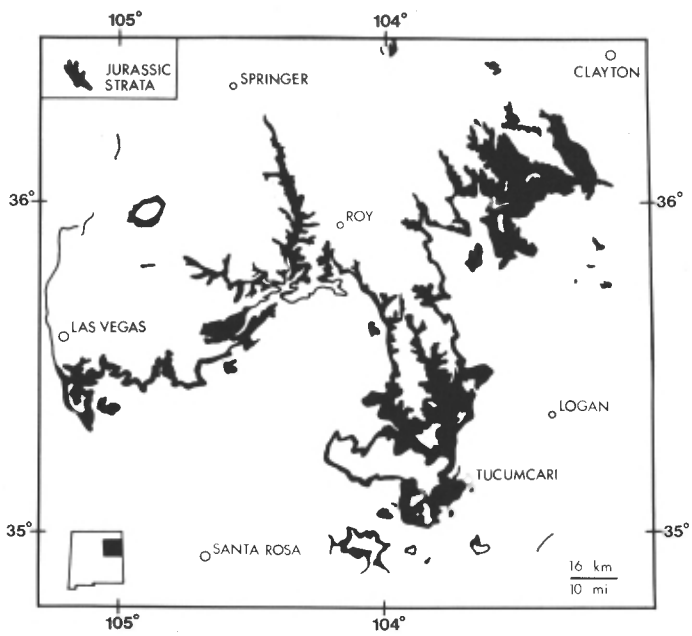


FIGURE 1. Outcrops of Jurassic rocks in east-central New Mexico (based on Dane and Bachman, 1965).

Furthermore, Bachman (1953) applied the term "Ocate Sandstone" to the basal Jurassic strata in northwestern Mora County.

Exeter Member

Lee (1902, pp. 45–46) named the Exeter Sandstone for strata near Exeter **[1]** in northeastern New Mexico (Fig. 3). He described it as "a firm, hard and rather coarse but evenly laminated sandstone, pink to white in color" (Lee, 1902, p. 45). Lee's (1902, fig. 5) measured stratigraphic section of the Exeter indicates two sand sequences split by a thin bed of shaly sandstone (Fig. 4). The entire Exeter in its type area is about 23 m thick (Lee, 1902).

Subsequent workers (Stanton, 1905; Duce, 1924; Rothrock, 1925; DeFord, 1927; Darton, 1928; Parker, 1930, 1933, 1934; Sanders, 1934) extended the distribution of the Exeter into southeastern Colorado and western Oklahoma. Some of these workers also argued over the precise stratigraphic position and, thus, the age of the Exeter Sandstone (assignments ranged from Permian through Early Cretaceous). However, in 1939 Heaton convincingly correlated the Exeter with the Entrada Sandstone, a conclusion later accepted by Stovall (1943). Stovall, however, continued to use the name Exeter. He also designated a type section of the Exeter in sec. 32, T32N, R35E, Union County, a locality different from, but near, that described by Lee (1902, figs. 4–5)**[2]**. Stovall (1943, p. 52) did not describe this section in detail, but noted that "the Exeter has a thickness of 80 feet [24.4 m], is typical of the formation as it is exposed at Ship Rock butte [Battleship Mountain of current usage] and elsewhere in the vicinity, and is sharply separated from overlying and underlying beds."

It is clear from the work of Heaton (1939), and subsequent work by Cooley (1955) and Baldwin and Muehlberger (1959), that the term Exeter Sandstone is synonymous with Entrada Sandstone. Therefore, the name Exeter should be rejected, and it should not have been used in east-central New Mexico by Mankin (1958a, b, 1972). Despite this, we continue usage of the term Exeter by redefining it as a member (upper tongue) of the Entrada Sandstone in northeastern and east-central New Mexico.

In a 3- to 4-km area around Battleship Mountain and Wedding Cake Butte (Fig. 4) in the Dry Cimarron Valley of northeastern Union County, the Exeter consists of two sandstone beds separated by a finer grained interval (Lee, 1902; Baldwin and Muehlberger, 1959). The lower sandstone is equivalent to the main body of the Entrada Sandstone elsewhere (Baldwin and Muehlberger, 1959). We believe the upper sandstone body is the same unit that overlies the Todilto Formation in Bull Canyon (Fig. 9). The thin, finer grained interval that separates the two Entrada sandstone bodies in the Dry Cimarron Valley represents the Todilto stratigraphic interval. This interval is thus homotaxial with the "notch" identified in west-central New Mexico by Anderson (1983a, b) within his Zuni Sandstone, that is, between the upper Entrada and the Cow Springs or Bluff Sandstones of most workers (Kietzke and Lucas, 1984). This "notch," and its apparent correlative in east-central and northeastern New Mexico, is the erosional unconformity that developed on top of the Entrada erg landward of the Todilto salina. The Exeter thus is homotaxial with the Cow Springs and Bluff Sandstones in the sense that these terms are used on the margins of the Todilto salina in west-central New Mexico (Condon and Huffman, 1984; Kietzke and Lucas, 1984).

We designate the type section of the Exeter Member as part of the section described by Lee (1902, fig. 5). We are in agreement with Baldwin and Muehlberger (1959, p. 46) that this section is in the SW¼ SE¼, sec. 28, T32N, R35E and is the section Lee (1902) intended to

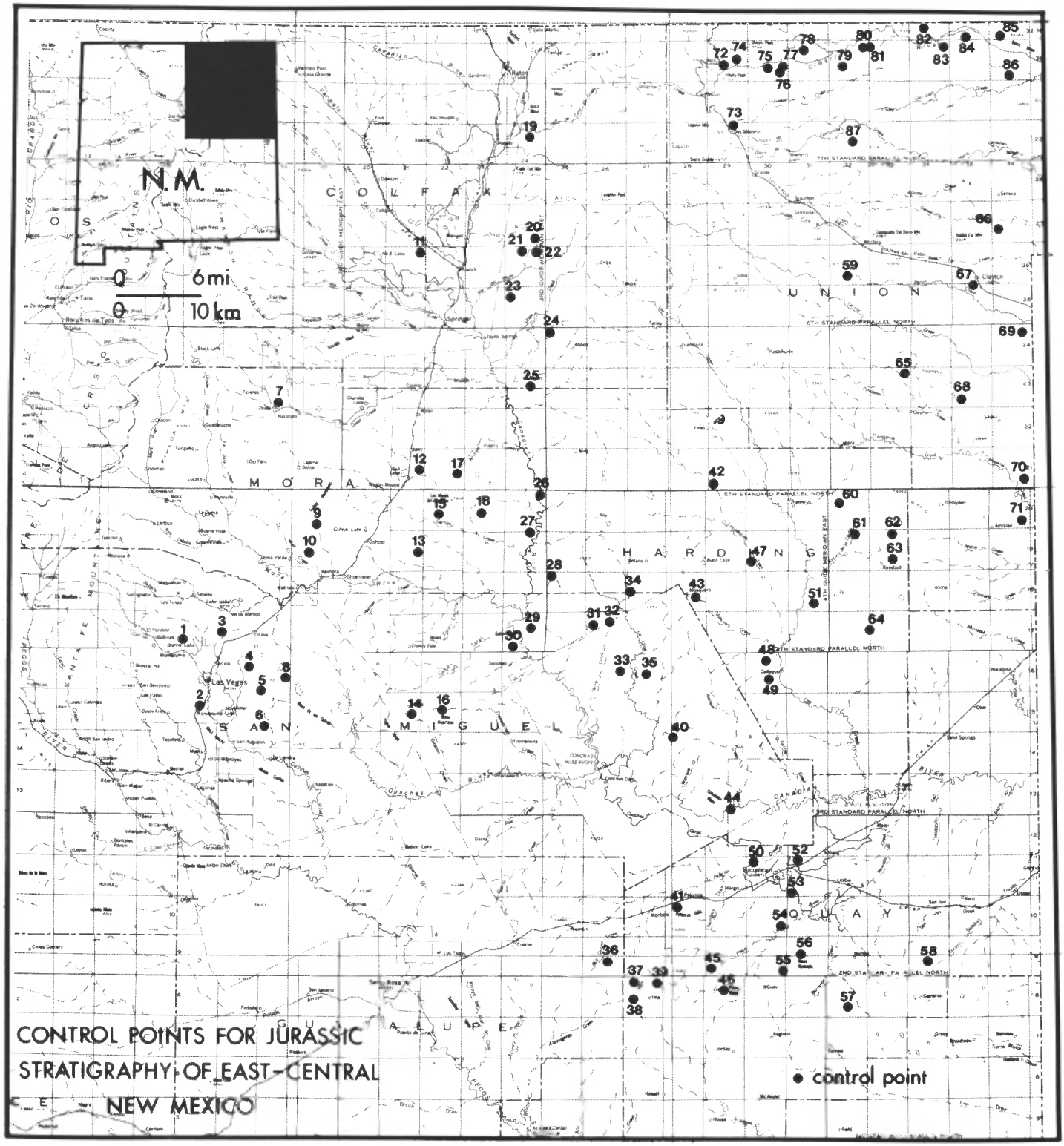


FIGURE 2. Distribution of the control points used in this study. See Appendix 2 for locations and sources of control points.

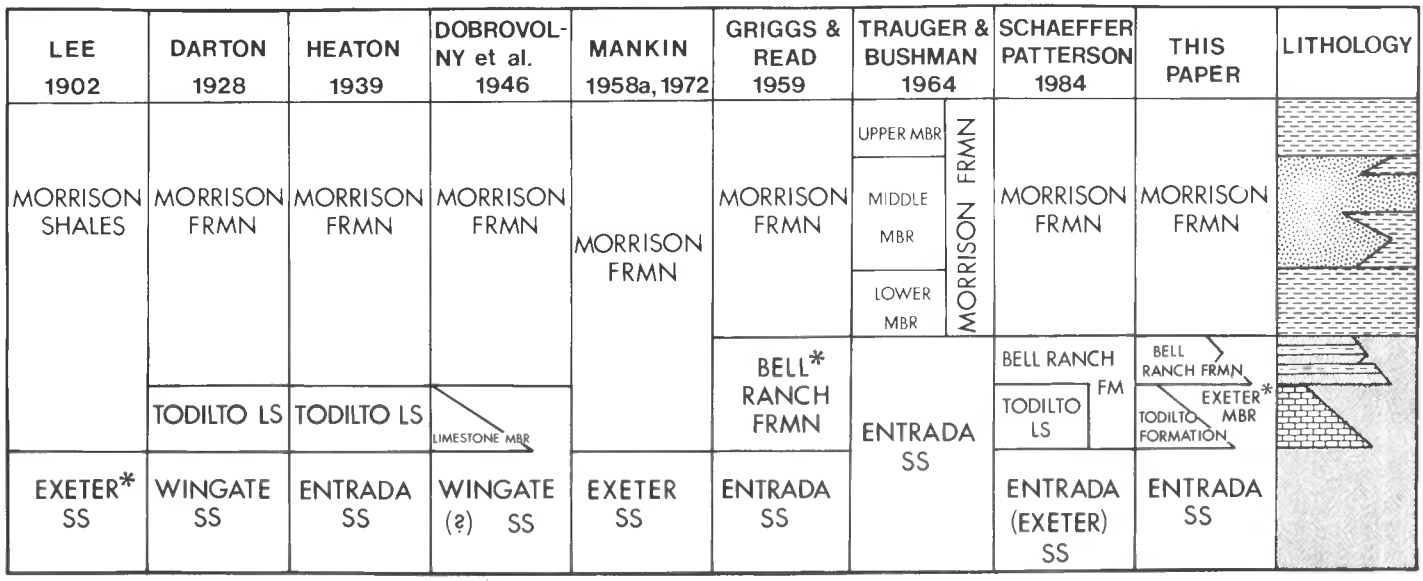


FIGURE 3. Stratigraphic nomenclature of Jurassic rocks in east-central and northeastern New Mexico used by previous workers compared with the nomenclature advocated in this paper.

be the type section of the Exeter. Because we have redefined the Exeter, only the upper 17.7 m of Lee's original Exeter are here identified as the Exeter Member of the Entrada Sandstone.

In the Dry Cimarron Valley (Cooley, 1955), south of Bueyeros (Baldwin and Muehlberger, 1959), south of Gallegos (Baldwin and Muehlberger, 1959), west of Stead (Baldwin and Muehlberger, 1959) and at Carpenter's Point (Figs. 18, 19), other tongues of the Entrada occur within or above the Bell Ranch Formation. It is likely that these tongues are not the same unit as the Exeter Member, but a more detailed study of these units is necessary to elucidate their stratigraphic relationships to the main Entrada body.

Ocate Sandstone

Bachman (1953), in a map of part of northwestern Mora County, named two rock-stratigraphic units he believed to be of Jurassic age, the Naranjo Formation and the Ocate Sandstone. The Naranjo clearly is equivalent to Dobrovolny et al.'s (1946) Redonda Member of the Chinle Formation and, therefore, is of Late Triassic age (Lucas et al., 1985). The Ocate Sandstone overlies the "Naranjo" in northwestern Mora County and was described by Bachman (1953) as follows:

> A gray, medium to massive, somewhat cross-laminated sandstone about 50 feet thick. . . . Typically the sandstone crops out in a rounded ledge. It is usually composed of medium-sized, well-rounded quartz grains that frequently have frosted surfaces. Ferruginous stains and calcite veinlets are common.

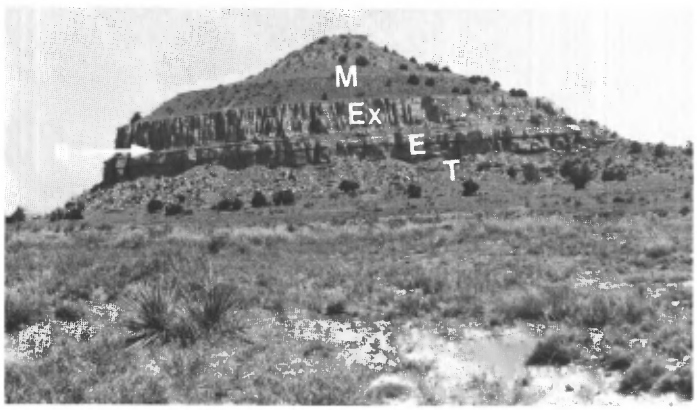


FIGURE 4. Wedding Cake Butte showing Triassic strata (T), main body of Entrada Sandstone (E), "notch" (n), Exeter Member of Entrada (Ex) and Morrison Formation (M).

In Bachman's (1953) map area, the Ocate underlies what he termed the Wanakah Formation "with apparent conformity." Bachman's Wanakah Formation clearly is equivalent to what most workers have termed the basal portion of the Morrison Formation in east-central and northeastern New Mexico (e.g., Mankin, 1958a, 1972; Baldwin and Muehlberger, 1959). Therefore, Bachman's Ocate Sandstone occupies the same stratigraphic position as does the Entrada Sandstone throughout east-central and northeastern New Mexico. Moreover, the lithology of the Ocate is identical to that of the Entrada. Indeed, Bachman (1953) stated that the Ocate "is probably correlative with the Entrada Sandstone of western New Mexico" and "may also be correlative with the Exeter Sandstone of northeastern New Mexico and northwestern Oklahoma." In light of this, we recognize the term Ocate Sandstone as synonymous with Entrada Sandstone and reject further usage of the term Ocate Sandstone.

Lithology

In east-central New Mexico, the Entrada Sandstone is dominated by massively crossbedded sandstone which is friable, poorly to moderately cemented, well-sorted and fine-grained (Mankin, 1958a). Unweathered samples range in color from white (N9) to pale reddish-brown (10 R 5/4) and, on weathered outcrop, range from white (N9) to yellowish gray (5 Y 8/1) (Mankin, 1958a). Throughout east-central New Mexico, the Entrada shows little variation in grain size or composition. The grains are well-sorted and well-rounded, and the sandstone is a mature to supermature subarkose (Mankin, 1958a). The most characteristic bedding is large-scale crossbedding, although both planar and small-scale crossbedding are present locally. Thin beds of red, silty mudstone are also present locally (e.g., Bull Canyon). The planar-bedded units may have coarse sand to pebble sized "lags" at their bases. Bioturbation has been reported from the top of the Entrada south of San Jon and in the Canadian River Canyon west of Roy (Savela, 1977), but these are in the Exeter Member as used in this report and not in the main body of the Entrada.

In most outcrops, the Entrada is a cliff-forming unit which can be identified easily from a distance by its topographic expression and its white to brownish-red color which contrasts markedly with the deep-red mudstones and lenticular sandstones of the units above and below it (Fig. 5). Where the Todilto Formation is present above the Entrada,

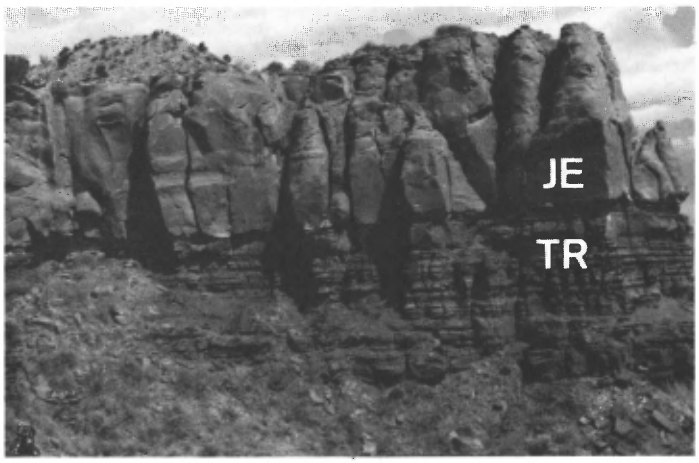


FIGURE 5. The Entrada Sandstone (JE) overlying the Redonda Member of the Chinle Formation (TR) at Carpenter's Point.

the underlying sandstone is often reduced (bleached); its color has been altered from the usual pale reddish-brown to pale green and white.

Lower contact

The lower contact of the Entrada is unconformable and locally angular, resting on either the Redonda Member of the Chinle Formation or, where the Redonda is absent, on the upper shale member of the Chinle Formation. The sandstones of the underlying Redonda are distinguished from those of the Entrada by their relatively thinner, planar bedding, poorer sorting and orangish-brown color. Redonda sandstones also are frequently bioturbated.

Thickness

The thickness of the Entrada in east-central New Mexico varies from 0 to about 53 m (Fig. 6). It is thickest near Ima (53.3 m) and is absent in the Saddleback Mesa area of Quay County where it appears to have been removed by post-Morrison, pre-Tucumcari tectonic activity and erosion.

There are five basins in east-central New Mexico where the Entrada is more than 25 m thick (Fig. 6). The largest basin extends northeastward from Las Vegas to western Harding County, where the Entrada reaches a thickness of 46.9 m. In northeastern Colfax County, the edge of a basin is preserved; it presumably extended into the northwestern portion of the county. In central Harding County, a smaller, shallower basin is present with a maximum thickness of 29 m of Entrada. The deepest basin is in Quay County, with 53.3 m of Entrada present at Tucumcari Mountain. In northeastern Union County, a northwest–southeast-trending basin contains up to 32.4 m of Entrada.

Throughout most of east-central New Mexico, the Entrada consists of a thick, cliff-forming, main sandstone member overlain by the thin Exeter Member. In the Exeter type area, this relationship is reversed, with the main sandstone body of the Entrada thin and the Exeter Member thicker and more prominent. It appears that the type area of the Exeter was a positive area during the deposition of Upper Triassic strata. Indeed, isopachs and sedimentological evidence indicate that a series of Late Triassic "hills" probably was present there (Baldwin and Muehlberger, 1959), and that the Upper Triassic Sheep Pen Sandstone (Parker, 1933) [3] represents alluvial aprons deposited around these topographic highs. Isopach data further indicate these "hills" were not completely buried until late in the Jurassic (Baldwin and Muehlberger, 1959). It therefore follows that the thinness of the main body of the Entrada Sandstone in northeastern New Mexico reflects deposition on these topographic highs and that deposition of the thicker Exeter Member followed the burial of these "hills."

Depositional environment

Numerous local studies have identified the Entrada Sandstone as an eolian sandstone in the Southwest (e.g., Kocurek and Dott, 1983). However, many studies also recognize local fluvial and lacustrine deposits within the Entrada. Mankin (1958a, b, 1972) studied the sedimentology of the Entrada in east-central New Mexico and concluded (Mankin, 1958b) that the Entrada in this region "was deposited as a dune sand in an interior basin" and that it contained "small playa lake-type deposits." This interpretation has been accepted by most subsequent authors with two exceptions.

Based on log probability graphs of grain-size distributions, Savela (1977, p. 35) concluded that the Entrada of east-central New Mexico "represents nearshore tidal currents, part of which may have been above sea level." Savela's (1977) studies were based on the work of Visher (1969) and Freeman and Visher (1975) on Recent environments. However, Walton et al. (1980) demonstrated that similar-looking cumulative frequency curves can be generated by a variety of truncation and mixing models, limiting their usefulness in environmental interpretation. Although some methods of grain-size analysis, particularly vertical grain-size-progression studies (e.g., Anderson et al., 1982) appear to be useful tools in the interpretation of depositional environments, random samples analyzed by log-normal plots appear to be of limited utility (Anderson et al., 1982). Jacka (1973) also considered the Entrada to be dominantly of marine origin, but provided no evidence to substantiate this view.

The combination of medium- to large-scale, planar crossbeds, with upward concave laminae, very good sorting and well-rounded grains indicates the dominant environment of Entrada deposition in east-central New Mexico was eolian (Bigurella, 1972; Collinson, 1978b). Smaller scale crossbeds plus laterally discontinuous sandstone bodies with planar bedding and basal lag deposits indicate that portions of the Entrada in east-central New Mexico were deposited by water. The water-laid deposits were deposited either on the "beaches" of playas, the shores of the Todilto salina or by ephemeral streams. The thin, lenticular mudstones were probably deposited in interdune playas.

Age

No age-diagnostic fossils are known from the Entrada Sandstone in east-central New Mexico. Therefore, the age assigned to the Entrada here is that assigned to it elsewhere, an assignment supported by its stratigraphic relationships to other, more securely dated rock-stratigraphic units. On the Colorado Plateau, the Entrada ranges in age from late Bathonian to late Callovian, but is usually of early to middle Callovian age (Imlay, 1980). Indications of the upper age limit of the Entrada can be gained from the Todilto Formation which lies within the Entrada in east-central New Mexico. The Todilto Formation contains a fish fauna considered early Callovian by Schaeffer and Patterson (1984). Since the Entrada rests unconformably on Upper Triassic strata, the lower age limit of the Entrada is open to question. It seems probable that the Entrada Sandstone in east-central New Mexico is early to middle Callovian in age, although its base could be older (Fig. 26).

TODILTO FORMATION

Introduction

Gregory (1916, 1917) coined the name Todilto Formation (originally Todilto Limestone) for rocks in Todilto Park, McKinley County, west-central New Mexico. Although Gregory first named the Todilto Formation, it had previously been observed near Fort Wingate, New Mexico, by Gilbert (1875) and, perhaps, Dutton (1885). Following Gregory's naming of the Todilto, it has been made a member of the Morrison Formation (Baker et al., 1936), a member of the Wanakah Formation (Baker et al., 1947) or a member of the Entrada Sandstone (Hoover, 1950). Most workers currently afford it formational status and include it in the San Rafael Group [4].

The Todilto in east-central New Mexico is of limited geographic extent and is rarely mentioned in the literature. Usually it has been mentioned with, or placed in, the Morrison or Bell Ranch Formations (Fig. 3). Foster et al. (1972) indicated its presence near Romeroville

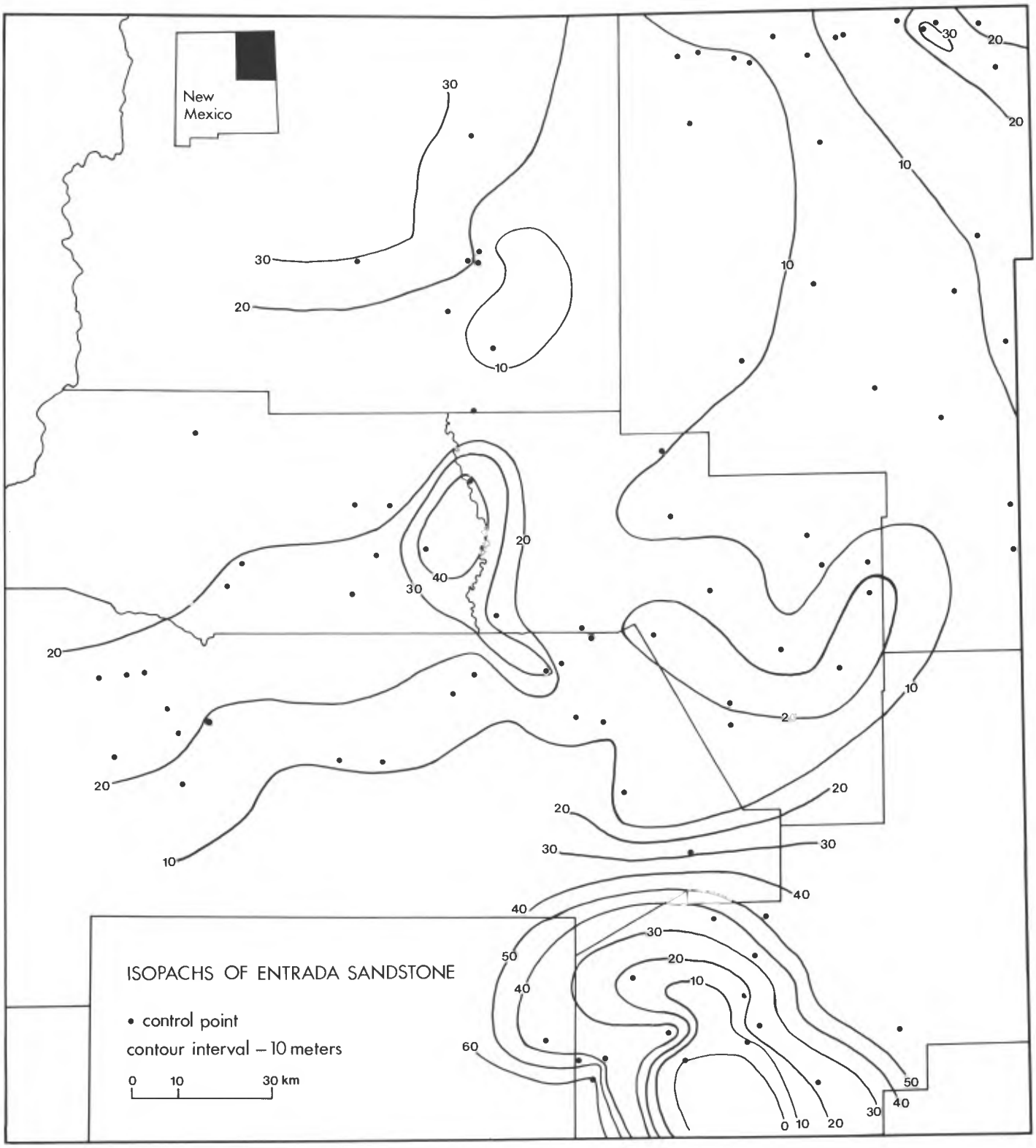


FIGURE 6. Isopach map of the Entrada Sandstone in east-central and northeastern New Mexico.

and near Montezuma, pinching out to the east. Dinwiddie and Clebsch (1973, p. 7) noted a "dark-gray, thin-bedded limestone" in the Bell Ranch Formation of Guadalupe County that is probably the Todilto Formation. The only specific studies of the Todilto in east-central New Mexico are those by Neef (1950) on outcrops near Las Vegas and some observations and a section of the Todilto by Ash (1958) on outcrops in the Bull Canyon area of Guadalupe County. We have published some preliminary observations on the Todilto Formation in Bull Canyon (Kietzke and Lucas, 1984; Lucas et al., 1984).

There has been considerable controversy concerning the origin of the Todilto Formation. The major area of contention is whether the Todilto was produced by a marine embayment (Harshbarger et al., 1957; Ridgley and Goldhaber, 1983; Schaeffer and Patterson, 1984) or was isolated from the sea (Rapaport et al., 1952; Anderson and Kirkland, 1960; Tanner, 1965, 1970, 1974; Vincelette and Chittum, 1981; Kocurek and Dott, 1983). We believe a salina model (Warren, 1982; Warren and Kendall, 1985) best fits the available evidence. To help put this model in perspective, a more regional, basinwide view of the Todilto is presented here instead of a view strictly centered on the Todilto in east-central New Mexico.

Lithology

The Todilto Formation is usually separated into a lower, more extensive, varved, limestone unit and an upper, less extensive, gypsum unit. These units are sometimes referred to as members (Anderson and Kirkland, 1960, p. 37). The limestone unit covers an area of about 88,000 km^2 in central and northwestern New Mexico and southern Colorado (Anderson and Kirkland, 1960, p. 37) (Fig. 7). It extends about 22 km into northeastern Arizona (O'Sullivan and Craig, 1973, p. 82). The gypsum unit is more restricted, being found in the basin axis and depocenter of northwestern and north-central New Mexico (Stapor, 1972, p. 59) (Fig. 7).

The Todilto Formation limestone unit is usually separated into a lower, thinly laminated, varved unit and an upper massive unit. The lower laminated unit is often referred to as the "platey limestone" (e.g., Lookingbill, 1953; Hutson, 1958). In some areas, the fine laminations are contorted and microfolded and are referred to as "crinkly limestone." The varved limestone has been shown to consist of three-part varves that consist of a precipitated limestone varve, a thin organic varve and a scattered, thin, but persistent, clastic varve (Anderson and Kirkland, 1960). Varve counting suggests that the limestone unit of the Todilto represents 14000 years (Anderson and Kirkland, 1960). Microfolding of the "crinkly" and brecciated zones has been shown by Kirkland and Anderson (1970) to be related to the hinge areas and limbs of large-scale, tectonic folds. Stapor (1972) considered the "limestone breccia member" to be a residual deposit of broken limestone laminae that followed karst removal of layers in the lower gypsum. Rawson (1980, pp. 306–308) considered the breccia zones to be the result of gypsum dissolution during low lake levels.

The "massive limestone" occurs over much of the Todilto depositional basin and is characterized by poorly developed bedding and laminae. This unit has been referred to as "recrystallized" by Rawson (1980), who also noted evidence of mud cracks and development of "algal domes." This unit is characteristically vuggy, sometimes having a "cellular appearance" (Emerick, 1950). In some areas this unit is composed of breccia (Harrison, 1949; Kelley and Northrop, 1975).

The gypsum unit of the Todilto is composed of thick, grayish-white gypsum that is anhydrite in the subsurface (Maxwell, 1982). Although this unit is often referred to as massive, Anderson and Kirkland (1960) found it to be varved and transitional with the underlying limestone. Kelley and Northrop (1975) recognized five different textures in the gypsum near Albuquerque. The thickness of the gypsum can vary greatly over a short distance (Lookingbill, 1953). This variation in thickness has been attributed to erosion (Lookingbill, 1953; Hutson, 1958), to the dune topography of the underlying Entrada (Tanner, 1965; Vincelette and Chittum, 1981), to a combination of dune and subaqueous bar formation modified by "non-karst solution" (Tanner, 1972) or to karst solution (Stapor, 1972). The karst hypothesis is supported by the presence of a limestone breccia blanketing the gypsum mounds in the Ghost Ranch area (Stapor, 1972) and a similar coating by red and gray chert fragments and carnelian grains (= "agate bed") **[5]** in the Albuquerque area (Reynolds, 1954; Kelley and Northrop, 1975). Also, Muehlberger (1967) noted fragments of Todilto Formation in the sandstones of the lower Morrison in the Chama area. Stapor (1972) reported draping of the lower Morrison over these karst features in the Chama area, indicating that karst formation continued into Morrison time. The period of karst formation thus may have extended from the period when the Todilto waterbody finally evaporated until shortly after the formation of the "agate bed" and deposition of the earliest Morrison sediments.

The Todilto Formation crops out in east-central New Mexico only in the area around Bull Canyon and Luciano Mesa east of Santa Rosa (Figs. 7, 8) and near Las Vegas. These small remnants are at, or near, the eastern edge of a once continuous depositional basin that extended into the present San Juan Basin (Fig. 7). At Romeroville Gap, the Todilto consists of finely laminated, petroliferous limestone, the upper part of which is brecciated and microfolded. This distortion of the upper laminations of the Todilto may represent the dissolution of formerly present anhydrite layers (R. Y. Anderson, oral comm., 1984). The contact between the Todilto and the Entrada at Romeroville is sharp, and apparently a very short period of clastic deposition occurred prior to the initiation of limestone deposition. The Todilto is overlain conformably by Bell Ranch Formation? clastics and nodular gypsum at Romeroville.

We have studied the Todilto Formation in the Bull Canyon/Luciano Mesa area in some detail (Figs. 8, 9). It consists of three units: (1) a lower, clastic-dominated "transition zone," (2) a middle, microlaminated limestone and (3) an upper, "vuggy" limestone.

The transition unit at Bull Canyon (Fig. 9) consists of a basal, strongly crossbedded, gray and green sandstone. The lower surface of this sandstone is an erosional unconformity on the underlying Entrada Sandstone. The contact is often marked by a thin, black sand or an indurated, iron-stained sandstone. This sandstone thickens as one approaches the limestone pinchout, and extends beyond the pinchout. Above the basal sandstone is a fining-upward, clastic, varved unit, which is very sandy at its base. It is separated from the basal sandstone by a change from crossbedding to planar bedding and a decrease in average grain size. The upper third of this unit is transitional with the limestone unit above it, but is characterized by numerous, thin sandstone lenses which are locally outlined by diagenetic gypsum.

The microlaminated limestone at Bull Canyon (Fig. 9) consists of a basal, very well indurated limestone which grades upward into a shaley, fissile limestone. Although the basal, blocky weathering limestone appears more massive, close examination reveals it to be microlaminated (varved) like the more shaley limestone above it. Numerous fossil fishes, rare insects and ostracodes come from this unit.

The upper limestone unit at Bull Canyon (Fig. 9) consists of a ledge-forming, poorly varved carbonate containing numerous vugs filled with secondary calcite. Sometimes, thin needles of secondary gypsum are found. These vugs are selectively located in rounded, oval, "algal"-like structures. These structures may be algal in origin, but lack the finely laminated structure typical of most algal stromatolites.

Lower contact

The contact between the Todilto Formation and the underlying Entrada Sandstone is usually sharp, and is often referred to as conformable or apparently conformable. Smith (1961) described the contact as intertonguing in some localities of the Grants-Gallup region and as an apparent angular unconformity at other localities of the same area. The contact is often characterized by a transition zone of clastic deposition. In the Bull Canyon area of east-central New Mexico, this transition zone is well developed (see above). Elsewhere in the Todilto depositional basin, the transition zone may be composed of thinly laminated sandstone (Harrison, 1949; Eckel, 1949), silt and variegated clay (Allen and Balk, 1954), limestone lenses (Smith, 1961) or sandstone/siltstone lenses (Maxwell, 1982). Maxwell (1982) suggested these transition beds represent the early infilling of the topographic lows in the Entrada dune field by the encroaching Todilto waterbody. This view is supported by our observations at Bull Canyon, where the initial crossbedded sand-

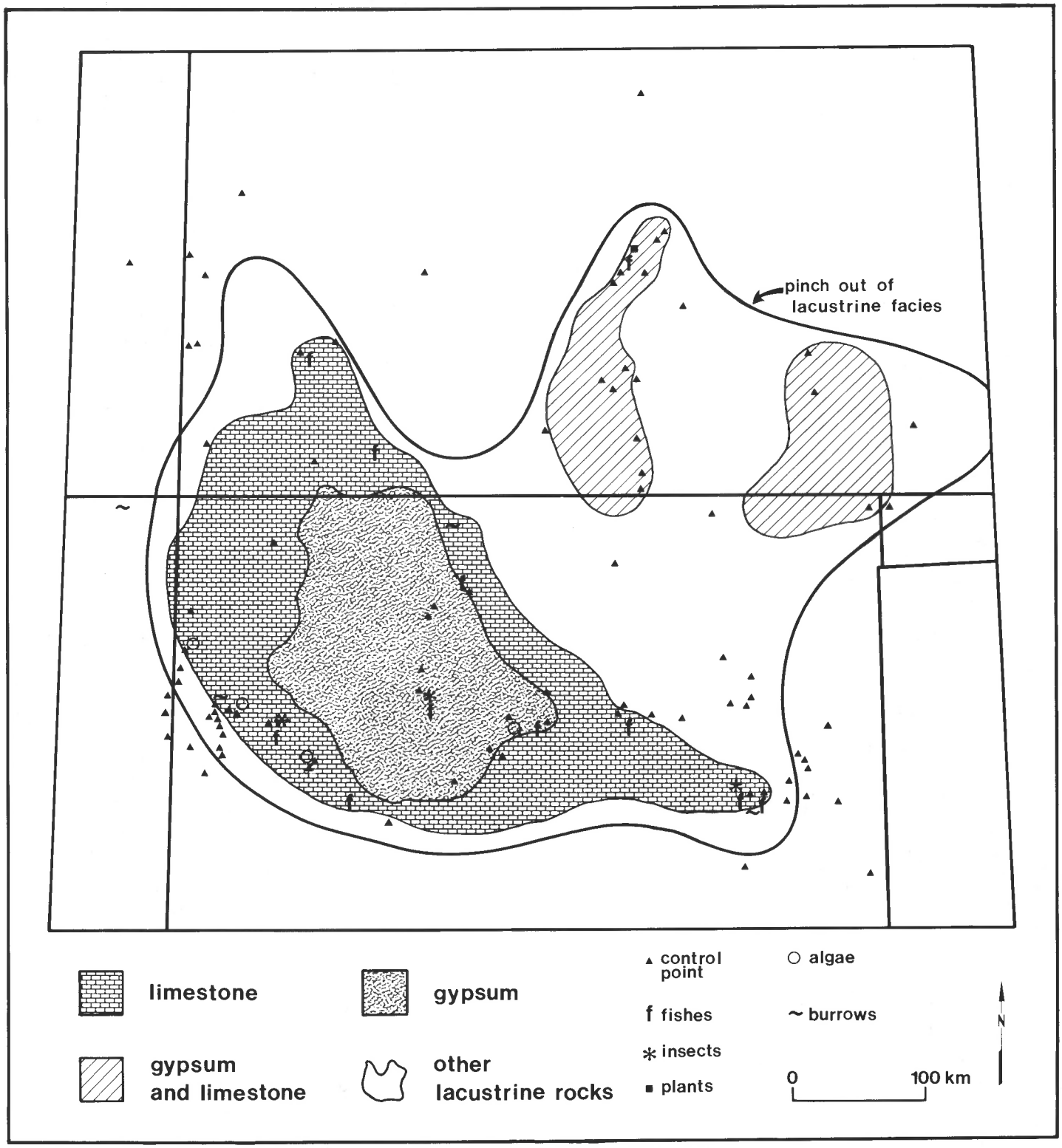


FIGURE 7. Map of Todilto basin showing facies distribution and fossil localities (see text for discussion).

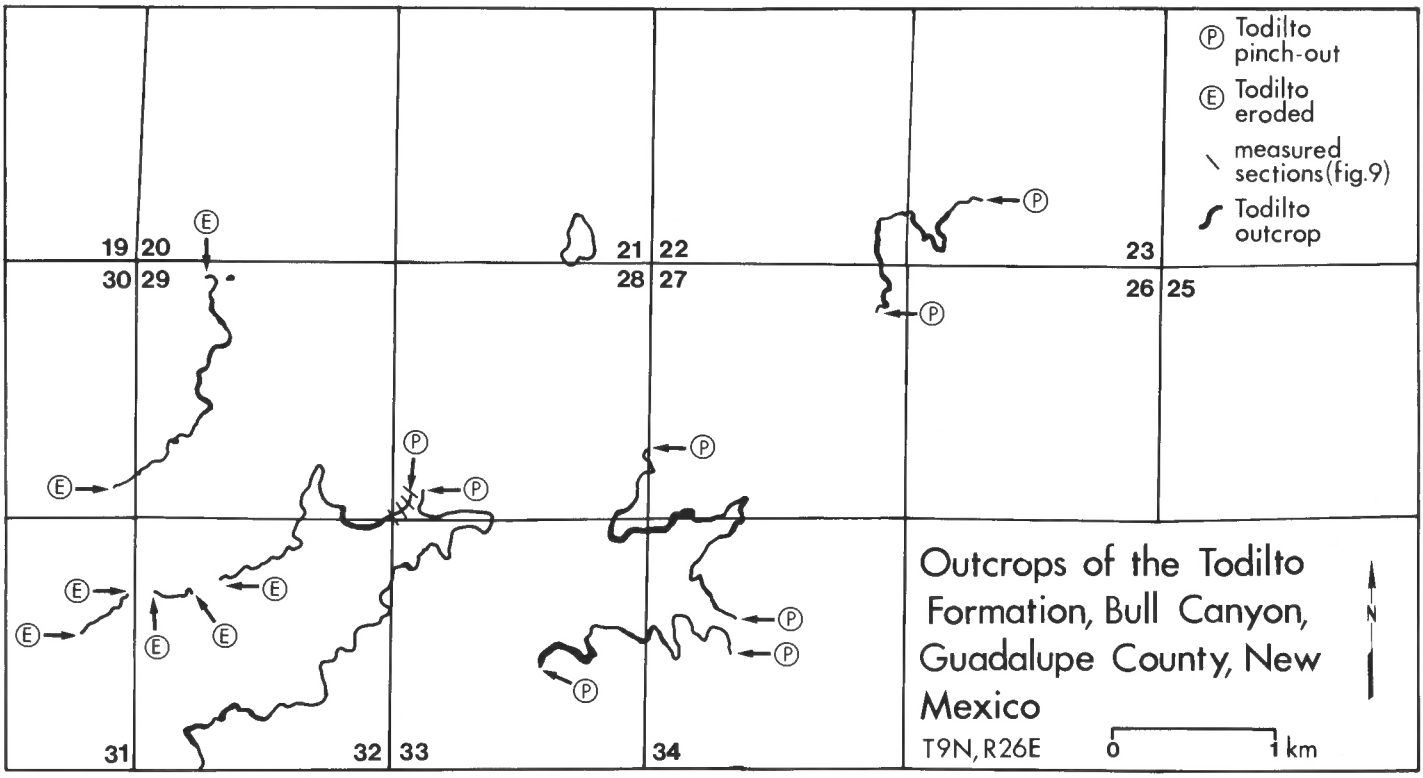


FIGURE 8. Distribution of the Todilto Formation at Bull Canyon, eastern Guadalupe County.

stone extends beyond the limestone pinchouts. The transition zone is apparently not well developed in the Las Vegas area where it consists of small lenses of sandstone incorporated into the basal Todilto Formation (Neef, 1950).

Thickness

In east-central New Mexico, the Todilto ranges from a wedge-out (0 m) to about 6 m in the Las Vegas region (Neef, 1950). In the Bull Canyon/Luciano Mesa area, the thickness ranges from a wedge-out (0 m) to 2 m. Variations in thickness of the Todilto are largely the result of relief on underlying Entrada dunes, with greater thicknesses on the interdune lows and lesser thicknesses on the dune axes (Vincelette and Chittum, 1980). Basinwide, the limestone of the Todilto Formation is from 0 to 13.3 m thick. Above the limestone, in the basin depocenter, the gypsum/anhydrite member varies from 0 to 80 m thick. The gypsum/anhydrite member is absent in east-central New Mexico, although the presence of considerable amounts of gypsum in the Las Vegas area (Neef, 1950), coupled with the extensive brecciation of the upper part of the limestone, may indicate its former presence.

Depositional environment

The Todilto Formation was deposited in a shallow, low-energy waterbody. The nature of that waterbody has been the subject of considerable speculation. The major question is whether the Todilto waterbody was landlocked (i.e., a lake) or was connected to the sea (i.e., an embayment). The following discussion attempts to answer this question by presenting paleontological and paleoecological evidence that supports the concept of a landlocked, salina origin of the Todilto

Paleontology

The fossil record of the Todilto Formation is rather meager, especially when compared to that of other varved sediments. The first fossils described from the "Todilto" were dinosaur footprints (Gregory, 1917). The most commonly collected fossils in the Todilto are two species of neopterygian fishes: *Hulettia americana* and *Todiltia schoewei* (Fig. 10). A third species, *Caturus dartoni,* has also been reported (Schaeffer and Patterson, 1984, p. 38). The preservation of these fossil fishes is exceptional, although they are not common at most localities. The known invertebrate fauna consists of one species of ostracode, *Theriosynoecum todiltensis* (Swain, 1946), and two undescribed species of aquatic Hemiptera (Bradbury and Kirkland, 1966). The flora of the Todilto is limited to what is variously referred to as "bioherms, probably of algal origin" (Perry, 1963) or "algal mounds" (Tanner, 1970). The organic varves contain "tracheids and fibers from vascular plants" (Anderson and Kirkland, 1960), but have failed to produce spores or pollen, despite extensive efforts to collect them (Ash, 1958).

The dinosaur tracks reported by Gregory (1917, p. 56) were from a "3-inch bed of highly calcareous sun-cracked sandstone 100 feet below the massive crossbedded Navajo Sandstone [=Bluff Sandstone]" in Navajo Canyon and at Willow Springs in northwestern New Mexico. This bed probably would now be called "Summerville Formation" or, more properly, Wanakah Formation **[6],** although Gregory considered it correlative with the Todilto Formation. Measurements and photographs of these tracks were studied by R. S. Lull (in Gregory, 1917) who suggested the presence of two types of bipedal, theropod dinosaur. One dinosaur had 55 cm by 35.6 cm prints and a stride of 2 m. The other dinosaur had 30-cm-long prints and a stride of 1 m. The tracks are three toed, the middle toe being the largest.

The fish from the Todilto were first found at a locality east of Santa Rosa, New Mexico in 1929 by Koerner (1930, p. 463). Koerner noted their resemblance to *"Pholidophorus americanus"* [=*Hulettia americana*], which was originally described from the lower part of the Sundance Formation south of Hot Springs, South Dakota (Eastman, 1899a, b). Dunkle (1942) described a second species of fish, *Leptolepis schoewei* [=*Todiltia schoewei*] from the Todilto Formation of east-central New Mexico and the Ralston Creek Formation near Cañon City, Colorado. The latter occurrence was first noted by Schoewe (1930, p. 206), who considered the fish-bearing rocks to be part of the Lykins Formation. These rocks are now considered part of the Ralston Creek Formation. The species *"Pholodophorus americanus"* was also noted from the Cañon City locality by Schultze and Encisco (1983), who believed the fish to be of middle Jurassic (Callovian) age. This age has

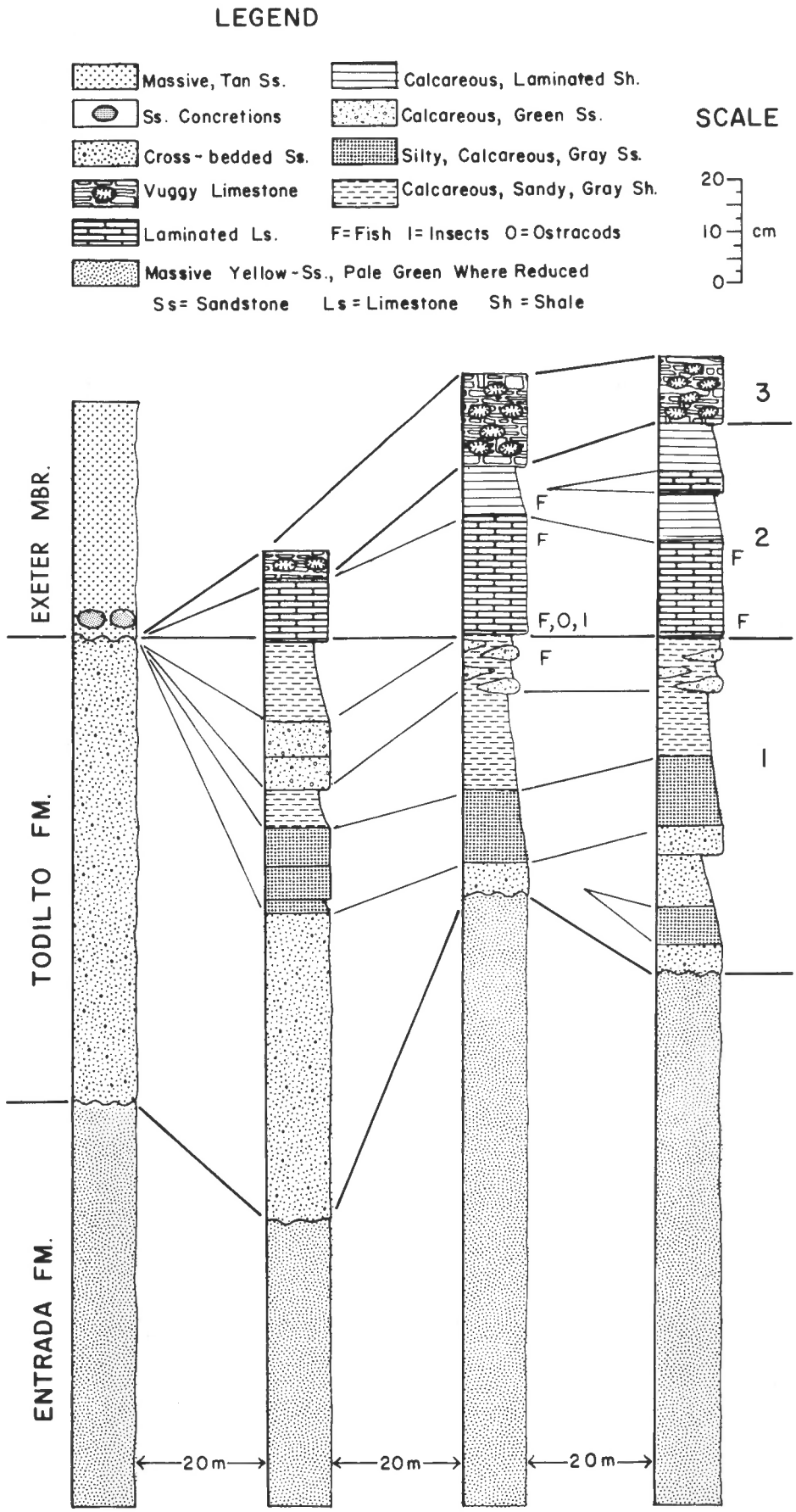


FIGURE 9. Measured stratigraphic sections illustrating the pinchout of the Todilto Formation at Bull Canyon. See Figure 8 for location of sections.

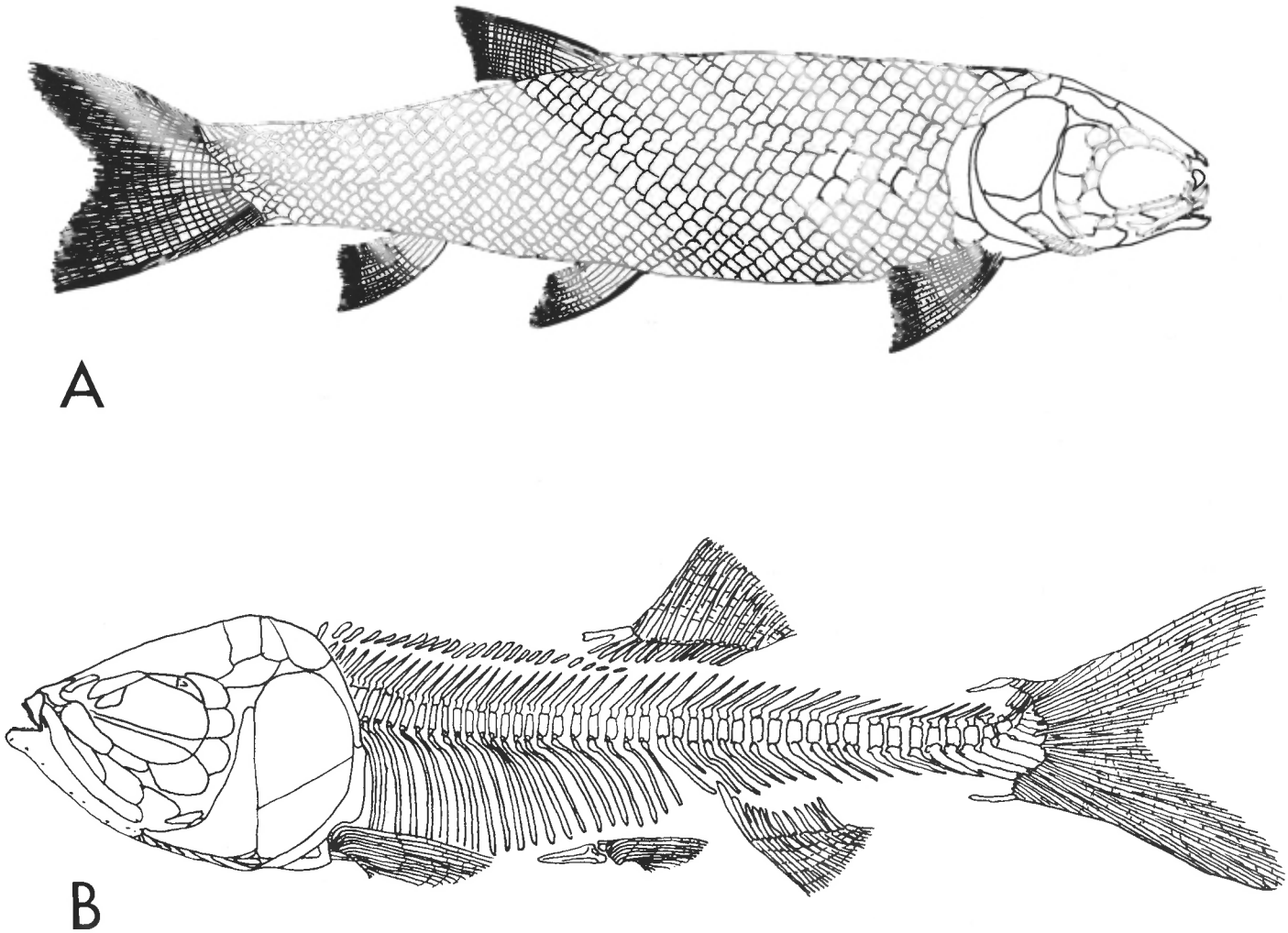


FIGURE 10. Restorations of *Hulettia americana* (A) and *Todiltia schoewei* (B) (after Schaeffer and Patterson, 1984).

been disputed by Schaeffer and Patterson (1984), who consider a late Bathonian age equally plausible. *Hulettia* has also been found in abundance near Hulett, Crook County, Wyoming (Burnt Hollow locality), at several localities near Gypsum Creek, Carbon County, Montana and in Big Horn County, Wyoming (Schaeffer and Patterson, 1984, pp. 8–10). A third species of fish, *Caturus dartoni,* has also been reported from the Todilto Formation at Bull Canyon (Schaeffer and Patterson, 1984, p. 38). Although we have not found or studied this rare species, it is probably the "large fish" reported from Bull Canyon by some private collectors, since it has a standard length of about 30 cm according to Schaeffer and Patterson (1984, p. 38). This fish was first described by Eastman (1899b, p. 406) as *Amiopsis*(?) *dartoni* from the Sundance Formation near Hot Springs, South Dakota. It is also found at the Burnt Hollow locality.

The localities near Santa Rosa collected by Koerner in 1929 were later referred to as the Bull Canyon, Merrill Ranch and Hornsby Ranch localities. Which of these localities was collected by Koerner is unknown. These localities were later collected by Sternberg, Dunkle and Pierce in 1947, by Henderson (date unknown), by Ash in 1958 and by Schaeffer in 1964. Colbert (1950) mentioned these localities, and local ranchers and private collectors have visited them. We collected the Bull Canyon locality in 1983–1984.

The localities at Bull Canyon are not the only ones to have produced fish from the Todilto, although the numbers found there are noteworthy. Bradbury and Kirkland (1966, p. 24) noted both *Hulettia* and *Todiltia* at their insect locality near Warm Springs, north of San Ysidro, New Mexico. The U.S. National Museum has fish from a locality near Lamy, New Mexico (Colbert, 1950, p. 65). Baltz and Bachman (1956, p. 103) noted two small fish from the Todilto 1.6 km north of Montezuma, New Mexico. Ash (1958, p. 34) reported fish in the Todilto at Suwanee, near Grants, New Mexico. Tanner (1970, p. 287) mentioned fish localities near Hot Springs and Echo Amphitheater, along New Mexico State Highway 84, south of Chama, New Mexico and near La Liendre, south of Las Vegas, New Mexico. Read et al. (1949) recorded fish from near Piedra, Colorado. Eckel (1949) mentioned fish from the Pony Express Limestone [= Todilto Formation] in the Animas Mountain area of southern Colorado. Ash (1958, p. 34) reported both species from southwestern Colorado. One specimen of *Hulettia* in the UNM collection collected by Marion Pierce in 1932 is from "Acoma Monument."

Several authors, including Baker et al. (1947, p. 1668), Imlay (1952, p. 960) and Harshbarger et al. (1957, p. 46) referred to the "marine affinities" of these fish. Romer (1966, p. 62) noted "abundant remains of *Leptolepis* [= *Todiltia* in part], a fish of herring-like appearance and modest size, found in Upper Jurassic marine deposits." Schaeffer and Patterson (1984, p. 12) suggested *Hulettia* and *Caturus* were marine species, whereas *Todiltia* "may have been a freshwater form." Anderson and Kirkland (1960, pp. 43–44) thought these fish were "probably adapted to living in streams or areas of essentially freshwater adjacent to the mouths of streams entering the Todilto basin." This hypothesis was based, in part, on the distribution of the fish known at that time, near the basin margins. The fossil record since that time indicates the fish occur throughout the basin, although they are still more abundant in marginal areas, particularly the eastern margin near Las Vegas and Santa Rosa (Fig. 7). The fish have not been reported from the area of

the "Todilto straits" (Harshbarger et al., 1957) in the Four Corners region.

Kirkland (1958, pp. 51–52) thought the Todilto fish lived in freshwater and were subjected to mass mortalities during droughts. Ash (1958, pp. 34–35) thought the fish were in the group Isospondyli, which "includes the present-day trout and other members of the salmon family." Schaeffer and Patterson (1984, p. 14) considered *Hulettia americana* to belong to the Neopterygii, Halecostomi, *incertae sedis*. *Todiltia* was placed by them in the Teleostei, *incertae sedis* (Schaeffer and Patterson, 1984, p. 51). *Caturus* belongs to the Halecomorphi, Caturidae, according to Schaeffer and Patterson (1984, p. 39). Tanner (1970, p. 287) considered the fish to be freshwater based on their resemblance to "salmonid types (supposedly tolerating fresh or salt water)." Perhaps the most convincing evidence for their freshwater origin is that they have not been reported from rocks containing a marine invertebrate fauna. They have been found with plant fossils in the Ralston Creek Formation (Schultze and Encisco, 1983, p. 1057), a unit that contains a unionid bivalve, *Vetulonaia faberi*, also known from the Morrison Formation (Imlay, 1952, p. 961). The fish also are associated with aquatic Hemiptera in the Todilto Formation of New Mexico (Bradbury and Kirkland, 1966, p. 24).

Taphonomy of Todilto fishes

Forty-nine specimens of *Hulettia americana* from Bull Canyon were studied to determine the taphonomic history of the species and to indicate some features of its population structure (Fig. 11). *H. americana* has small conical teeth and rare gut contents which contain small fish(?) bones and, possibly, scales of *Todiltia schoewei*(?). The length data indicate three distinct peaks, perhaps reflecting year classes. The collections from Bull Canyon do not indicate the presence of small individuals (shorter than 50 mm) of *H. americana*. This is also reflected in the data presented by Schaeffer and Patterson (1984, p. 19). These same authors do record some slightly larger specimens (longer than 120 mm) than those found at Bull Canyon. This may indicate that this species did not breed in the Todilto waterbody, or that young individuals were not involved in mass mortality. *Hulettia* is far more abundant than *Todiltia*, a condition not typical in predator-prey relationships, where prey usually outnumber predators. Two explanations are possible: either *Hulettia* was preferentially prone to the Todilto fish-kill mechanism(s) or was preferentially transported to the burial site.

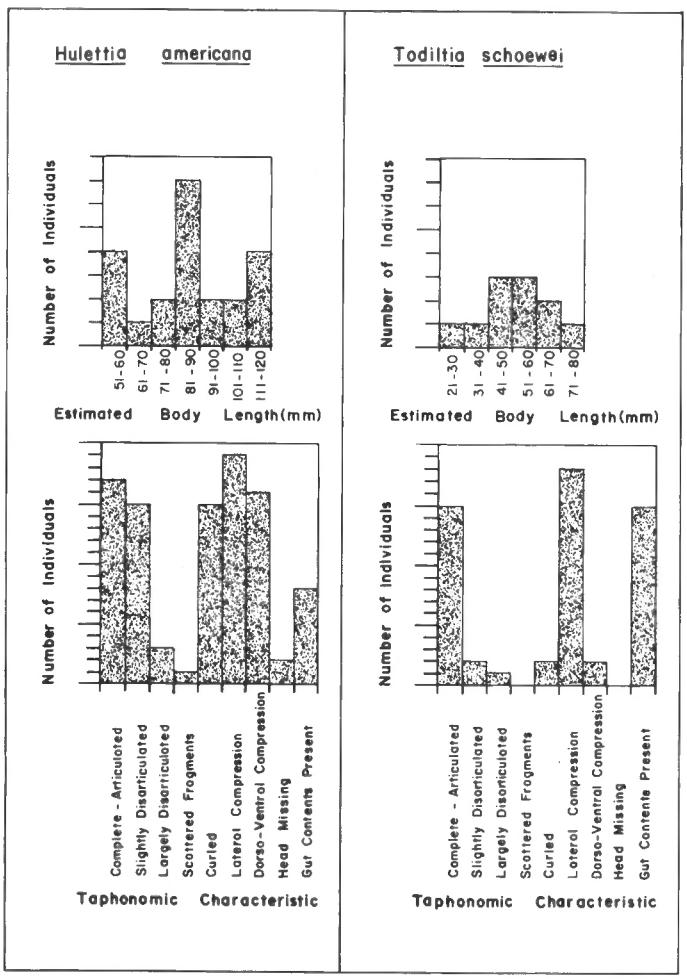


FIGURE 11. Histograms of taphonomic characteristics of Todilto fishes collected at Bull Canyon.

Many specimens of *Hulettia* are complete (34.7%), curled (30.6%) and/or slightly disarticulated (30.6%). Rarely, specimens occur as scattered fragments or are represented by head or tail fragments (Fig. 12). Very few specimens show advanced disarticulation. The number of curled specimens indicates the majority of specimens of *Hulettia* floated after death. The arc of the curl indicates that decompositional gases were concentrated in the body cavity just posterior to the head. *Hulettia* floated side up. Some isolated heads or heads with short vertebral sections have been found. Also, tails and body sections lacking heads are occasionally found. We believe that these specimens represent late stages of flotation where the body separated from the floating head and sank to the bottom, while the head came to rest elsewhere. Certainly, many specimens of *Hulettia* did not reach this stage of decomposition before the release of decompositional gases and final sinking to the bottom. Specimens of this fish begin to disarticulate in the head region, probably due to the release of gases during decomposition. When disarticulation of the head region is well underway, patches of scales begin to come loose. Eventually, the entire fish is reduced to isolated scales and bones (Fig. 13). Grande (1980, p. 182) speculated that dead fish that float are more subject to scavenging than are those which remain on the bottom. Since a potential scavenger in the Todilto fauna has not been identified, this is not likely in the case of the Todilto fish unless *Hulettia* was a scavenger.

Twenty specimens of *Todiltia schoewei* from Bull Canyon were studied to determine population structure and taphonomic history (Fig. 11). *Todiltia* has what appears to be a normal size distribution, and the data from Schaeffer and Patterson (1984, p. 54) fall into the Bull Canyon size range. The vast majority of specimens are complete (75%), laterally compressed (80%) and have visible gut contents (70%) (Fig. 14). Schaeffer and Patterson (1984, p. 61) described the gut contents as being "a white or yellowish, featureless, phosphatic mass," suggesting a "microphagous diet." This suggests the fish were killed quickly during a feeding period, and that they were not disturbed or refloated once they reached the floor of the Todilto waterbody. The few specimens that show signs of disturbance are of two types. In the first type, the skull of some laterally compressed specimens is slightly disarticulated, while the rest of the body is not. In the second type, separate skulls with axial skeletons and bones and fins are found. This latter situation is thought to have arisen from the same situation postulated for *Hulettia*, that is, the head floated after the decaying body had fallen to the bottom. This is supported by the usual dorsoventral compression of these specimens and their curling. The nature of curling in *Todiltia* indicates the decompositional gases were concentrated in the skull.

The effects of decomposition and postmortem flotation on modern fish from the North Sea have been described by Shafer (1972, pp. 59–60), who observed that both low oxygen and high salinity can retard or prevent the production of decompositional gases. He also noted that different fish species show different patterns of flotation. Shafer went on to observe that dead fish can be disturbed by scavengers, wave action and currents, as well as by buoyancy, and that complete, undisturbed fish are found in closed, deep, stagnant basins without bottom currents, where anoxic and azoic conditions prevail. The relatively small number of disarticulated fish in the Bull Canyon Todilto collection is similar to the situation described by McGrew (1975, pp. 260–261) for fishes from the Green River Formation. McGrew also noted that the Green River fish disarticulated head first.

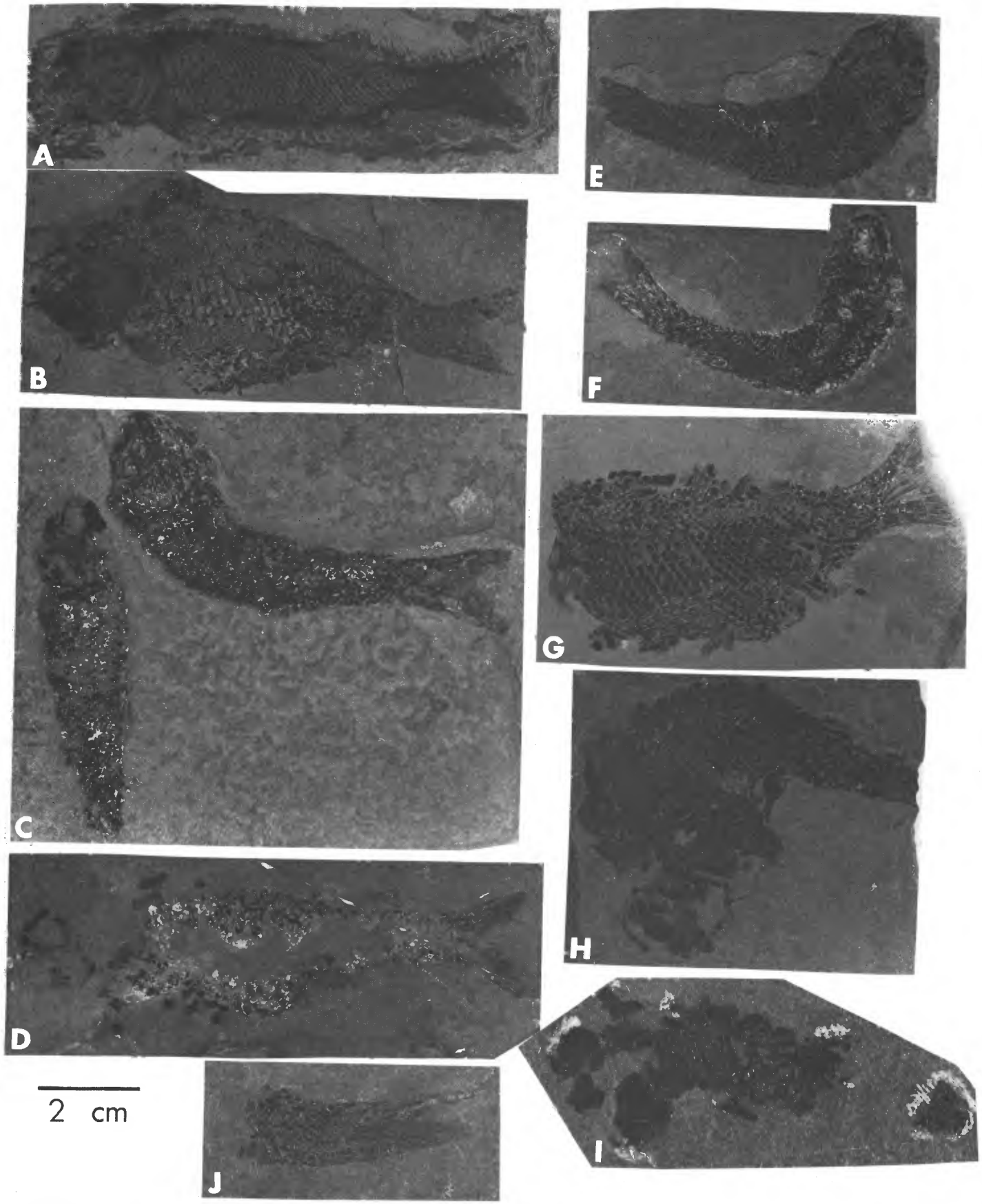


FIGURE 12. Specimens of *Hulettia americana* from the Todilto Formation at Bull Canyon showing different stages of disarticulation. A, B, Complete fishes, laterally compressed. C, Two fishes, one laterally compressed (on left), the other dorso-ventrally compressed and curled. D, Laterally compressed, greatly disarticulated fish. E, F, Complete fishes, dorso-ventrally compressed and curled. G, Laterally compressed fish without head. H, Dorso-ventrally compressed and curled fish with head largely disarticulated. I, Patches of fish skull and scales. J, Laterally compressed, isolated fish tail. Specimens in the New Mexico Museum of Natural History collection.

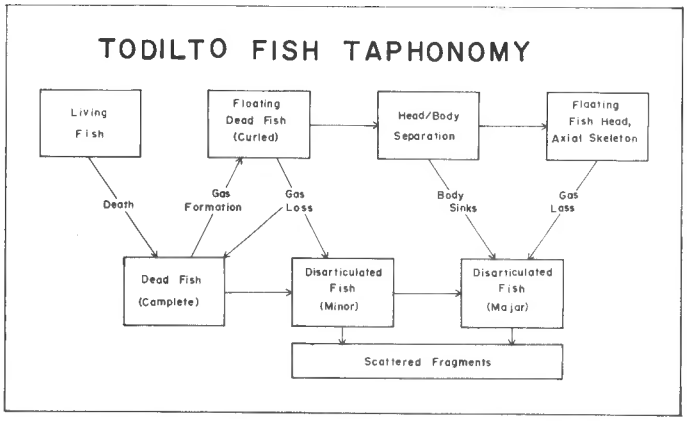


FIGURE 13. Inferred taphonomic history of Todilto fishes from Bull Canyon.

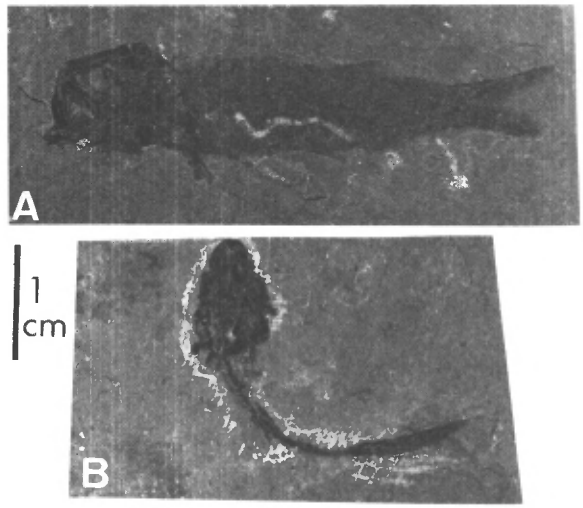


FIGURE 14. Specimens of *Todiltia schoewei* from the Todilto Formation at Bull Canyon showing different stages of disarticulation. A, Laterally compressed, complete fish (note light-colored gut contents). B, Dorso-ventrally compressed and curled skull and axial skeleton.

The concentration of fish at Bull Canyon may represent mechanical accumulation due to weak bottom currents or local circulation patterns. It could also be the product of localized mass mortalities from one cause or a combination of causes. Whatever the cause(s), the fish concentration in the Todilto at Bull Canyon is clearly anomalous when compared to other Todilto outcrops, even in nearby areas. However, the numbers and nature of the fish kills in the Todilto are not on the scale of those recorded in the Green River Formation (McGrew, 1975; Grande, 1980), where multiple species and/or basinwide mortalities are recorded.

The Todilto fish do not show obvious preferential orientation and are rarely stacked one on another. They do, however, have a decided preference for the limestone pinchouts on the northwest "shores" of the northeast- to southwest-trending interdune fingers of the Todilto waterbody in Bull Canyon. This suggests some mechanical concentration of the Todilto fish is involved, particularly in the case of *Hulettia*. This still does not address the problem of the death of such large numbers of fishes in the Bull Canyon area. A mechanism of mass mortality must be involved.

The mechanisms of modern fish kills are numerous and varied. Gunter (1947) noted that fish kills in semi-restricted lagoons of the Gulf of Mexico were caused by cold waves, high salinity and plankton blooms. Brongersma-Sanders (1957) observed that other causes of fish mass-mortality in the sea include: volcanism, earth- and sea-quakes, stranding and mortality related to spawning runs. There is no evidence of either volcanism or earthquake activity in the Todilto basin, so these can be excluded as causes of the Bull Canyon fish mortalities. The remaining causes deserve further examination.

The Todilto is an organic-rich limestone, and fish kills due to plankton blooms or associated oxygen depletion and hydrogen sulfide production are possible. The plankton blooms that are responsible for many marine fish kills are referred to as "red tides." These blooms are usually the result of monospecific dinoflagellate blooms. Both Brongersma-Sanders (1957, p. 953) and Sleidinger and Hoddad (1981, p. 814) noted that plankton blooms can be toxic due to the plankton species themselves, or to the associated oxygen depletion caused by the death and decay of the plankton. Blooms can also kill fish by clogging their gills (Brown and Urban, 1969). Decaying plankton or other plant materials also produce large amounts of hydrogen sulfide, which is toxic to fish (Jones, 1964, pp. 89–90). Brongersma-Sanders (1957, p. 957) noted that most plankton-related fish kills in freshwater are due to blue-green algae, while marine kills are primarily due to dinoflagellates. Serruya and Pollingher (1983, p. 418) found that in the salt lakes of Australia, unialgal blooms, including dinoflagellate blooms, occur during periods of increased salinity. Brongersma-Sanders (1957, p. 955) stated that kills due to waterblooms are restricted to "highly eutrophic, and particularly to hypertrophic water." He also noted that such blooms may occur where nutrient-rich rivers enter restricted marine environments. Bailey (1955, p. 527) observed that fish that die from oxygen depletion usually have distended gills and gaping mouths.

Two major problems thus are apparent when invoking plankton blooms as the cause of fish kills in the Todilto. First, the features of oxygen depletion are not present in the Todilto fish. Second, there is no evidence of dinoflagellates in Todilto palynological samples. Such fish kills would also be expected to have a more widespread distribution than is evident in the Todilto.

The Todilto was probably deposited in a saline environment, and salinity changes are known to produce fish kills among modern fish faunas. Such fish mortalities may be triggered by the rapid and/or prolonged reduction of salinity in marine lagoons and bays (Brongersma-Sanders, 1957, p. 946). This type of mortality is not common since most fish living near areas of mixing are able to tolerate such changes. Hypersalinity can also cause fish mortality. Ruello (1976, p. 670) suggested that fish kills resulted from mixing of saline bottom waters by wind-induced seiches in Lake Eyre, central Australia. Brongersma-Sanders (1957, pp. 946–947) gave other examples and observed that "fish enter the lakes in a layer of freshwater floating on the highly saline lake water, and they perish when this layer evaporates or is mixed with underlying water."

Kirkland (1958, pp. 50–51) and Anderson and Kirkland (1960) have suggested salinity changes as the mechanism causing the Todilto fish kills. While this mechanism is attractive and difficult to refute, one would expect the fish kills to be more common in the later, more saline, period of Todilto deposition if salinity was a major factor. This is not the case at Bull Canyon, where fish first appear during the late transgressive phase of lake development, continue with about the same frequency throughout the main lake stand and disappear before the regressive stage commences.

Rapid temperature changes have also been linked to modern fish kills in both marine (Gunter, 1947) and freshwater (Ruello, 1976) environments. Most often, these fish kills are caused by rapid drops in temperature (Brongersma-Sanders, 1957, pp. 947–948). However, high temperature, especially in enclosed basins, can also trigger fish kills (Bailey, 1955). Fish kills caused by temperature changes are often species selective.

The location of the Todilto basin in a desert environment within a generally equable, Jurassic climatic zone (Kocurek and Dott, 1983) makes temperature changes an unlikely mechanism to explain the Bull Canyon fish kills. The restricted, rather than basinwide, nature of the fish kills also argues against this mechanism.

Fish mortality following spawning is a common phenomenon. The death of salmon following spawning is well known, and spawning mortality is also common in other fish, particularly anadromous species. Indeed, examination of some Recent fish adapted to live in saline lakes in Australia and New Zealand (Fig. 15) provides a good analogy to the

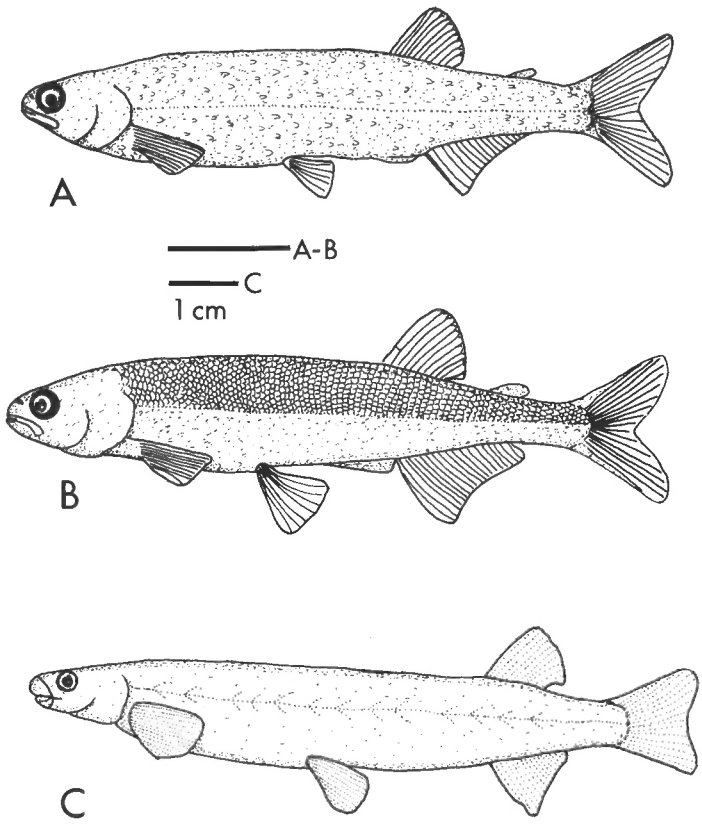


FIGURE 15. Extant fishes from saline lakes in Australia and New Zealand. A, B, *Retropinna retropinna,* adult female (A) and adult male (B). C, *Galaxias maculatus*. After McDowall (1978).

Todilto fish, their ecology and their life histories, supporting the hypothesis that the Todilto fish kills were a result of mass mortality following spawning.

The Jollytail, *Galaxias maculatus,* a diadromous (*sensu* Myers, 1949) fish (McDowall, 1968), is widespread in southern Australia, New Zealand and the southern tip of South America. This species has been intensively studied by Pollard (1971) in Australia and by McDowall (1970, 1978) in New Zealand, from whom the following abstract of its life history is taken. *G. maculatus* normally lives in rivers entering the sea and has a marine juvenile stage, migrating to the sea to spawn. Some members of this species have become acclimated to dune lakes in New Zealand and saline, coastal lakes in Australia. The lake-living forms spawn in small, intermittent streams that enter the lake during the early rainy season. The eggs can tolerate drying for up to two weeks between flooding of the streams. The next rain that floods the streams causes the larvae to hatch and wash into the lakes where they grow to maturity. Following spawning, *Galaxias* usually die in large numbers. This species rarely lives beyond three seasons, reaching its peak breeding in the second season.

A second species of fish from Australia and New Zealand is the southern hemisphere smelt, *Retropinna retropinna*. Like *Galaxias,* this anadromous fish (McDowall, 1968) has also adapted to life in coastal dune and saline lakes in Australia and New Zealand (McDowall, 1978). *Retropinna* is marine in its early life, migrating to coastal estuaries and river mouths to spawn. The eggs are laid in mud and sand bottoms of these habitats. The larvae are planktonic in the open marine environment. *Retropinna* adapted to saline lakes usually spawn and release their eggs in shallow waters of sandy beaches or slack waters of inflowing streams. The larval fish are then planktonic in the lakes. As with *Galaxias,* the spent adults of *Retropinna* die in large numbers following spawning.

The fish from the Todilto have several striking similarities to the Australian–New Zealand species. First, they share some structural features, such as a fusiform body and posteriorly positioned dorsal fin. Second, growth rates and the three, year-classes of *Hulettia* resemble those of *Galaxias*.

If the Todilto fish are catadromous and the Todilto lake was isolated from the sea, how did they first enter the Todilto waterbody? In *Galaxias,* the fish initially entered the basin when a river was diverted by a lava flow and rapidly filled the lake basin. The river later reestablished its route to the sea, leaving behind the evaporating lake complex populated by the fish. The anadromous/diadromous fish species rapidly adapted to the new environment, perhaps in a single year. A similar introduction of the Todilto fish is possible, although diversion of streams by dune migration rather than lava flows best fits the available evidence. Stream piracy in the highlands north of the Todilto basin may also have populated the basin with fish. Another method the fish may have used to gain access to the Todilto lake was the flooding of salt lakes on the edges of the Entrada dune field.

Todilto invertebrates, trace fossils and plants

The Todilto is characterized by a very meager invertebrate fauna, as one might expect in a basin with a toxic bottom. A single species of ostracode, *Theriosynoecum todiltensis* (*sensu* Markhoven, 1963, p. 415), was described as *Metacypris todiltensis* by Swain (1946, p. 553) based on specimens collected by R. H. Wilpolt and J. B. Reeside, Jr. from a Todilto outcrop at Satan Pass, on New Mexico State Highway 56 about 10 km north of Thoreau. The only other reference to ostracodes from the Todilto by Reeside (in Bush et al., 1959) indicates unidentified ostracodes from near Durango, Colorado. Several poorly preserved ostracodes were found by us while examining fish specimens from the Todilto at Bull Canyon. The Bull Canyon specimens are rare, unlike the "numerous ostracodes, all apparently belonging to a single species" reported by Swain (1946, p. 553). Swain (1946, p. 545) also noted that *Theriosynoecum todiltensis* most closely resembles *T. whitei* Jones from the Morrison Formation. The ornamented nature of *T. todiltensis* indicates a swimming rather than a burrowing habit.

The insects from the Todilto Formation include two species of aquatic Hemiptera described by Bradbury and Kirkland (1966) from a locality south of Warm Springs, New Mexico. These insects were said to belong to two species of aquatic Hemiptera which resemble "the modern genera *Belestoma, Benacus* and *Notonecta* and may belong to an ancestral family of Notonectidae and Bellostomatidae" (Bradbury and Kirkland, 1966, p. 24). These insects are presently under study and are said to belong to the Naucoridae (J. P. Bradbury, written comm., 1985). Some poorly preserved insects occur with the fossil fish at the Bull Canyon locality. These insects seem to represent a single species. Bradbury and Kirkland (1966) noted that one of their insect species represented 95% of the entire sample.

The presence of aquatic insects in the Todilto Formation is a strong argument in favor of a freshwater origin of, or strong freshwater influence on, the Todilto waterbody. Insects have been notably unsuccessful in penetrating the marine environment. The Todilto insects are associated with the fossil fish at both the Warm Springs and Bull Canyon localities, an unusual association given the appetite for insects of most fish species. J. Kukalova-Peck (oral comm., 1976) observed that most fossil insect localities lack fish in direct association with the insects. The insects from Warm Springs were recovered from thin shale beds near the base of the Todilto, those from Bull Canyon were recovered from the limestone beds well above the base of the formation.

Trace fossils have been reported from units associated with the Todilto. Saucier (1967, p. 36) reported "fossil trails or worm burrows" from the uppermost part of the "Zuni Sandstone" (= "Bluff Sandstone") at Pyramid Mountain, near Gallup, New Mexico. These "burrows" are perpendicular to bedding and are very closely packed. Saucier noted the same "burrows" are abundant in the Recapture Member of the overlying Morrison Formation. These "burrows" may represent root casts. If they are "burrows," they resemble those usually referred to *Skolithos*.

Ridgley (1982, p. 48) reported trace fossils referable to *Rhizocorallum* from the top of a clastic unit "tentatively referred to as the

Summerville Formation–Wanakah Formation interval." These burrows are parallel to bedding and occur at "six widely spaced localities along the eastern, southern and western outcrop belt of the Chama basin." In marine situations, this trace fossil is typical of the lower shelf or tidal flat facies. Ridgley (1982, p. 48) further noted that "the problem of whether these burrows may occur in lacustrine environments has not been resolved."

At Bull Canyon, in east-central New Mexico, several very large vertical burrows were found in the basal Exeter Member of the Entrada Sandstone immediately above the Todilto. These burrows are backfilled and superficially resemble *Skolithos,* but are much larger than any described forms.

If the fauna of the Todilto is sparse, its flora is almost nonexistent. Despite numerous attempts, no pollen or spores have been recovered from the Todilto Formation (Ash, 1958, p. 40). Tracheids "believed to be from conifers" (Ash, 1958, p. 40) and "tracheids and fibers from vascular plants" (Anderson and Kirkland, 1960, p. 39) have been mentioned. These fibers occur in such abundance that they may be removed as a series of matts following acid digestion of the limestone layers (Kirkland, 1958, pp. 16–17). Vincelette and Chittum (1981, p. 2566) noted that the oil in the Entrada of the San Juan Basin, which they believed is derived from the Todilto, has a high pour point and is paraffinic in nature, "characteristic of oils derived from lacustrine source rocks in other areas of the world."

Structures of algal origin in the Todilto have been reported by several authors. Kirkland (1958, p. 15) suggested that "plankton, possibly algae" or bacteria were a factor in the formation of the limestone laminae and also compose the organic laminae. Perry (1963, p. 150) found irregular reefs or "bioherms, probably of algal origin" in the Todilto of the Grants Uranium district. These structures host uranium and appear to lack internal structure, suggesting a diagenetic, rather than algal, origin. Similar "algal mounds" are mentioned by Tanner (1970, p. 287). Ash (1958, p. 36) recorded "an alga, not yet described" found by John R. Peters in the Todilto at Todilto Park. Ash also noted "small, circular, unidentifiable structures" which may be organic. Small (0.07–0.35 mm), round objects, originally described by Kirkland (1958, p. 21) as "calcitic oolites," may represent some type of algal structure. These same structures are found at Bull Canyon, where they are inside fish coprolites.

The upper vuggy limestone of the Todilto at Bull Canyon is composed of lens-shaped structures that superficially resemble algal structures. They are, however, composed of unlaminated, microgranular, equidimensional calcite and are the focus of diagenetic activity, suggesting a diagenetic origin. Some of these structures have limonite filled "filaments" about their periphery and could be of algal origin.

Salina model of the Todilto

A saline lake origin of the Todilto Formation is supported by an examination of fish diversity versus waterbody area (Fig. 16). This relationship was first noted by Barbour and Brown (1974), and was used by Grande (1980) to draw some environmental interpretations of the fish fauna of the Eocene Green River Formation of Wyoming, Utah and Colorado. One oversight of both of these authors was their failure to consider saline lakes or estuary/lagoon habitats. They did, however, include some modern inland seas. When these habitats are included, a pattern becomes apparent (Fig. 16). Modern inland seas and estuary/lagoons fall in the high range of diversity, as do the freshwater lakes, whereas saline lakes fall in the low range of diversity, usually below five species. The Todilto clearly falls in the range of saline lakes and not in the range of freshwater lakes, inland seas or lagoons.

Some authors (Ridgley and Goldhaber, 1983; Ridgley, 1984; Schaeffer and Patterson, 1984) have suggested that the Todilto might have formed in a saline bay of the Curtis sea of Utah by way of a connection with that sea through west-central Colorado. The fish fauna of the Todilto suggests otherwise. Normal marine, high diversity fish faunas are absent from the Todilto and related formations in Colorado. A relatively recent analogue of an inland sea which later dries up is found in the Messinian (Miocene) "event" in the Mediterranean (Drooger, 1973). The fish fauna associated with this event has been studied in some detail by Sturani (1973), who found that during the Messinian event the fish fauna of the Piedmontese basin of Italy hovered in the range of one to three species, strikingly similar to the situation in modern

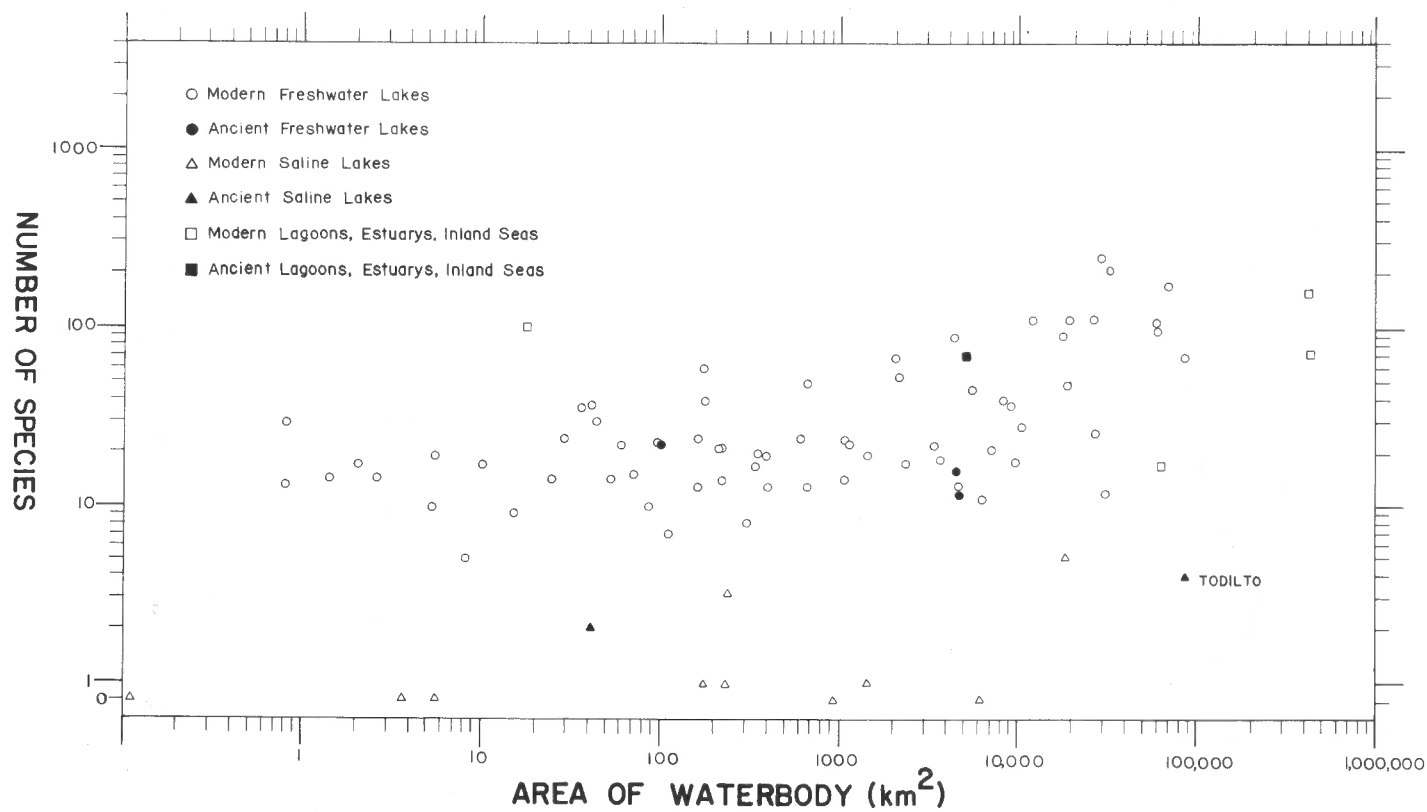


FIGURE 16. Graph of species diversity of fishes vs. area of waterbody for various types of waterbodies (data primarily from Barbour and Brown, 1974).

saline lakes and the Todilto Formation. The surviving species in the Piedmontese basin are pre-adapted catadromous or lagoonal species (e.g., *Pachylebias, Spratelloides* and *Anguilla*). The Todilto situation diverges from this situation because in the Mediterranean, the basal unit of the Messinian event contains a diverse fauna of mesopelagic fishes. If the Todilto basin were flooded by normal marine waters, a normal marine fauna of fish and invertebrates would be expected. Such a fauna has not been recovered anywhere in the Todilto basin.

The problem of the origin of the Todilto involves several factors. As we have pointed out, the biology of the Todilto indicates a saline lake lacking a connection to the sea. Ridgley and Goldhaber (1983), however, have presented compelling isotopic evidence that the Todilto evaporites are marine in origin. We believe this seemingly contradictory evidence can best be explained using the salina model first detailed by Warren (1982) and recently expanded by Warren and Kendall (1985). This model proposes the introduction of marine waters to isolated basins through porous sands separating the sea from the basins (Warren, 1982). The Todilto shares several characteristics with Warren and Kendall's (1985) salinas: aggradation, high coastal dunes, evaporite dominated, aragonite-calcite (minor dolomite) and massive, laminated or rippled gypsum. It may also share resurging ground water and stromatolites. The Todilto has anhydrite in the subsurface, but this may be the result of diagenesis of the original gypsum during burial. The Todilto also seems to lack the tepee structures which characterize salinas, although the brecciated zones of the upper limestone may represent these structures.

Conclusion

In conclusion, the Todilto waterbody is envisioned as a salina formed by the flow of saline marine waters from the Curtis sea through the Entrada Sandstone erg along the western margin of the basin, a concept alluded to by Kocurek and Dott (1983, p. 113). The waterbody also had a freshwater component in the form of streams, possibly of a intermittent nature, which introduced the limited biota to the waterbody. The biota may have lived either in a fresh layer above the lake chemocline or were largely restricted to areas of freshwater inflow. The fish were probably preadapted catadromous species that spent part of their lives in the streams and part in the saline Todilto waterbody. The large numbers of these fish found in certain marginal areas, such as Bull Canyon, may represent death assemblages of individuals which died following spawning.

Age

The Todilto Formation in east-central New Mexico contains *Caturus dartoni*, which also occurs in the Canyon Springs Member of the Sundance Formation in South Dakota and Stockade Beaver Member of the Sundance Formation in Wyoming. Also, the actinopterygian *Hulettia americana* occurs in the above mentioned members of the Sundance Formation and Ralston Creek Formation (= Wanakah Formation) of southern Colorado. The third fish, *Todiltia schoewei*, also occurs in the Ralston Creek Formation of southern Colorado. Using these fish occurrences, Schultz and Encisco (1983) thought the Todilto Formation was middle Jurassic (Callovian) in age. Schaeffer and Patterson (1984) considered the fish to be in rocks of late Bathonian to middle Callovian age based on the ages of the Sundance Formation members in which they occur. Since the underlying Entrada Sandstone is never older than late Bathonian, and its top is not younger than earliest Callovian (Imlay, 1980), the Todilto is most likely of middle Callovian age (Fig. 26). This suggests that the Todilto is slightly younger than the members of the Sundance with which it has been correlated based on the fish faunas.

BELL RANCH FORMATION

Introduction

Griggs and Read (1959) proposed the name Bell Ranch Formation for strata exposed at Carpenter's Point, then believed by them to be part of the Bell Ranch, northwest of Tucumcari, Quay County, New Mexico (Fig. 3) **[7]**. Prior to Griggs and Read (1959), strata now referred to the Bell Ranch were either referred to the Wanakah Formation (Bachman, 1953; Wood et al., 1953; Cooley, 1955) or were not distinguished from the Morrison Formation (Mankin, 1958a).

Type section and lithology

Griggs and Read (1959, p. 2006) stated that the type section of the Bell Ranch Formation "is at Carpenter's Point, 18 miles southeast of the Bell Ranch headquarters and 13 miles northwest of Tucumcari." They described this section as follows:

> At the type locality the Bell Ranch rests conformably on the Entrada Sandstone and is overlain conformably by the Morrison Formation. At the type locality it is 66 feet thick, and ranges in thickness from 0 to about 65 feet in the Tucumcari–Sabinoso area. It consists of an alternating sequence of light gray sandstone and brownish red siltstone beds. The alternating, parallel beds are 2–10 feet thick in sharp contrast to the massive Entrada below and the poorly bedded Morrison above. Small nodules of gypsum are present in the uppermost bed of siltstone in the northeastern part of the Tucumcari-Sabinosa area (Griggs and Read, 1959, p. 2006).

Griggs and Read (1959) presented no additional information regarding the Bell Ranch type section, and no subsequent worker has commented on the section at Carpenter's Point. To elucidate better the nature of the Bell Ranch Formation, we describe in detail its type section



FIGURE 17. Carpenter Mesa looking northwest across the Canadian River, showing cliff of Entrada Sandstone (E) overlying Redonda Member of Chinle Formation (R). Ribbed cliff of Bell Ranch Formation (B) overlies Entrada, and slope of Morrison Formation (M) is above the Bell Ranch. Cretaceous Mesa Rica Sandstone (K) caps mesa.

(Figs. 17, 18, 19). We also designate and describe a reference section of the formation at Punta de Gallegos (Figs. 20, 21).

The Bell Ranch Formation, at its type section, is 18 m thick and overlies the Entrada Sandstone with apparent conformity. The upper 0.25 m of the Entrada is more clay-rich than the rest of the unit, perhaps the result of alteration prior to or during Bell Ranch deposition. The Bell Ranch proper consists of cyclically bedded, fine- to coarse-grained sandstone and siltstone. The individual beds are laterally continuous over at least hundreds of meters and vary in thickness from 0.1 m to 5.25 m. The beds show a range of coloration from very pale orange (10 YR 8/2) to light brown (5 YR 6/4). Several quartzose sandstones contain appreciable quantities of gypsum, which is moderate orangish-pink (10 R 7/4). Bedding consists entirely of cyclic pairs of siltstone and sandstone. The lower unit is always a thin siltstone, which varies from 0.1 to 1.25 m in thickness and lacks sedimentary structures. This unit is overlain by a fine- to medium-grained sandstone from 1.5 to 5.25 m thick. The upper 0.3 m of the sandstone often contains small-scale, trough crossbeds and grain sizes range up to coarse. Seven such cycles are recognizable at the type locality.

The lithology of the Bell Ranch outside the type area is similar to that in the type area (Figs. 20, 21). In the Ocate area, Bachman (1953) reported the "Wanakah Formation" to contain limestone and jasper fragments. Although limestone beds may be present in some facies of the Bell Ranch Formation, the jasper almost certainly refers to the "agate bed" at the base of the Morrison Formation. The percentage of disseminated or nodular gypsum varies within the Bell Ranch and may be associated with siltstones as well as sandstones.

Lower contact

The contact between the Bell Ranch and the Entrada is sharp, but not obviously unconformable. The Bell Ranch is easily separated from the Entrada by its laterally continuous bedding, reddish coloration, lack of large-scale crossbeds and poorer sorting. The Bell Ranch typically forms a low angle, "ribbed" slope above the cliff-forming Entrada (Fig. 17).

Thickness

The distribution of the Bell Ranch is hard to evaluate because some authors have failed to distinguish the unit (e.g., Mankin, 1958a), while others have referred it to other, probably equivalent units (e.g., "brown silt member" of the Morrison: Baldwin and Muehlberger, 1959). The Bell Ranch is rarely reported in the subsurface since it is difficult to distinguish from the Morrison on the basis of cuttings or geophysical logs (Foster et al., 1972). The Bell Ranch appears to interfinger to the south and east with the Exeter Member of the Entrada Sandstone. It also thins considerably to the west, and is only about 11 m thick at Romeroville Gap, south of Las Vegas. Dinwiddie and Clebsch (1973) noted that it is present only in small areas of northeastern Quay County, New Mexico. The "brown silt member" of the Morrison in Union County to the north is 28.5 m thick, but may include some units which should be included in the Morrison (*sensu stricto*). Thus, the Bell Ranch Formation in east-central New Mexico varies from 0 to about 20 m in thickness.

Depositional environment

The Bell Ranch is in many ways similar to the Triassic Redonda Member of the Chinle Formation. Both have similar bed geometry, vertical cyclicity of sandstones and siltstones and similar coloration. The Redonda is considered to be of lacustrine origin (Lucas et al., 1985). Lacustrine deposits are often difficult to recognize in the stratigraphic record (Picard and High, 1972), but a variety of features suggests the Bell Ranch is of lacustrine origin: great lateral continuity of beds, enclosure by nonmarine units, presence of nodular and bedded gypsum, locally common ripple marks and vertically cyclic sequences (Picard and High, 1972, 1981). At its type locality, the Bell Ranch is composed of stacked, coarsening upward sequences (Figs. 18, 19), each showing similarities to the "agitated lacustrine sequence" of Picard and High (1981, fig. 14). The repetition of these sequences suggests allocyclic control of sedimentation by climate and/or tectonics.

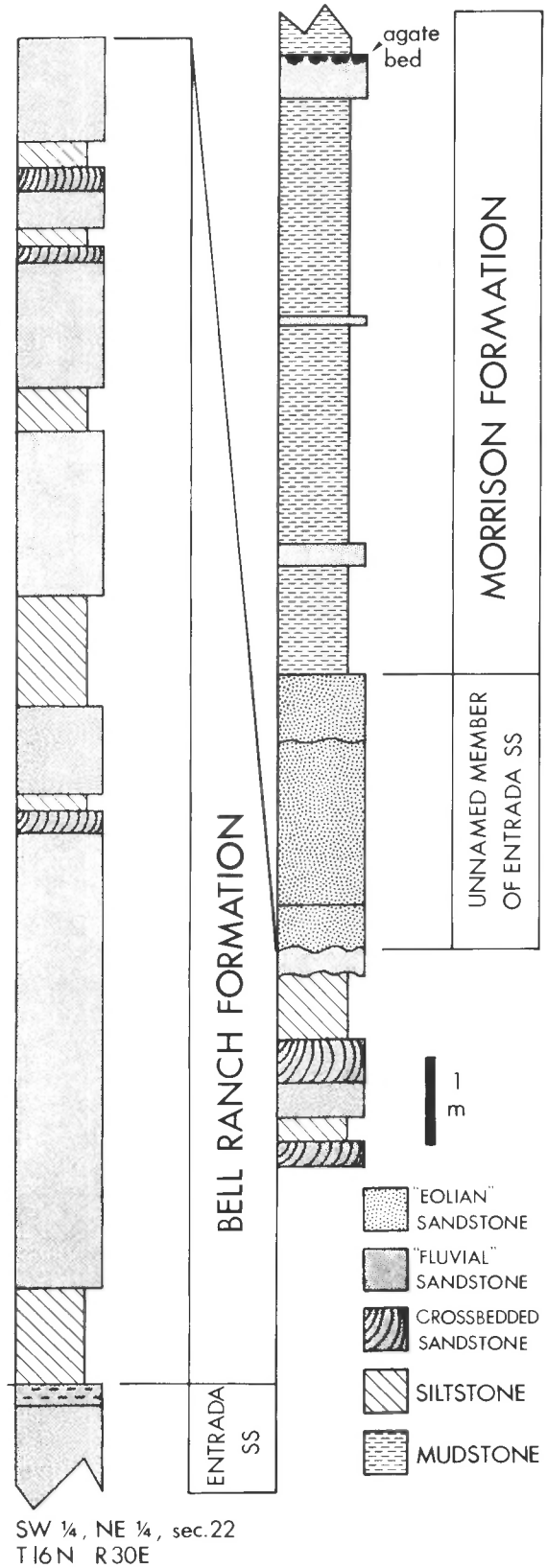


FIGURE 18. Type section of the Bell Ranch Formation at Carpenter's Point.

The Bell Ranch is intimately associated with the Todilto Formation below it (locally), which is clearly of lacustrine origin. The regional picture suggests it is a shoreline facies of the Todilto waterbody, deposited in the better aerated areas shoreward of the anaerobic area of limestone deposition. As the Todilto waterbody shrank toward the basin

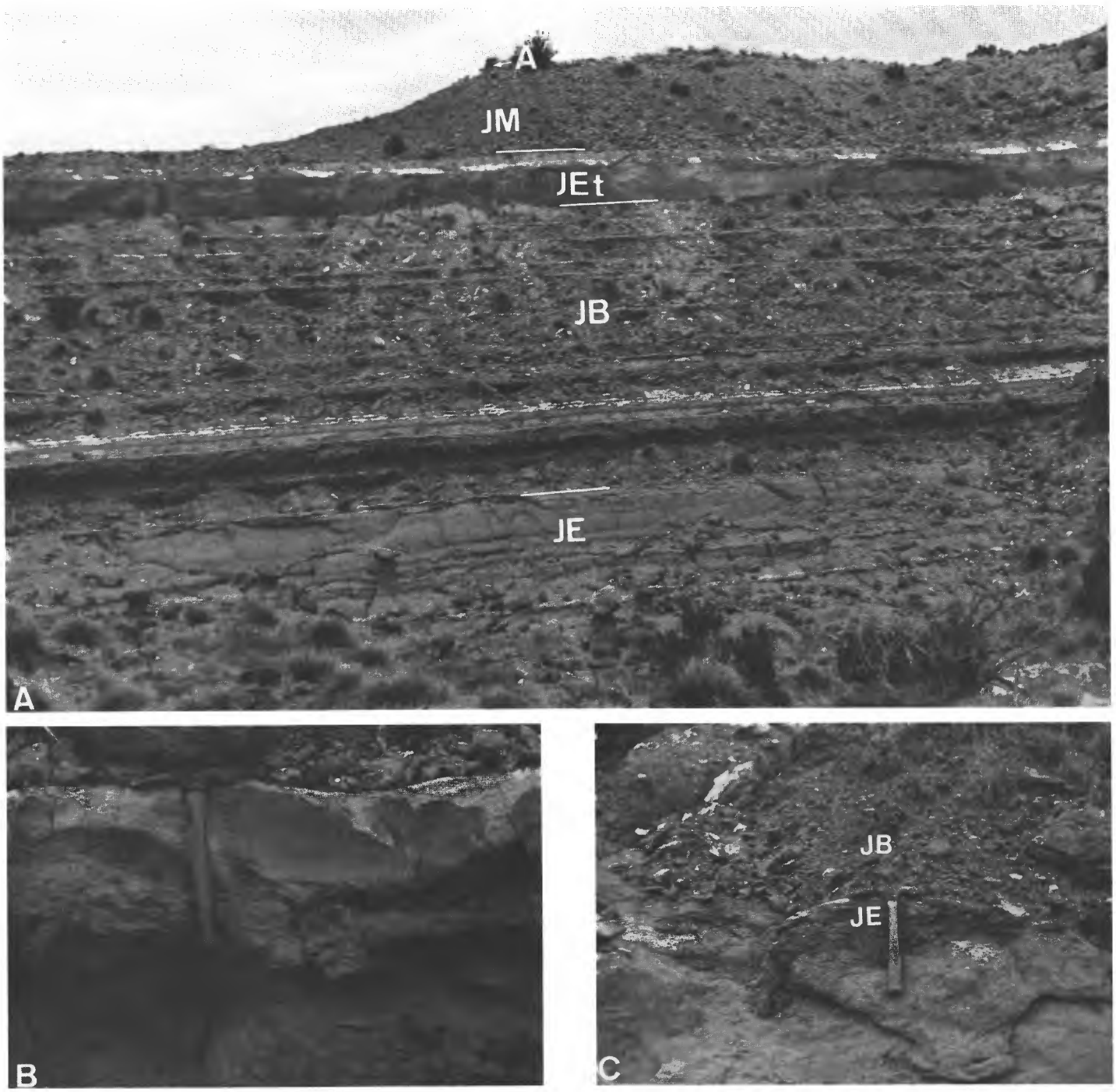


FIGURE 19. Type section of the Bell Ranch Formation at Carpenter's Point. A, Overview of type section, showing main body of Entrada Sandstone (JE), Bell Ranch Formation (JB), unnamed tongue of Entrada Sandstone (JEt) and Morrison Formation (JM) and its "agate bed" (A). B, Typical Bell Ranch sandstone bed showing lower unit of massive, fine- to medium-grained sandstone overlain by trough crossbedded, medium- to coarse-grained sandstone. Rock hammer is 28 cm long. C, Contact of main body of Entrada Sandstone (JE) and Bell Ranch Formation (JB).

depocenter, the Bell Ranch regressed over the Todilto, as did the Exeter Member of the Entrada in some areas (e.g., Bull Canyon). If the Bell Ranch is a regressive facies of the Todilto waterbody, it is equivalent to the Wanakah Formation of southwestern Colorado and the "Summerville Formation" (*sensu lato*) along the southern and western Todilto basin.

Age

The Bell Ranch and equivalent units have not yielded any identifiable body fossils. Thus, the age of the Bell Ranch must be bracketed using adjacent and equivalent units. Stratigraphic position and lithology support correlation of the Bell Ranch with the Wanakah, Ralston Creek and "Summerville" Formations (McKee et al., 1956; Imlay, 1980). These units underlie the "J-5 unconformity," a hiatus that represents part of the late Oxfordian (Pipiringos and O'Sullivan, 1978). Imlay (1980) assigned a late Callovian age to the Wanakah and Ralston Creek Formations. Thus, the Bell Ranch is probably late Callovian in age (Fig. 26).

MORRISON FORMATION

Introduction

Eldridge named the Morrison Formation in 1896 for exposures about

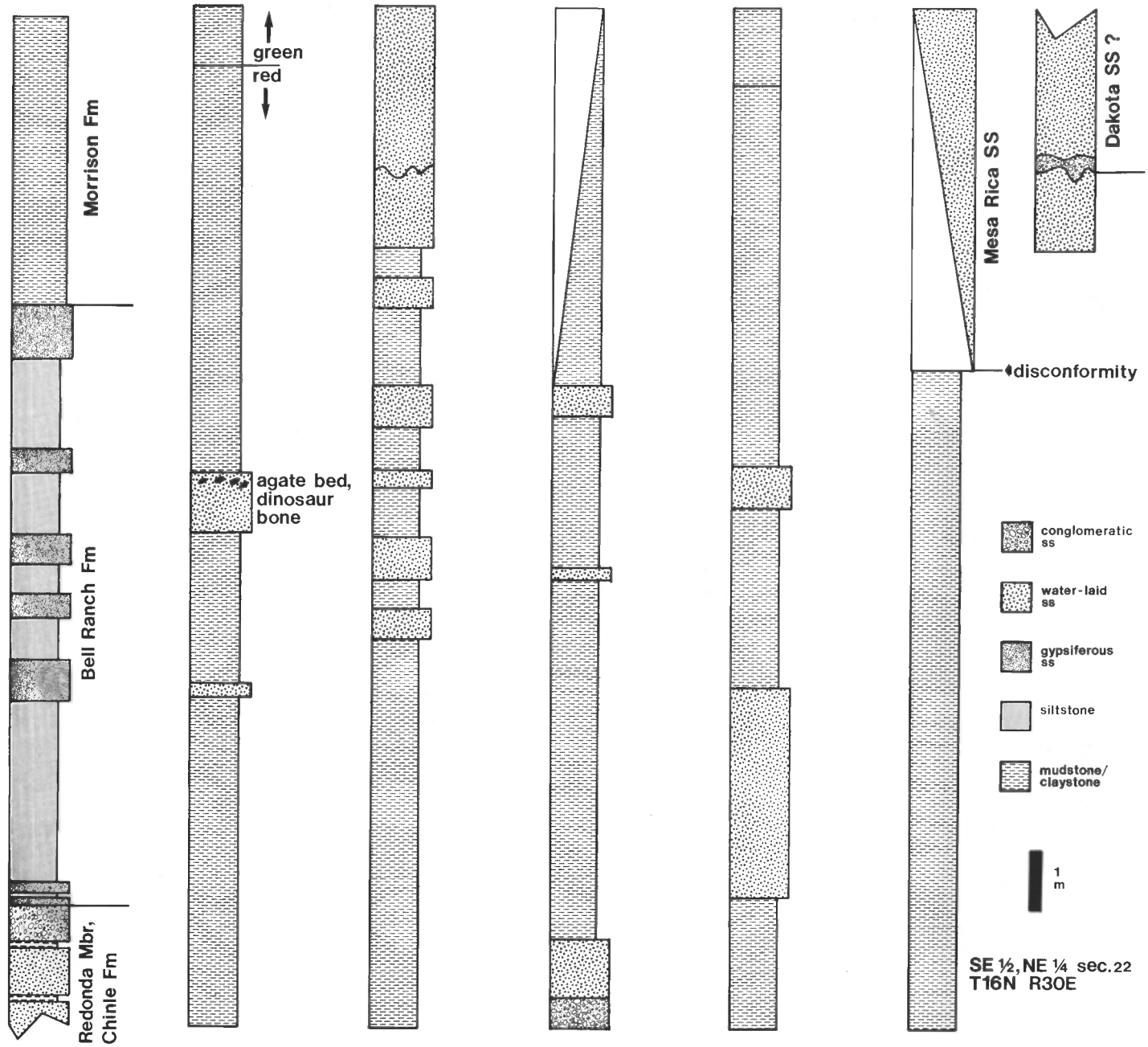


FIGURE 20. The Jurassic section at Punta de Gallegos. Note the absence of the Entrada Sandstone in this section.

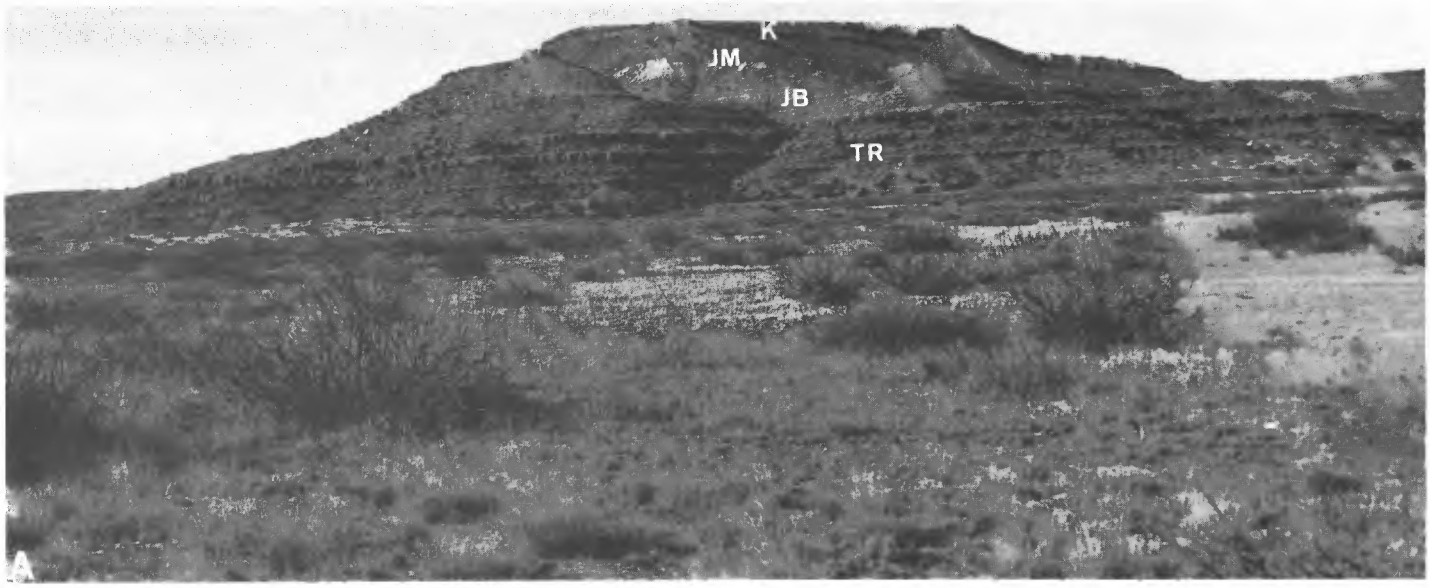
3.2 km north of Morrison, Colorado. The Gunnison Formation, named earlier by the same author (Eldridge, 1894), was subsequently found to be partially equivalent to the Morrison Formation (Cross, 1899; Goldman and Spencer, 1941), but the name Morrison was retained. Lee (1902) first recognized the Morrison in east-central New Mexico, followed closely by Stanton (1905). Subsequently, the Morrison Formation was recognized and mapped in northeastern and east-central New Mexico by numerous workers (e.g., Dobrovolny et al., 1946; Bachman, 1953; Wood et al., 1953; Cooley, 1955; Mankin, 1958a; Baldwin and Muehlberger, 1959; Wanek, 1962).

Lithology

The dominant lithology of the Morrison Formation in east-central New Mexico is variegated shale with a lesser contribution of laterally discontinuous sandstone beds. Near the base of nearly all stratigraphic sections are one or more thin (<45 cm) beds of coalesced, nodular chert referred to as the "agate bed" (Figs. 18A, 19, 20, 22). Locally, volcanic ash-beds more than 30 cm thick and thin limestone beds are present. The dominant clay minerals in the finer grained rocks are illite, montmorillonite, montmorillonite-illite mixed layer clays and minor kaolinite (Mankin, 1958a, 1972). The lower half of the Morrison is dominated by degraded illite and montmorillonite, while the upper half is dominated by mixed layer montmorillonite-illite (Mankin, 1958a).

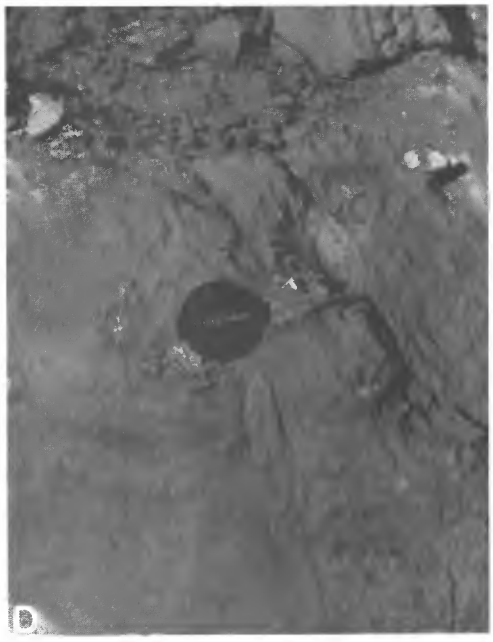
Morrison sandstones show a relatively small range of composition from subarkose to arkose. The percentage of feldspar increases, then decreases vertically, in each stratigraphic section examined in detail (Mankin, 1958a). Sandstone sorting varies greatly from well sorted to very poorly sorted (Mankin, 1958a). The most common sandstones are fine-grained with a tendency for grain size to increase upward. The upper sandstones tend to be coarse-grained (Mankin, 1958a).

An informal tripartite division of the Morrison (Fig. 3) [8] can be seen in parts of San Miguel, Quay, Guadalupe and Harding Counties (Dobrovolny et al., 1946; Mankin, 1958a; Wanek, 1962; Trauger and Bushman, 1964). The lower division of the Morrison is characterized


K
JM
JB
TR
A


B


C


D


E

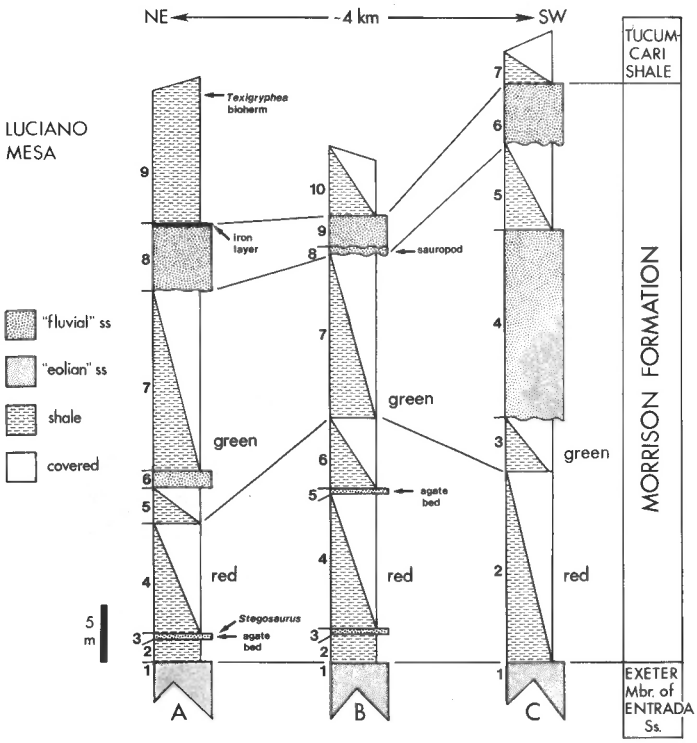


FIGURE 22. Measured sections of the Morrison Formation at Bull Canyon. Locations of sections are: A. – SE¼, sec. 22, T9N, R26E; B. – SW¼, sec. 27, T9N, R26E; C. – SE¼, sec. 33, T9N, R26E.

by brick-red mudstone and minor, discontinuous sandstone (red shale member of Wanek, 1962). The middle division is dominated by laterally discontinuous, fine-grained sandstone with minor, pale-green mudstone and local chert and clay-pebble conglomerate, particularly at the bases of sandstones (medial sandstone member of Wanek, 1962). The upper division is characterized by green and variegated mudstone with minor discontinuous sandstone (green shale member of Wanek, 1962) (Fig. 21E). At the top of the Morrison, a coarse-grained sandstone is present locally (Trauger and Bushman, 1964). In northeastern New Mexico, a unit possibly equivalent to this sandstone was questionably placed in the Morrison by Baldwin and Muehlberger (1959), but was placed in the basal Purgatoire Formation (i.e., Tucumcari Shale) by Cooley (1955). At Luciano Mesa, the top of the Morrison is a cliff-forming sandstone with "salt-and-pepper" coloration and an abundance of epsilon cross-bedding (Fig. 22). Due to the abundance of mudstone and the poor consolidation of the sandstone, the Morrison is usually a slope former and frequently is covered by colluvial debris and vegetation (e.g., Figs. 17, 20A).

Contacts

Over much of east-central New Mexico, the Morrison rests with apparent conformity on the Bell Ranch Formation or the Exeter Member of the Entrada Sandstone. The basal beds of the Morrison are frequently marked by from one to six "agate beds," and the contact is at the top of the uppermost laterally continuous sandstone or siltstone of the Bell Ranch Formation. For mapping in areas of poor exposures, the presence of the carnelian colored "agate bed" can be used to mark the base of the Morrison. In areas where the Morrison is underlain by the Exeter Member of the Entrada Sandstone, the base is taken as the top of the uppermost eolian sandstone, and again the "agate bed" is usually present in the basal Morrison.

The Morrison Formation is unconformably overlain by the marine Cretaceous Tucumcari Shale and/or the Mesa Rica Sandstone or equivalents (Fig. 22). This boundary often appears conformable, but, upon closer examination, its unconformable nature is apparent. The pale, olive-green to dark-gray shale of the Tucumcari Shale contrasts with the variegated, bright-green shale of the Morrison. Also, the Tucumcari Shale has a characteristic marine fauna in most outcrops. The base of the Mesa Rica Sandstone, where it rests on the Morrison, is usually characterized by a conglomeratic, channeled zone, sometimes with numerous specimens of *Texigryphaea*. It is often extensively bioturbated, unlike the sandstones of the upper Morrison. The upper sandstone contact of the Morrison frequently is enriched with iron that has produced a limonitic zone, suggesting a subaerially weathered surface (Fig. 22).

Thickness

The Morrison Formation in east-central New Mexico varies in thickness from 0 m in the south to 186 m along the Canadian River west of Roy (Fig. 23). Isopachs of the Morrison indicate four distinct centers of deposition. The largest and deepest basin of Morrison deposition was a north–south-trending linear basin extending from near Sanchez in San Miguel County to north of Springer in Colfax County. In this basin, the Morrison reaches its maximum thickness of 186.2 m. To the southeast of this basin is a shallower basin covering the northeastern portion of the Pablo Montoya Grant and extending east past Gallegos in Harding County. The Morrison reaches a thickness of 157.3 m in this basin. Near Las Vegas are the remnants of another deep basin (167.9 m). The margin of another deep basin can be delineated in central Union County and extends into western Oklahoma. Between these basins, the Morrison averages 50–90 m thick. The Morrison in Quay and Guadalupe Counties thins and is totally absent in the structurally complex area of Ragland–Quay–Mesa Redonda, probably due to Cretaceous uplift and erosion.

Depositional environment

The Morrison Formation was deposited as a laterally extensive, though relatively thin, sequence of nonmarine rocks in the Western Interior from Montana to New Mexico (Peterson, 1972). Commercial accumulations of coal and prominent limestones are restricted to Montana and North Dakota (Fig. 24). Elsewhere, the Morrison is fluviatile in origin (Mook, 1916; Dodson et al., 1980).

In east-central New Mexico, Morrison facies consist of variegated green and red mudstone, siltstone and fine- to coarse-grained sandstone (Mankin, 1958a, 1972). The Morrison sandstones occur either as discrete channel-form bodies or as more continuous sheets with scour bases, basal conglomeratic "lags" and crossbedding characteristic of fluvial deposition. These sands are arkosic and variably sorted (Mankin, 1972), further supporting their fluvial origin.

The volumetrically dominant (50–80%) fine-grained facies of the Morrison can be readily interpreted as overbank, floodplain deposits. Although individual mudrock beds are very continuous laterally, they are often truncated by sandstone bodies. Three significant subfacies exist:

1. At most places near the base of the Morrison there are from one to six beds of thin, resistant, nodular limestone with an abundance of carnelian-colored, microcrystalline quartz. This unit, often termed the "agate bed," is essentially continuous over all of eastern New Mexico where it has not been removed by post-Jurassic erosion. It has also been called the "Carnelian Sandstone" (Goldman and Spencer, 1941) in southwestern Colorado and the "welded chert zone" by Fredrickson et al. (1956). Despite several previous reports in the literature, only Ogden (1954) appears to have grasped the potential of this widespread unit for regional correlation. Beds equivalent to this "agate bed" have been reported from eastern Colorado (Fredrickson et al., 1956), southeastern Utah (Goldman and Spencer, 1941), western Kansas (Merriam, 1955), northeastern Utah (Ogden, 1954), southwestern Wyoming (Ogden, 1954), southwestern Nebraska (McKee et al., 1956) and western Oklahoma (McKee et al., 1956). In New Mexico this unit is recog-

← FIGURE 21. The section at Punta de Gallegos. A, Overview of section showing Redonda Member of Chinle Formation (TR), Bell Ranch Formation (JB), Morrison Formation (JM) and Cretaceous strata (K). Note the absence of the Entrada Sandstone in this section. B, Interbedded sandstones and siltstones of the Bell Ranch Formation. C, Close-up of typical Bell Ranch sandstone. D, Nodular gypsum (white clasts) in Bell Ranch sandstone. E, Claystones and sandstones of the lower part of the Morrison Formation.

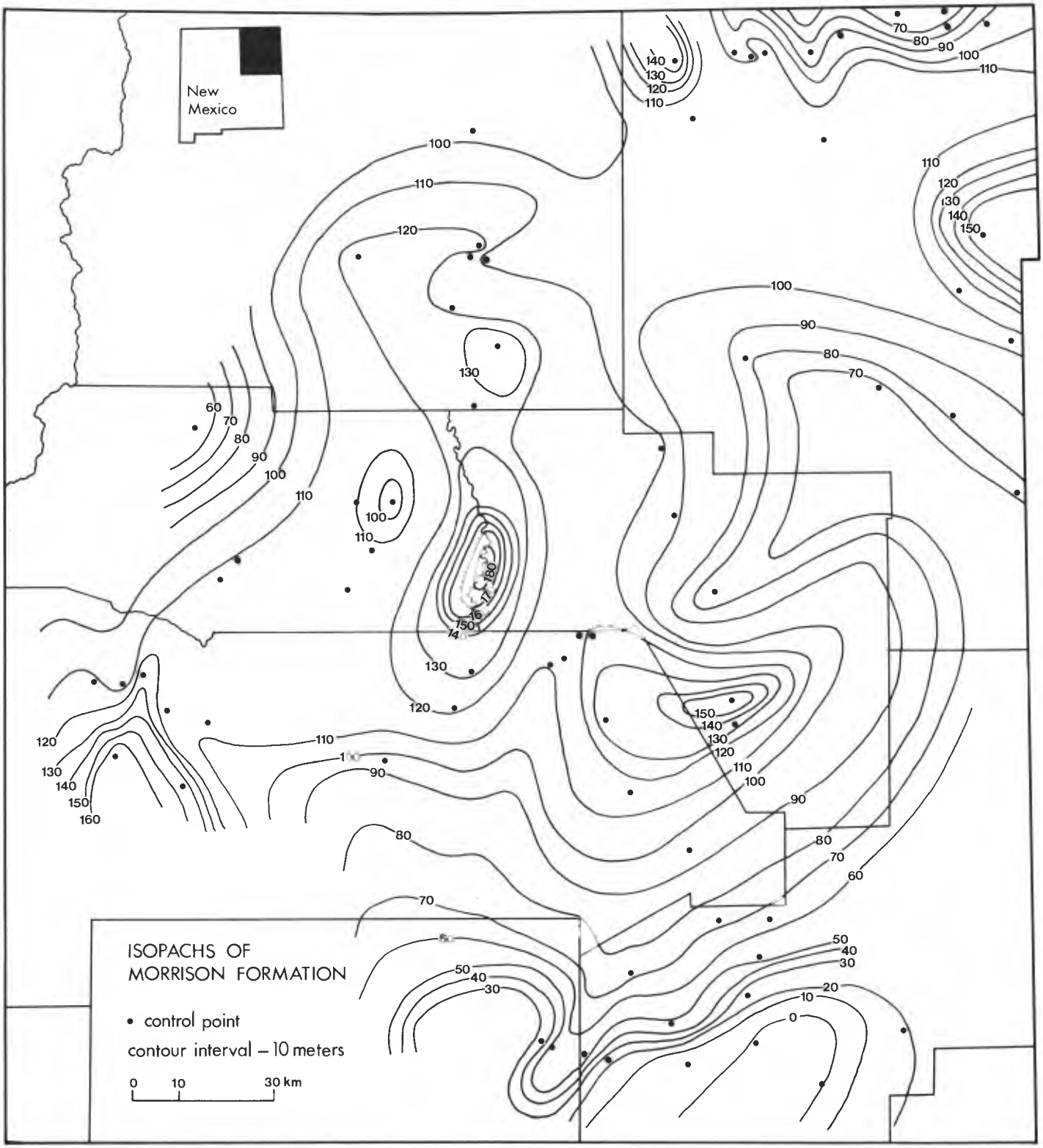


FIGURE 23. Isopach map of the Morrison Formation in east-central and northeastern New Mexico.

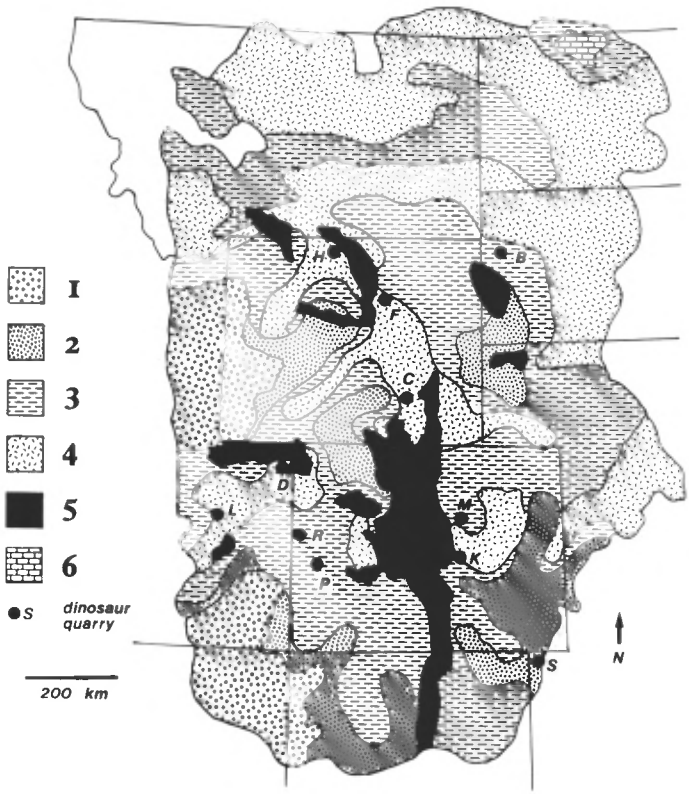


FIGURE 24. Facies map and major dinosaur quarries of the Morrison Formation in western North America. Facies are: 1 – more than 50% sandstone (mostly conglomerate), 2 – more than 50% sandstone, 3 – 20–50% sandstone/50–80% variegated mudrock, 4 – more than 80% variegated mudrock, 5 – Precambrian crystalline rocks exposed, 6 – more than 50% lacustrine limestone. Dinosaur quarries are: B – *Barosaurus* quarry, C – Como Bluff, D – Dinosaur National Monument, F – Red Fork Quarry, H – Howe Quarry, K – Cañon City/Garden Park, L – Cleveland-Lloyd Quarry, M – Morrison, P – Potter Creek, R – Riggs Quarry, S – Stovall Quarries. After Peterson (1972) and Dodson et al. (1980).

nizable in the central (Ogden, 1954; Kelley and Northrop, 1975) and northeastern (Lee, 1902; Mankin, 1958a) parts of the state. Proposed origins for these "agate beds" include altered volcanic ash (Ogden, 1954) and ground-water replacement of calcium carbonate concretions (Fredrickson et al., 1956). Microstratigraphy of these beds at Bull Canyon in east-central New Mexico indicates that these siliceous beds are components of a series of thin, widespread horizons which contain root casts and concretions strongly suggestive of a weathering profile or paleosol.

2. Locally, thin (10 cm) limestone beds are present. These beds contain a large percentage of clastics and may represent minor lacustrine development (Mankin, 1972) or possibly additional paleosol (calcrete) horizons.

3. Bentonites up to 30 cm thick occur, particularly in the upper part of the formation in east-central New Mexico (Cooley, 1955; Mankin, 1972).

The Morrison environment in east-central New Mexico was dominated by fluvial deposition. The large amount of fine-grained overbank deposits and the presence of abundant epsilon (lateral accretion) cross-beds suggest the rivers were of high sinuosity (Collinson, 1978a). The environment differs in some respects from Morrison environments in the Colorado Plateau. Although dinosaur bone is fairly common in the Morrison of eastern New Mexico, there are no major accumulations of bone like those in the Colorado Plateau (Hunt and Lucas, 1984; Lucas and Hunt, in press). In general, organic matter is less common in the Morrison of east-central New Mexico than elsewhere, suggesting a drier climate with less stream discharge (Abbott, 1979; Reid et al., 1980, 1982).

Age

Aside from fragments of petrified wood, the only fossils thus far known from the Morrison of east-central New Mexico are isolated dinosaur bones. Stanton (1905, p. 665) first reported dinosaurs from the Morrison of New Mexico when he mentioned that "fragmentary, undetermined, dinosaur remains were seen in [the Morrison] on the Cimarron near Exter [=Exeter], New Mexico." Stanton (1905, p. 666) went on to note "fragmentary bones of large dinosaur" from the Morrison about 16 km northwest of Tucumcari. These occurrences are documented by the following specimens (J. McIntosh, written comm., 1984) collected by Stanton, C. W. Gilmore and W. T. Lee in June, 1905:

1. USNM (United States National Museum) 5735: three sauropod caudal vertebrae from the west side of the Cimarron River, 5 km west of Exter [=Exeter].

2. USNM 337832: an ornithopod cervical vertebra from the same locality as USNM 5735.

3. USNM uncatalogued: two *Allosaurus* vertebrae bearing the same accession number as USNM 337832, and presumably from the same locality.

4. USNM 337830: a sauropod phalanx from a locality 16 km northwest of Tucumcari.

There are only three other published references to Morrison dinosaurs in eastern New Mexico:

1. Baldwin and Muehlberger (1959, p. 49) noted that "dinosaur bones, in part replaced by uranium, have been reported from Ute Creek," in southern Harding County. This is in the same general area where USNM 337830 was collected.

2. Mankin (1972, p. 95) made the following observations:

> Fragments of bones are present in a few localities [in the Morrison of east-central New Mexico]. The bone fragments are considered to be dinosaur remains based largely on the size and bone structure of the individual specimens. No further delineation of the bone fragments has been attempted.

3. Lucas et al. (1984), Hunt and Lucas (1984) and Lucas and Hunt (in press) mentioned fragmentary sauropod bones from the Morrison Formation at Bull Canyon.

We further document the Jurassic dinosaurs from the Morrison Formation of east-central New Mexico with the following brief descriptions of additional dinosaur remains from Bull Canyon and Punta de Gallegos (Fig. 25):

1. Sauropod indeterminate: UNM MV-052 (Fig. 25A–B). This specimen consists of the right posterior portion of an anterior caudal centrum of a sauropod. It has a height of about 15 cm and an approximate length of 14 cm. Part of the transverse process and posterior articular surface for the chevron are preserved.

2. *Stegosaurus* sp.: UNM MV-561 (Fig. 25C–E). This specimen is an abraded centrum of an ornithischian dinosaur. It has a height of 11 cm and a length of 9 cm. In ventral view, this centrum has the hourglass shape characteristic of *Stegosaurus* centra (Ostrom and McIntosh, 1966, pls. 14–18), and it is tentatively referred to this genus.

3. Sauropod indeterminate: UNM MV-560 (Fig. 25F–H). This specimen is an abraded centrum of a mid-caudal sauropod vertebra. It has a height of 15 cm (including the base of the neural arch) and a length of 10 cm.

4. Dinosaur indeterminate: UNM MV-562 (Fig. 25I). This indeterminate and incomplete dinosaurian centrum displays the siliceous replacement characteristic of bones found in the "agate bed" of the basal Morrison in east-central New Mexico.

Upper and lower age limits on the Morrison Formation in east-central New Mexico are imposed by the early to middle Callovian fishes from the Todilto Formation below it and the middle to late Albian microfauna and invertebrate megafauna of the overlying Tucumcari Shale (Kietzke, 1985; Kues et al., 1985). The only direct biostratigraphic correlation of the Morrison in east-central New Mexico is based on the remains of *Stegosaurus* from the basal Morrison "agate bed" at Bull Canyon. While the distribution of *Stegosaurus* in the Morrison Formation throughout the Western Interior has not been fully documented, it is

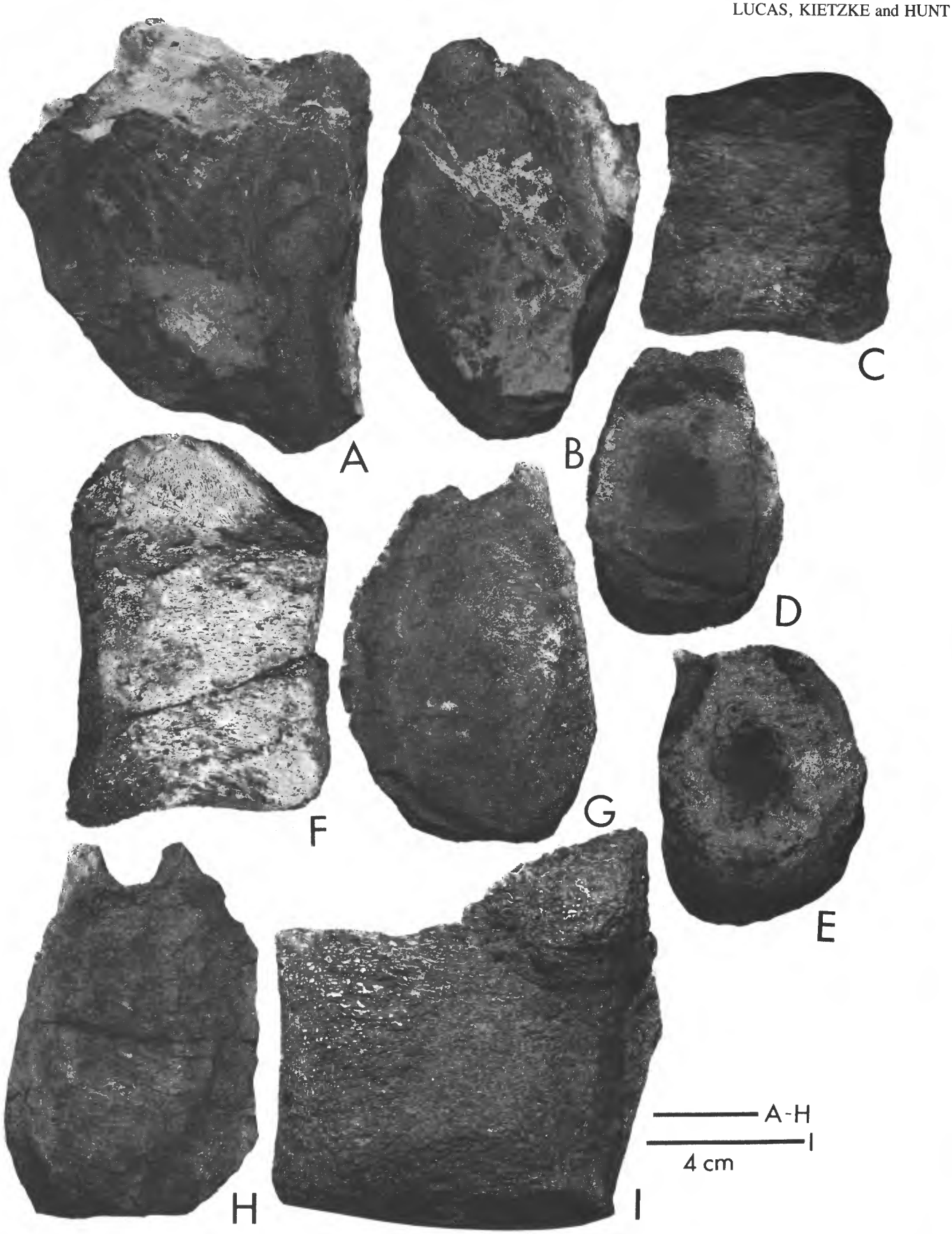


FIGURE 25. Dinosaur fossils from the Morrison Formation in east-central New Mexico. A, B, UNM MV-052, part of an anterior caudal centrum of a sauropod, lateral (A) and posterior (B) views. Specimen from Bull Canyon (see Fig. 22, section B). C, D, E, UNM MV-561, vertebral centrum of *Stegosaurus* sp., lateral (C), anterior (D) and posterior (E) views. Specimen from Bull Canyon (see Fig. 22, section A). F, G, H, UNM MV-560, caudal centrum of a sauropod, lateral (F), anterior (G) and posterior (H) views. Specimen from the same locality as UNM MV-561. I, UNM MV-562, lateral view of abraded dinosaur bone showing replacement with agate. Specimen from the agate bed at Punta de Gallegos (Fig. 21).

known from Quarry 13 (Wyoming), the quarry at Morrison (Colorado) and the Bone Cabin Quarry (Wyoming) (Fig. 24). These quarries are in the lower, middle and upper third, respectively, of the Morrison Formation (Dodson et al., 1980, 1983). This suggests that at least the lower part of the Morrison Formation in east-central New Mexico is correlative with the classic Morrison sections in Colorado, Utah and Wyoming.

The age of the Morrison in these states has been the subject of some debate (Simpson, 1926). The oldest rock-stratigraphic unit that overlies the Morrison is the Dakota Formation, which contains Valanginian (Early Cretaceous) ostracodes (Sohn, 1979). The youngest well-dated marine units underlying the Morrison probably are of late Oxfordian age (Imlay, 1947, 1980). Fossil remains of reptiles (Schuchert, 1918; Simpson, 1926; Galton, 1977), mammals (Simpson, 1926), megaflora (Berry, 1915) and pollen (Dodson et al., 1980), supported by magnetic-polarity stratigraphy (Steiner, 1980) and radiometric dating (Brookins, 1980) are consistent with assignment of a late Oxfordian to Tithonian age (*sensu* Harland et al., 1982) to the Morrison Formation throughout much of the Western Interior. The Morrison in east-central New Mexico is thus of the same general age (Fig. 26).

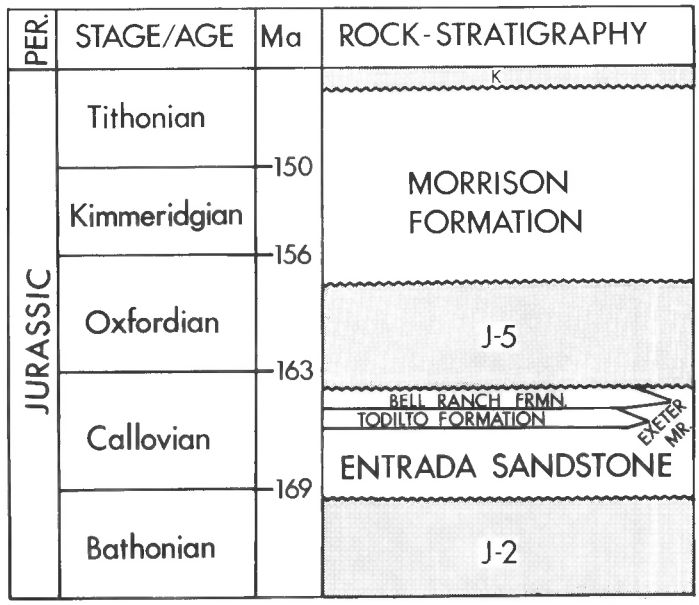


FIGURE 26. Jurassic strata of east-central New Mexico correlated with the chronostratigraphic scale. Unconformities are identified according to the scheme of Pipiringos and O'Sullivan (1978).

STRUCTURAL HISTORY

Isopachs of the Jurassic in northeastern and east-central New Mexico (Figs. 6, 23) indicate several, distinct syndepositional downwarps. In northern Mora County, both the Entrada and Morrison show thickening trends, but not in coincident areas. A major north–south sequence of basins runs from southern Colfax to northern San Miguel Counties. Another major basin is centered in the eastern Pablo Montoya Grant, and the Morrison displays distinct thickening around Las Vegas.

South of Tucumcari, both the Entrada and Morrison show complex thinning patterns with both units disappearing in the Mesa Redonda–Saddleback Mesa area. This is the area of the Tucumcari basin (*sensu* Suleiman and Keller, 1985, fig. 6) and of a Pennsylvanian-age basin (Broadhead and King, 1985, fig. 1). Examination of the outcrops and stratigraphic sections in this area suggests it was an area of post-Morrison uplift. The lack of syntectonic conglomerates and sandstones in the Morrison south of Tucumcari indicates that uplift occurred after deposition of the Morrison. The Morrison at Luciano Mesa (Fig. 22), for example, contains far more mudstone than sections farther to the north. The sandstone capping the Morrison at Luciano Mesa is laterally continuous and contains abundant, lateral accretion crossbeds, suggesting deposition by sinuous streams and, hence, tectonic stability. The uplift and the erosion of the uplift both occurred prior to the deposition of the Albian Tucumcari Shale.

Three major unconformities are found associated with Jurassic deposition in east-central New Mexico (Fig. 26). The unconformity that marks the base of the Jurassic is the regionally extensive J-2 unconformity (Pipiringos and O'Sullivan, 1978). In east-central New Mexico, this unconformity marks the break between the Triassic Chinle Formation and the Jurassic Entrada Sandstone. Pipiringos and O'Sullivan (1978, p. 22) consider this unconformity to represent a "relatively short period of time," whereas Kocurek and Dott (1983, p. 107) find it "difficult to explain the generation of a terrestrial unconformity of regional scale developed in an eolian sand sea."

The second major unconformity is between the Morrison Formation and the Bell Ranch Formation/Exeter Member of the Entrada Sandstone. This unconformity is the J-5 unconformity of Pipiringos and O'Sullivan (1978) that extends from New Mexico north to Montana. It is demonstrably not synchronous over its entire extent, and the Morrison Formation thus has a diachronous base on a regional scale (Imlay, 1980).

The third major unconformity in east-central New Mexico occurs at the top of the Morrison Formation. This is the K unconformity of Pipiringos and O'Sullivan (1978), present throughout the southern Rocky Mountains.

REGIONAL CORRELATION AND DEPOSITIONAL SYNTHESIS

Having reviewed the Jurassic sequence in east-central New Mexico (Fig. 26), we attempt here, in a tentative way, to place these rocks in a more regional context. Although we have examined Jurassic stratigraphic relationships in east-central New Mexico in some detail, further studies are needed between east-central New Mexico and the better studied Colorado Plateau before a detailed, regional synthesis can be presented. A further complicating factor is that east-central New Mexico lies near the eastern edge of the depositional basin of the Jurassic units under consideration, which may confuse correlation with units nearer the centers of the Jurassic depositional basins.

During the middle and Late Jurassic, the supercontinents of Laurasia and Gondwanaland were just beginning to separate so that North America moved slowly northward, and the Equator crossed northern Yucatan by middle Callovian to middle Oxfordian time (Kocurek and Dott, 1983). The climate during the middle and Late Jurassic was very warm and dry, with marked global equability (Frakes, 1979). New Mexico was, due to a variety of climatic and tectonic factors, subjected to periodic aridity (Kocurek and Dott, 1983).

The earliest Jurassic lithosome preserved in east-central New Mexico is the Entrada Sandstone (Fig. 27). The Entrada of the Colorado Plateau can be securely traced into eastern New Mexico, based on its position above the J-2 unconformity of Pipiringos and O'Sullivan (1978) and its position below (and lateral to) the Todilto Formation. Interpretations of the depositional environment of the Entrada in east-central New Mexico conform to broader scale models of Entrada deposition. The Entrada represents a large eolian sand sea (erg) which prograded northwestward during the regional retreat of the Carmel Sea and, again, during the retreat of the Curtis Sea (Kocurek and Dott, 1983). Our studies, those of Mankin (1958a, b, 1972) and the preliminary results of Kocurek and Dott (1983) indicate that the Entrada in east-central and northeastern New Mexico represents inland dunes and thin eolian interdune areas. Eastern New Mexico appears to lie near the edge of the Entrada depositional basin, although Kocurek and Dott (1983) infer the Entrada erg was thin but extensive eastward across the southern margin of the North American craton.

The Todilto Formation in east-central New Mexico overlies the Entrada Sandstone with apparent conformity and, in turn, is locally overlain by tongues of the Entrada (Fig. 27). These stratigraphic relationships, together with lithology, vertebrate fauna and inferred depositional environment, indicate that the Todilto of east-central New Mexico represents the same unit as the Todilto Formation in north-central and northwestern New Mexico. The Todilto represents a large salina formed by marine waters of the Curtis Sea percolating through the sands of the

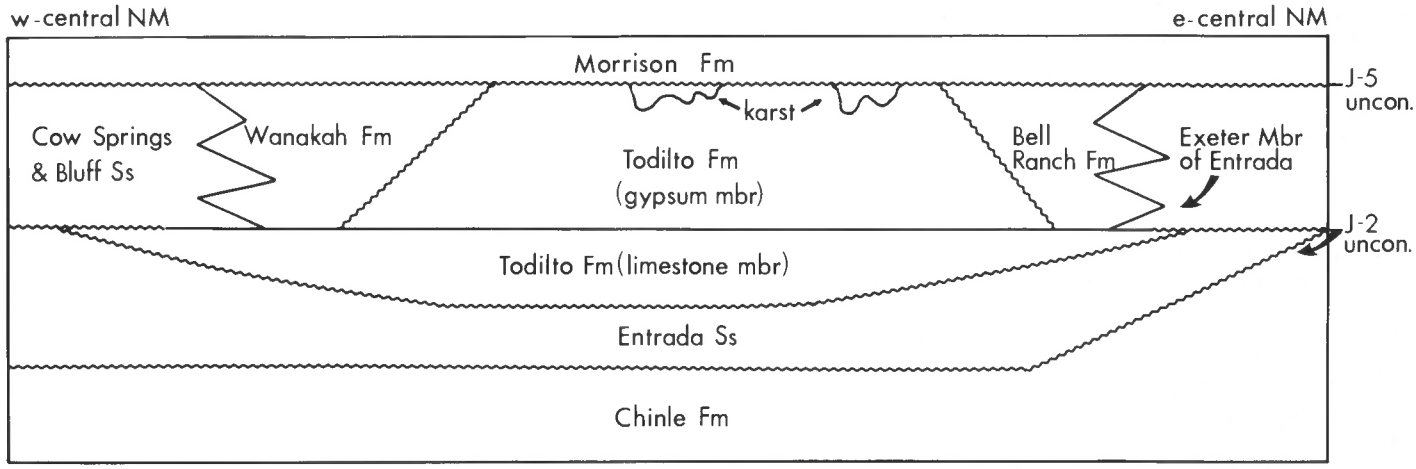


FIGURE 27. Preliminary assessment of the regional relationships of Jurassic strata in northern New Mexico (see text for discussion).

Entrada erg along the western margins of the depositional basin, probably in the Four Corners area. Localities in east-central New Mexico represent the easternmost occurrences of the Todilto, and several good exposures show the Todilto pinching out into the Entrada Sandstone. Similar stratigraphic relationships are seen between the Todilto and the Entrada/Zuni Sandstone in the southern San Juan Basin. In both areas, the Todilto salina was at its depositional margin and was being encroached upon by sand dunes of the Entrada which surrounded the lake. In east-central New Mexico, the principal progradational sandstone is represented by the Exeter Member of the Entrada. Where the Todilto is not present in northeastern and east-central New Mexico, a prominent topographic notch is present within the Entrada, for example at the type locality of the Exeter. This notch apparently represents a landward, clastic facies equivalent to the Todilto and Bell Ranch (lower part) Formations (Fig. 27).

In east-central New Mexico, the Bell Ranch Formation overlies, and interfingers with, tongues of the Entrada Sandstone and underlies the Morrison Formation (Fig. 27). It is composed of laterally continuous siltstones and sandstones. On the basis of these characteristics, and its stratigraphic position, the Bell Ranch is equivalent to the Wanakah and Ralston Creek Formations of southern Colorado. Based upon its superposition above the Todilto limestone unit, the Bell Ranch would appear to be equivalent, at least in part, to the gypsum member of the Todilto Formation in the San Juan Basin and adjacent areas. In the San Juan Basin, subsurface studies indicate that the lower portion of the Summerville (Wanakah) Formation is laterally equivalent to the gypsum member of the Todilto, but that the majority of the clastic unit is younger than the gypsum (Vincelette and Chittum, 1983, fig. 8). The Bell Ranch and Wanakah are thus the prograding marginal clastics of the evaporating Todilto salina (Fig. 27).

The youngest Jurassic lithosome in east-central New Mexico is the Morrison Formation (Fig. 27). Its lithology and stratigraphic position above the Entrada/Bell Ranch Formations allow confident correlation with the Morrison Formation elsewhere in the Western Interior. The dominantly fluvial origin of the Morrison in east-central New Mexico is consistent with depositional models of the Morrison in the Rocky Mountain region (Peterson, 1972; Dodson et al., 1980). East-central New Mexico is on the eastern margin of the Morrison depositional basin, and the unit is thinner than in the Colorado Plateau. This may be the result of less deposition and/or the presence of unconformities in the Morrison section.

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REFERENCES

Abbott, M. M., 1979, A basic evaluation of the uranium potential of the Morrison Formation of northwestern Cimarron County, Oklahoma and adjoining areas of New Mexico and Colorado [M.S. thesis]: Norman, Oklahoma State University, 93 pp.

Allen, J. E. and Balk, R., 1954, Mineral resources of Fort Defiance and Tohatchi quadrangles, Arizona and New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 36, 192 pp.

Anderson, J. B., Wolfreich, C., Wright, R. and Cole, M. L., 1982, Determination of depositional environments of sand bodies using vertical grain-size progressions: Gulf Coast Association of Geological Societies, Transactions, v. 32, pp. 565–577.

Anderson, O. J., 1983a, What is the Zuni Sandstone today—100 years after Dutton? A discussion and review of Jurassic stratigraphy in west-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 174, 34 pp.

Anderson, O. J., 1983b, Preliminary report on redefinition of Zuni Sandstone, west-central New Mexico: New Mexico Geology, v. 5, pp. 56–59.

Anderson, R. Y. and Kirkland, D. W., 1960, Origin, varves, and cycles of the Jurassic Todilto Formation, New Mexico: American Association of Petroleum Geologists Bulletin, v. 44, pp. 37–52.

Ash, H. O., 1958, The Jurassic Todilto Formation of New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 63 pp.

Bachman, G. O., 1953, Geology of a part of northwestern Mora County, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM-137.

Bailey, R. M., 1955, Differential mortality from high temperature in a mixed population of fishes in southern Michigan: Ecology, v. 36, pp. 526–528.

Baker, A. A., Dane, C. H. and Reeside, J. B., Jr., 1936, Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U.S. Geological Survey, Professional Paper 183, 66 pp.

Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., 1947, Revised correlation of Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: American Association of Petroleum Geologists, Bulletin, v. 31, pp. 1664–1677.

Baldwin, B. and Muehlberger, W. R., 1959, Geological studies of Union County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 63, 171 pp.

Baltz, E. H. and Bachman, G. O., 1956, Notes on the geology of the southeastern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 7, pp. 96–108.

Barbour, C. D. and Brown, J. H., 1974, Fish species diversity in lakes: American Midland Naturalist, v. 108, pp. 423–489.

Berry, E. W., 1915, Paleobotanic evidence of the age of the Morrison Formation: Geological Society of America, Bulletin, v. 26, pp. 335–342.

Bigurella, J. J., 1972, Eolian environments: their characteristics, recognition

and importance: Society of Economic Paleontologists and Mineralogists, Special Publication 16, pp. 12–62.
Bradbury, J. P. and Kirkland, D. W., 1966, Upper Jurassic aquatic Hemiptera from the Todilto Formation: Geological Society of America, Special Paper 101, p. 24.
Broadhead, R. F. and King, W. E., 1985, Preliminary report on the stratigraphy and structure of Pennsylvanian and Lower Permian strata, Tucumcari basin: New Mexico Geological Society, Guidebook 36.
Brongersma-Sanders, M., 1957, Mass mortality in the sea: Geological Society of America, Memoir 67, pp. 941–1010.
Brookins, D. G., 1980, Geochronologic studies in the Grants mineral belt: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, pp. 52–58.
Brown, L. H. and Urban, E. K., 1969, The breeding biology of the great white pelican *Pelecanus onocratalus roseus* at Lake Shala, Ethiopia: Ibis, v. 111, pp. 199–237.
Burbank, W. S., 1930, Revision of geological structure and stratigraphy in the Ouray district of Colorado, and its bearing on ore deposition: Colorado Scientific Society, Proceedings, v. 12, pp. 151–232.
Bush, A. L., Bromfield, C. S. and Pierson, C. T., 1959, Areal geology of the Placerville Quadrangle, San Miguel County, Colorado: U.S. Geological Survey, Bulletin 1072-E, pp. 299–384.
Colbert, E. H., 1950, Mesozoic vertebrate faunas and formations of northern New Mexico; *in* Colbert, E. H. and Northrop, S. A., eds., Guidebook for the 4th field conference, Society of Vertebrate Paleontology: New York and Albuquerque, American Museum of Natural History and University of New Mexico, pp. 57–73.
Collinson, J. D., 1978a, Alluvial sediments; *in* Reading, H. G., ed., Sedimentary environments and facies: Amsterdam, Elsevier, pp. 15–60.
Collinson, J. D., 1978b, Deserts; *in* Reading, H. G., ed., Sedimentary environments and facies: Amsterdam, Elsevier, pp. 80–96.
Condon, S. M. and Huffman, A. C., 1984, Stratigraphy and depositional environments of Jurassic rocks, San Juan Basin, New Mexico, with emphasis on the south and west sides: Rocky Mountain Section, Geological Society of America, 37th Annual Meeting Fieldtrip Guidebook, pp. 93–107.
Cooley, B. B., Jr., 1955, Areal geology of Dry Cimarron Canyon, Union County, New Mexico [M.S. thesis]: Austin, University of Texas, 93 pp.
Cross, W., 1899, Description of Telluride Quadrangle, Colorado: U.S. Geological Survey, Geological Atlas, Folio 57, pp. 1–19.
Dane, C. H. and Bachman, G. O., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.
Darton, N. H., 1928, "Red beds" and associated formations in New Mexico, with an outline of the geology of the state: U.S. Geological Survey, Bulletin 794, 356 pp.
DeFord, R. K., 1927, Areal geology of Cimarron County, Oklahoma: American Association of Petroleum Geologists, Bulletin, v. 11, pp. 753–755.
Dinwiddie, G. A. and Clebsch, A., Jr., 1973, Water resources of Guadalupe County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 3, 43 pp.
Dobrovolny, E., Summerson, C. H. and Bates, R. L., 1946, Geology of northwestern Quay County, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 62.
Dodson, P., Behrensmeyer, A. K., Bakker, R. T. and McIntosh, J. S., 1980, Taphonomy and paleoecology of the dinosaur beds of the Jurassic Morrison Formation: Paleobiology, v. 6, pp. 208–232.
Dodson, P., Bakker, R. T. and Behrensmeyer, A. K., 1983, Paleoecology of the dinosaur-bearing Morrison Formation: National Geographic Society, Research Reports, v. 15, pp. 145–156.
Drooger, C. W., ed., 1973, Messinian events in the Mediterranean: Amsterdam, North-Holland Publishing Co., 272 pp.
Duce, J. T., 1924, Geology of parts of Las Animas, Otero and Bent Counties: Colorado Geological Survey, Bulletin 27, pp. 73–102.
Dunkle, D. H., 1942, A new fossil fish of the family Leptolepidae: Cleveland Museum of Natural History, Science Publications, v. 8, pp. 61–64.
Dutton, C. E., 1885, Mount Taylor and the Zuni Plateau: U.S. Geological Survey, 6th Annual Report, pp. 105–198.
Eastman, C. R., 1899a, Some new American fossil fishes: Science, v. 9, pp. 642–643.
Eastman, C. R., 1899b, Jurassic fishes from the Black Hills of South Dakota: Geological Society of America, Bulletin, v. 10, pp. 397–408.
Eckel, E. B., 1949, Geology and ore deposits of the La Plata District, Colorado: U.S. Geological Survey, Professional Paper 219, 179 pp.
Eldridge, G. H., 1894, Description of sedimentary formations—Anthracite, Crested Butte Quadrangles, Colorado: U.S. Geological Survey, Geological Survey Atlas, Folio 9, pp. 1–11.
Emerick, W. L., 1950, Geology of the Golden area, Santa Fe County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 66 pp.
Foster, R. W., Frentress, R. M. and Riese, W. C., 1972, Subsurface geology of east-central New Mexico: New Mexico Geological Society, Special Publication 4, 22 pp.
Frakes, L. A., 1979, Climates through geologic time: New York, Elsevier, 310 pp.
Fredrickson, E. A., Delay, J. M. and Saylor, W. W., 1956, Ralston Formation of Cañon City embayment, Colorado, 1956: American Association of Petroleum Geologists, Bulletin, v. 40, pp. 2120–2148.
Freeman, N. E. and Visher, G. S., 1975, Stratigraphic analysis of the Navajo Sandstone: Journal of Sedimentology Petrology, v. 45, pp. 651–661.
Galton, P. M., 1977, Upper Jurassic ornithopod dinosaur *Dryosaurus* and Laurasia-Gondwanaland connection: Milwaukee Public Museum, Special Publications in Biology and Geology, v. 2, pp. 41–54.
Gilbert, G. K., 1875, Report on the geology of portions of New Mexico and Arizona examined in 1873: U.S. Geographical and Geological Surveys west of the 100th Meridian [Wheeler], Report, v. 3, pp. 503–567.
Gilluly, J. and Reeside, J. B., Jr., 1928, Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U.S. Geological Survey, Professional Paper 150-D, pp. 61–110.
Goddard, E. N., Trask, P. D., DeFord, R. K., Rove, O. N., Singewald, J. T., Jr. and Overbeck, R. M., 1979, Rock-color chart: Boulder, Geological Society of America.
Goldman, M. I. and Spencer, A. C., 1941, Correlation of Cross' La Plata Sandstone of southwestern Colorado: American Association of Petroleum Geologists, Bulletin, v. 25, pp. 1745–1767.
Grabau, A. W., 1917, Age and stratigraphic relations of the Olentangy shale of central Ohio, with remarks on the Prout limestone and so-called Olentangy shales of northern Ohio: Journal of Geology, v. 25, pp. 337–343.
Grande, L., 1980, Paleontology of the Green River Formation, with a review of the fish fauna: Geological Survey of Wyoming, Bulletin 63, 333 pp.
Gregory, H. E., 1916, The Navajo Country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geological Survey, Water-Supply Paper 380, 219 pp.
Gregory, H. E., 1917, Geology of the Navajo Country: U.S. Geological Survey, Professional Paper 93, 161 pp.
Griggs, R. L. and Read, C. B., 1959, Revisions in stratigraphic nomenclature in Tucumcari-Sabinoso area, northeastern New Mexico: American Association of Petroleum Geologists, Bulletin, v. 43, pp. 2003–2007.
Gunter, G., 1947, Catastrophism in the sea and its paleontological significance, with special reference to the Gulf of Mexico: American Journal of Science, v. 245, pp. 669–676.
Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C. A. G., Smith, A. G. and Walters, R., 1982, A geologic time scale: Cambridge, Cambridge University Press, 131 pp.
Harrison, E. P., 1949, Geology of the Hagan coal basin [M.S. thesis]: Albuquerque, University of New Mexico, 177 pp.
Harshbarger, J. W., Repenning, C. A. and Irwin, J. H., 1957, Stratigraphy of the uppermost Triassic and Jurassic rocks of the Navajo Country: U.S. Geological Survey, Professional Paper 291, 74 pp.
Heaton, R. L., 1939, Contribution to Jurassic stratigraphy of Rocky Mountain region: American Association of Petroleum Geologists, Bulletin, v. 23, pp. 1153–1177.
Hoover, W. B., 1950, Jurassic formations of parts of Utah, Colorado and New Mexico: New Mexico Geological Society, Guidebook 1, pp. 76–81.
Hunt, A. P. and Lucas, S. G., 1984, Rarity of dinosaurs in the Upper Jurassic Morrison Formation, New Mexico: Geological Society of America, Abstracts with Programs, v. 16, p. 225.
Hutson, O. C., 1958, Geology of the northern end of San Pedro Mountain [M.S. thesis]: Albuquerque, University of New Mexico, 55 pp.
Imlay, R. W., 1947, Marine Jurassic of Black Hills area, South Dakota and Wyoming: American Association of Petroleum Geologists, Bulletin, v. 31, pp. 227–273.
Imlay, R. W., 1952, Correlation of the Jurassic formations of North America, exclusive of Canada: Geological Society of America, Bulletin, v. 63, pp. 953–992.
Imlay, R. W., 1980, Jurassic paleobiogeography of the coterminous United States in its continental setting: U.S. Geological Survey, Professional Paper 1062, 134 pp.
Jacka, A. D., 1973, Exeter-Morrison boundary; *in* Phillips, K. A., ed., Guidebook of interpretation of depositional environments from selected exposures of Paleozoic and Mesozoic rocks in north-central New Mexico: Amarillo, Panhandle Geological Society, pp. 27–30.
Jones, J. R. E., 1964, Fish and river pollution: London, Butterworths, 203 pp.
Kehler, P. L., 1975, The lower Zuni sequence in the southwestern United States: Institute for the Study of Earth and Man, Report of Investigations 1, 27 pp.

Kelley, V. C. and Northrop, S. A., 1975, Geology of the Sandia Mountains and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 29, 136 pp.

Kietzke, K. K., 1985, Microfauna of the Tucumcari Shale, Lower Cretaceous of east-central New Mexico: New Mexico Geological Society, Guidebook 36.

Kietzke, K. K. and Lucas, S. G., 1984, Middle Jurassic stratigraphy and fossil fishes, Bull Canyon, Guadalupe County, east-central New Mexico: New Mexico Geology, v. 6, p. 84.

Kirkland, D. W., 1958, The environment of the Jurassic Todilto basin, northwestern New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 69 pp.

Kirkland, D. W. and Anderson, R. Y., 1970, Microfolding in the Castile and Todilto evaporites, Texas and New Mexico: Geological Society of America, Bulletin, v. 81, pp. 3259–3282.

Kocurek, G. and Dott, R. H., Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountain region; *in* Reynolds, M. W. and Dolly, E. D., eds., Mesozoic paleogeography of the west-central United States: Denver, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, pp. 101–118.

Koerner, H. E., 1930, Jurassic fishes from New Mexico: American Journal of Science, Series 5, v. 19, p. 463.

Kues, B. S., Lucas, S. G., Kietzke, K. K. and Mateer, N. J., 1985, Synopsis of Tucumcari Shale, Mesa Rica Sandstone and Pajarito Shale paleontology, Cretaceous of east-central New Mexico: New Mexico Geological Society, Guidebook 36.

Lee, W. T., 1902, The Morrison shales of southern Colorado and northern New Mexico: Journal of Geology, v. 10, pp. 36–58.

Lookingbill, J. L., 1953, Stratigraphy and structure of the Gallina uplift, Rio Arriba County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 118 pp.

Lucas, S. G. and Hunt, A. P., in press, Dinosaurs from the Upper Jurassic Morrison Formation in New Mexico: New Mexico Journal of Science.

Lucas, S. G., Hunt, A. P. and Morales, M., 1985, Stratigraphic nomenclature and correlation of the Triassic of east-central New Mexico: a preliminary report: New Mexico Geological Society, Guidebook 36.

Lucas, S. G., Kietzke, K. K., Sobus, J., Weadock, G., Mateer, N. J. and Hunt, A. P., 1984, Upper Triassic–Upper Jurassic stratigraphy, fossil vertebrates and depositional environments, Bull Canyon, Guadalupe County, east-central New Mexico: Geological Society of America, Abstracts with Programs, v. 16, p. 245.

Mankin, C. J., 1958a, Stratigraphy and sedimentary petrology of Jurassic and pre-Graneros Cretaceous rocks, northeastern New Mexico [Ph.D. dissertation]: Austin, University of Texas, 208 pp.

Mankin, C. J., 1958b, Sedimentary petrology of the Exeter Sandstone, northeastern New Mexico: Geological Society of America, Bulletin, v. 69, p. 1609.

Mankin, C. J., 1972, Jurassic strata in northeastern New Mexico: New Mexico Geological Society, Guidebook 23, pp. 91–97.

Marcou, J., 1855, Resume of a geological reconnaissance extending from Napoleon, at the junction of the Arkansas with the Mississippi, to the Pueblo de Los Angeles in California; *in* Whipple, A. W., Report of explorations for a railway route near the thirty-fifth parallel of latitude from the Mississippi River to the Pacific Ocean: 33rd Congress, 1st Session, House Executive Document 129, pp. 40–48.

Markhoven, F. P. C. M., van, 1963, Post Paleozoic Ostracoda, their morphology, taxonomy, and economic use, v. II, Generic descriptions: Amsterdam, Elsevier, 478 pp.

Maxwell, C. H., 1982, Mesozoic stratigraphy of the Laguna-Grants region: New Mexico Geological Society, Guidebook 33, pp. 261–266.

McDowall, R. M., 1968, The application of the terms anadromous and catadromous to the southern hemisphere salmoniid fishes: Copeia, 1968, pp. 176–178.

McDowall, R. M., 1970, The galaxiid fishes of New Zealand: Harvard Museum of Comparative Zoology, Bulletin, v. 139, pp. 341–432.

McDowall, R. M., 1978, New Zealand freshwater fishes: a guide and natural history: Aukland, Heinemann, 230 pp.

McGrew, P. O., 1975, Taphonomy of Eocene fish from Fossil basin, Wyoming: Fieldiana, Geology, v. 33, pp. 257–270.

McKee, E. D., Oriel, S. S., Swanson, V. E., MacLachlan, M. E., MacLachlan, J. C., Ketner, K. B., Goldsmith, J. W., Bell, R. Y., Jameson, D. J. and Imlay, R. W., 1956, Paleotectonic maps of the Jurassic system: U.S. Geological Survey, Miscellaneous Geological Investigations Map I-175.

Merriam, D. F., 1955, Jurassic rocks of Kansas: American Association of Petroleum Geologists, Bulletin, v. 39, pp. 31–46.

Mook, C. C., 1916, Study of the Morrison Formation: New York Academy of Science, Annals, v. 27, pp. 39–191.

Muehlberger, W. R., 1967, Geology of the Chama Quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 89, 114 pp.

Myers, G. S., 1949, Usage of anadromous, catadromous and allied terms for migratory fishes: Copeia, 1949, pp. 89–97.

Neef, G. H., 1950, Sedimentation of the Todilto Limestone in San Miguel County, New Mexico [M.S. thesis]: Lubbock, Texas Technological College, 21 pp.

Ogden, L., 1954, Rocky Mountain Jurassic time surface: American Association of Petroleum Geologists, Bulletin, v. 38, pp. 914–916.

Ostrom, J. H. and McIntosh, J. S., 1966, Marsh's dinosaurs: New Haven, Yale University Press, 388 pp.

O'Sullivan, R. B., 1980, Stratigraphic sections of middle Jurassic San Rafael Group and related rocks from the Green River to the Moab area in east-central Utah: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1247.

O'Sullivan, R. B. and Craig, L. C., 1973, Jurassic rocks of northeastern Arizona and adjacent areas: New Mexico Geological Society, Guidebook 24, pp. 79–85.

O'Sullivan, R. B. and Pierce, F. W., 1983, Stratigraphic diagram of middle Jurassic San Rafael Group and associated formations from the San Rafael Swell to Bluff in southeastern Utah: U.S. Geological Survey, Oil and Gas Investigations Chart OC-119.

Parker, B. H., 1930, Notes on occurrence of clastic plugs and dikes in the Cimarron Valley area of Union County, New Mexico: Fourth Annual Field Conference of the Kansas Geological Society, Proceedings, pp. 131–136.

Parker, B. H., 1933, Clastic plugs and dikes of the Cimarron Valley area of Union County, New Mexico: Journal of Geology, v. 41, pp. 38–51.

Parker, B. H., 1934, Discussion—geology of Two Buttes Dome in southeastern Colorado: American Association of Petroleum Geologists, Bulletin, v. 18, pp. 1544–1546.

Pearce, T. M., 1965, New Mexico place names: Albuquerque, University of New Mexico Press, 187 pp.

Perry, B. L., 1963, Limestone reefs as an ore control of the Grants District: New Mexico Bureau of Mines and Mineral Resources, Memoir 15, pp. 150–156.

Peterson, J. A., 1972, Jurassic System; *in* Mallory, W. W., ed., Geologic atlas of the Rocky Mountain region: Denver, Rocky Mountain Association of Geologists, pp. 177–189.

Picard, M. D. and High, L. R., 1972, Criteria for recognizing lacustrine rocks: Society of Economic Paleontologists and Mineralogists, Special Publication 16, pp. 108–145.

Picard, M. D. and High, L. R., 1981, Physical stratigraphy of ancient lacustrine deposits: Society of Economic Paleontologists and Mineralogists, Special Publication 31, pp. 233–260.

Pipiringos, G. N. and O'Sullivan, R. B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey: U.S. Geological Survey, Professional Paper 1035-A, 29 pp.

Pollard, D. A., 1971, The biology of a landlocked form of the normally catadromous salmoniform fish *Galaxias maculatus* (Jenyns): I. Life cycle and origin: Australian Journal of Marine and Freshwater Research, v. 22, pp. 91–123.

Rapaport, I., Hadfield, J. P. and Olson, R. H., 1952, Jurassic rocks of the Zuni uplift, New Mexico: U.S. Atomic Energy Commission, Report, RMO-642, 47 pp.

Rawson, R. R., 1980, Uranium in Todilto Limestone (Jurassic) of New Mexico—example of a sabkha-like deposit: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, pp. 304–312.

Read, C. B., Wood, G. H., Wanek, A. A. and MacKee, P. V., 1949, Stratigraphy and geologic structure of the Piedra River Canyon, Archuleta County, Colorado: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 96.

Reid, B. E., Griswold, G. B., Jacobsen, L. C. and Lessard, R. H., 1980, National uranium resource evaluation, Raton quadrangle, New Mexico: U.S. Department of Energy, Report GJQ-005(80), 83 pp.

Reid, B. E., Griswold, G. B., Jacobsen, L. C. and Lessard, R. H., 1982, National uranium resource evaluation, Santa Fe quadrangle, New Mexico: U.S. Department of Energy, Report PGJIF-021C82, 41 pp.

Reynolds, C. B., 1954, Geology of the Hagan–La Madera area, Sandoval County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 82 pp.

Ridgley, J. L., 1982, *Rhizocorallum* burrows in the Jurassic Todilto Limestone: U.S. Geological Survey, Professional Paper 1275, p. 48.

Ridgley, J. L., 1984, Paleogeography and facies distribution of the Todilto Limestone and Pony Express Limestone Member of the Wanakah Formation, Colorado and New Mexico: Geological Society of America, Abstracts with Programs, v. 16, p. 252.

Ridgley, J. L. and Goldhaber, M., 1983, Isotopic evidence for a marine origin of the Todilto Limestone, north-central New Mexico: Geological Society of America, Abstracts with Programs, v. 15, p. 414.
Romer, A. S., 1966, Vertebrate paleontology: Chicago, University of Chicago Press, 468 pp.
Rothrock, E. P., 1925, Geology of Cimarron County, Oklahoma: Oklahoma Geological Survey, Bulletin 34, 128 pp.
Ruello, N. V., 1976, Observations on some massive fish kills in Lake Eyre: Australian Journal of Marine and Freshwater Research, v. 27, pp. 667–672.
Sanders, C. W., 1934, Geology of Two Buttes Dome in southeastern Colorado: American Association of Petroleum Geologists, Bulletin, v. 18, pp. 860–870.
Saucier, A. E., 1967, The Morrison and related formations in Gallup region [M.S. thesis]: Albuquerque, University of New Mexico, 106 pp.
Savela, C. E., 1977, Textural analysis of the Exeter Sandstone, northeastern New Mexico: The Compass of Sigma Gamma Epsilon, v. 54, pp. 29–35.
Schaeffer, B. and Patterson, C., 1984, Jurassic fishes from the western United States, with comments on Jurassic fish distribution: American Museum Novitates, no. 2796, 86 pp.
Schoewe, W. H., 1930, Significance of fossil fish in the Lykins Formation in Garden Park, Colorado: Geological Society of America, Bulletin, v. 41, p. 203.
Schuchert, C., 1918, Age of the American Morrison and east African Tendaguru Formation: Geological Society of America, Bulletin, v. 29, pp. 245–280.
Schultze, H-P. and Enciso, G., 1983, Middle Jurassic age of the fish-bearing horizon in the Cañon City embayment, Colorado: Journal of Paleontology, v. 57, pp. 1053–1060.
Serruya, C. and Pollingher, U., 1983, Lakes of the warm belt: Cambridge, Cambridge University Press, 569 pp.
Shafer, W., 1972, Ecology and paleoecology of marine environments: Chicago, University of Chicago Press, 568 pp.
Simpson, G. G., 1926, The age of the Morrison Formation: American Journal of Science, v. 12, pp. 198–216.
Sleidinger, K. A. and Hoddad, K., 1981, Biologic and hydrographic aspects of red tides: Bioscience, v. 31, pp. 814–819.
Smith, C. T., 1961, Triassic and Jurassic rocks of the Albuquerque area: New Mexico Geological Society, Guidebook 12, pp. 121–128.
Smith, S. W., 1951, Sedimentary study of the Jurassic of Quay County, New Mexico [M.S. thesis]: Lubbock, Texas Technological College, 61 pp.
Sohn, I. G., 1979, Nonmarine ostracodes in the Dakota Formation (Lower Cretaceous) from South Dakota and Wyoming: U.S. Geological Survey, Professional Paper 1069, 24 pp.
Stanton, T. W., 1905, The Morrison Formation and its relations with the Comanche Series and the Dakota Formation: Journal of Geology, v. 13, pp. 657–669.
Stapor, F. W., Jr., 1972, Origin of the Todilto gypsum mounds in the Ghost Ranch area, north-central New Mexico: The Mountain Geologist, v. 9, pp. 59–63.
Steiner, M. B., 1980, Investigations of the geomagnetic field polarity during the Jurassic: Journal of Geophysical Research, v. 85B, pp. 3572–3586.
Stovall, J. W., 1943, Stratigraphy of the Cimarron Valley (Mesozoic rocks), geology and groundwater resources of Cimarron County, Oklahoma: Oklahoma Geological Survey, Bulletin, v. 64, pp. 43–132.
Sturani, C., 1973, A fossil eel (*Anguilla* sp.) from the Messinian of Alba (Tertiary Piedmontese basin), paleoenvironmental and paleogeographic implications; *in* Drooger, C. W., ed., Messinian events in the Mediterranean: Amsterdam, North Holland Publishing Co., pp. 243–255.
Suleiman, A. S. and Keller, G. R., 1985, A geophysical study of basement structure in northeastern New Mexico: New Mexico Geological Society, Guidebook 36.
Swain, F. M., 1946, Middle Mesozoic nonmarine Ostracoda from Brazil and New Mexico: Journal of Paleontology, v. 20, pp. 543–555.
Tanner, W. F., 1965, Upper Jurassic paleogeography of the Four Corners area: Journal of Sedimentary Petrology, v. 35, pp. 564–574.
Tanner, W. F., 1970, Triassic–Jurassic lakes in New Mexico: The Mountain Geologist, v. 7, pp. 281–289.
Tanner, W. F., 1974, History of Mesozoic lakes of northern New Mexico: New Mexico Geological Society, Guidebook 25, pp. 219–223.
Trauger, F. D. and Bushman, F. X., 1964, Geology and groundwater in the vicinity of Tucumcari, Quay County, New Mexico: New Mexico State Engineer, Technical Report 30, 178 pp.
Vincelette, R. R. and Chittum, W. E., 1981, Exploration for oil accumulations in Entrada Sandstone, San Juan Basin, New Mexico: American Association of Petroleum Geologists, Bulletin, v. 65, pp. 2546–2570.
Visher, G. S., 1969, Grain size distributions and depositional processes: Journal of Sedimentary Petrology, v. 39, pp. 1074–1106.
Walton, E. K., Stephens, W. E. and Shawa, M. S., 1980, Reading sedimented grain-size curves: Geological Magazine, v. 117, pp. 517–544.
Wanek, A. A., 1962, Reconnaissance geologic map of parts of Harding, San Miguel, and Mora Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM-208.
Warren, J. K., 1982, The hydrological setting, occurrence and significance of gypsum in late Quaternary salt lakes in South Australia: Sedimentology, v. 29, pp. 609–637.
Warren, J. K. and Kendall, C. G. S. C., 1985, Comparison of sequences formed in marine sabkha (subaerial) and salina (subaqueous) settings—modern and ancient: American Association of Petroleum Geologists, Bulletin, v. 69, pp. 1013–1023.
Wilwarth, M. G., 1938, Lexicon of geologic names of the United Staes: U.S. Geological Survey, Bulletin 896, 2396 pp.
Wood, G. H., Northrop, S. A. and Griggs, R. L., 1953, Geology and stratigraphy of Koehler and Mount Laughlin Quadrangles, eastern Colfax County, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM-141.

APPENDIX 1: FOOTNOTES

[1] Exter (original spelling) was a small settlement with a post office from 1890–1903 (Pearce, 1965). Its name was subsequently changed to Valley, which was in sec. 26, T32N, R33E, Union County (Baldwin and Muehlberger, 1959). Lee (1902) misspelled the name as "Exeter," but the U.S. Geological Survey approved Lee's spelling (Wilmarth, 1938).

[2] Stovall (1943, pp. 51–52) made the following observations on the type locality of the Exeter Sandstone:

> A photograph in the paper in which Lee described the Exeter, shows Ship Rock Butte (Mountain) [Battleship Mountain] in the left hand side. He, therefore, possibly referred to exposures at that location. . . . Because a few feet of the upper part of the formation may have been removed by erosion at Ship Rock Butte, and because Lee's type locality cannot be identified positively, the writer is here designating the type section of the Exeter Sandstone as the almost vertical cliffs south of U.S. Highway 64, in sec. 32, T.32N., R.35E., Union County, New Mexico.

We, however, reject Stovall's type section of the Exeter Sandstone for the following reasons:

1. Lee was far too astute a stratigrapher to have considered Battleship Mountain, where the top of the Exeter obviously has been removed by erosion, to be the type section of the Exeter.

2. Lee (1902) described the Exeter from the measured stratigraphic section in his figure 5. This section is not at Battleship Mountain and contains a significant thickness of Morrison Formation above the Exeter.

Therefore, Lee's (1902, fig. 5) section of the Exeter, located correctly by Baldwin and Muehlberger (1959), is considered by us to be the type section of the Exeter Sandstone.

[3] Recent fieldwork by one of us (SGL) confirms that Parker's Sheep Pen Sandstone is a very localized, fluvial facies of the upper part of the Triassic Sloan Canyon Formation. The Sloan Canyon Formation (Parker, 1933) clearly is the same unit as Dobrovolny et al.'s (1946) Redonda Member of the Chinle Formation in east-central New Mexico.

[4] It is clear that the U.S. Geological Survey now intends to reduce the Todilto from formation to member rank (also see Baker et al., 1947) and include it in the Wanakah Formation as a basal member (Condon and Huffman, 1984; J. Ridgley, oral comm., 1984). This change is primarily the result of recognizing that the basal, Pony Express Limestone Member of the Wanakah Formation of southwestern Colorado is the same unit as the Todilto Formation of northern New Mexico. Nevertheless, there are several reasons why we find this change objectionable, and thus prefer to recognize the Todilto as a formation. They are:

1. The Todilto Formation in north-central and northwestern New Mexico has been divided into two, readily mappable informal members, a lower, limestone member and an upper, gypsum member. Reducing the Todilto to member rank reduces these informal members to bed rank, hardly an appropriate rank to apply to either member of the Todilto.

2. The Todilto was originally recognized as a unit of formational rank, and has been so recognized by a plethora of workers who have produced a voluminous literature that uses the terms Todilto Limestone or Todilto Formation. Less disruption of accepted usage would be achieved by eliminating the name Pony Express Limestone Member of the Wanakah Formation and recognizing that the Wanakah Formation (restricted to its upper part, *sensu* Condon and Huffman, 1984, fig. 3) overlies the Todilto Formation in southwestern Colorado.

3. Burbank's (1930) Wanakah Member of the Morrison Formation was named for rocks near Ouray in southwestern Colorado. Baker et al. (1947) raised it to formational rank. The name Wanakah thus postdates Gregory's (1916, 1917) name Todilto. Furthermore, the complexly faulted and limited exposures in the Ouray area are less easily correlated with outcrops in other areas (witness prob-

lems with the term Wanakah evident in the work of Goldman and Spencer, 1941; Baker et al., 1936, 1947; and Eckel, 1949, among others) than are the type outcrops of the Todilto Formation in Todilto Park, northwestern New Mexico. Thus, the name Todilto has priority over the name Wanakah and seems to represent a more easily mappable and correlateable unit than does the term Wanakah.

4. Finally, the name Wanakah Formation (or Shale) was introduced by Grabau (1917) for middle Devonian rocks in western and central New York. This antedates Burbank's (1930) proposal of the name Wanakah and poses a potential source of stratigraphic confusion within the coterminous United States.

[5] As later discussion in the text reveals, the term "agate bed" refers to a thin layer (or layers) of nodular, reddish-brown chalcedony, which forms a persistent marker bed near the base of the Morrison Formation. Lee (1902, p. 44) first noted the presence of this lithology in New Mexico in Union County. Our preliminary studies suggest that the agate bed is a thin interval of silcretes of pedogenic origin.

[6] Gilluly and Reeside's (1928) Summerville Formation in Utah represents a tidal flat facies of the Curtis Sea during the middle Jurassic (Imlay, 1980). Rapaport et al. (1952) and Harshbarger et al. (1957) readily extended the term Summerville into the San Juan Basin of northwestern New Mexico. However, O'Sullivan (1980) and O'Sullivan and Pierce (1983) have demonstrated that the Summerville Formation, *sensu stricto*, is not present southeast of Moab, Utah (it is truncated by an unconformity in the Four Corners region). Therefore, the term Summerville probably should be replaced by Wanakah in the San Juan Basin (Condon and Huffman, 1984).

[7] James Vanice, foreman of Chaparral Spade Ranch, informed us (oral comm., 1984) that in the 1940's, the land at Carpenter's Point was purchased from the Bell Ranch and became part of the Chaparral Spade Ranch. Thus, in 1959, when Griggs and Read coined the name Bell Ranch Formation, the type section they designated no longer was part of the Bell Ranch.

[8] Smith (1961) indicated most of the Morrison Formation in east-central New Mexico is equivalent to the Brushy Basin Member in north-central and northwestern New Mexico. Kehler (1975), on the other hand, suggested that the Morrison of northeastern New Mexico could be equivalent to the Recapture Member of the San Juan Basin. We favor the idea that the Morrison of east-central New Mexico represents the upper part of the Morrison near the center of its depositional basin to the north and west for three reasons:

1. It is reasonable to envision filling of the Morrison basin depocenter producing the lower part of the Morrison Formation in north-central and part of northwestern New Mexico. After this filling, upper Morrison deposits would have lapped onto the basin margins, producing the sequence in east-central New Mexico.

2. Dinosaur bones from the Morrison Formation of northwestern and north-central New Mexico are primarily found in the middle–upper part of the formation (Westwater Canyon, Brushy Basin and Jackpile Members) (Hunt and Lucas, 1984; Lucas and Hunt, in press). No bones are known from the Recapture Member in this region. The presence of dinosaur bones throughout the Morrison section in east-central New Mexico thus suggests that equivalents of the Recapture Member are not present in this part of the state.

3. Morrison lithologies in east-central New Mexico most closely resemble the variegated claystones and fluvial sandstones of the Brushy Basin Member in north-central and northwestern New Mexico.

Clearly, these reasons are not conclusive, and the problem of Morrison correlations between east-central New Mexico and other areas deserves further consideration.

APPENDIX 2: CONTROL POINTS

1. Monument Energy Corporation, No. 2 Sedberry: sec. 25, T17N, R16E; Silver Monument Minerals, Iva Sedberry No. 1: sec. 25, T17N, R16E.
2. Mankin (1958a, section 56-2): sec. 16, T15N, R16E.
3. Monument Energy Company, Sue Ann No. 1: sec. 19, T17N, R17E.
4. Continental Oil Company, Leatherwood-Read No. 1: sec. 15, T16N, R17E.
5. Continental Oil Company, Emma V. Hunker No. 1: sec. 36, T16N, R17E.
6. Mankin (1958a, section 57-3): sec. 6, T14N, R18E.
7. Bachman (1953, section 5): sec. 32, T23N, R18E.
8. Continental Oil Company, Schumacher Reed No. 1: sec. 28, T16N, R18E.
9. Cities Services Company, Fort Union No. 1: sec. 33, T20N, R19E.
10. Cities Services Company, Fort Union No. 2: sec. 18, T19N, R19E.
11. American Manufacturing Company, W. S. Ranch No. 1: sec. 1, T26N, R20E.
12. William Gruenerwald and Associates, Gonzales-Pitman No. 1: sec. 24, T21N, R21E.
13. Mobil Oil Company, E. G. Wiggin S No. 1: sec. 24, T19N, R21E.
14. Mankin (1958a, section 57-4): sec. 15, T15N, R21E.
15. Mobil Oil Company, Sanford Estate et al. No. 1: sec. 27, T20N, R22E.
16. Wanek (1962, section 6): sec. 19, T15N, R22E.
17. Brooks Exploration Company, Berlier No. 2: sec. 23, T21N, R21E.
18. Mobil Oil Company, Mobil No. 1 R. S. Coon et al.: sec. 22, T20N, R23E.
19. Wood et al. (1953, section 12): sec. 10, T29N, R24E.
20. Wood et al. (1953, section 11): sec. 35, T27N, R24E.
21. Wood et al. (1953, section 9): sec. 3, T26N, R24E.
22. Wood et al. (1953, section 10): sec. 2, T26N, R24E.
23. Wood et al. (1953, section 8): sec. 7, T25N, R24E.
24. Wood et al. (1953, section 7): sec. 6, T24N, R25E.
25. Wood et al. (1953, section 6): sec. 15, T23N, R24E.
26. Mankin (1958a, section 57-7): sec. 3, T20N, R24E.
27. Mankin (1958a, section 57-6): sec. 35, T20N, R24E.
28. This report, Hartley Ranch: T18N, R25E.
29. Mankin (1958a, section 57-5): T17N, R24E.
30. Wanek (1962, section 5): sec. 33, T17N, R24E.
31. Lee (1902, section 4): sec. 8, T17N, R26E.
32. Wanek (1962, section 4): sec. 10, T17N, R26E.
33. Wanek (1962, section 3): sec. 13, T16N, R26E.
34. Mankin (1958a, section 57-8): sec. 20, T18N, R27E.
35. Wanek (1962, section 2): secs. 15–22, T16N, R27E.
36. This report, Bull Canyon: secs. 28–29, secs. 20–23, secs. 32–33, T9N, R26E.
37. Dobrovolny et al. (1946, section 6): sec. 5, T8N, R27E.
38. Smith (1951): sec. 20, T8N, R27E.
39. Dobrovolny et al. (1946, section 7): sec. 11, T8N, R27E.
40. Wanek (1962, section 1): sec. 1, T14N, R27E.
41. Savela (1977, section 2): sec. 8, T10N, R28E.
42. Mankin (1958a, section 56-2): sec. 21, T21N, R29E.
43. CO_2 in Action, George Trujillo No. 1: sec. 23, T18N, R28E.
44. This report, Carpenter Mesa: sec. 33, T13N, R29E.
45. This report, Pyramid Mountain: sec. 19, T9N, R29E.
46. Dobrovolny et al. (1946, section 5): secs. 9–15, T8N, R29E.
47. Carbonic Chemical Corporation, Mitchell No. 10: sec. 19, T19N, R30E.
48. Mankin (1958a, section 57-9): sec. 9, T16N, R30E.
49. This report, Punta de Gallegos: T16N, R30E.
50. Dobrovolny et al. (1946, section 2): sec. 5, T11N, R30E.
51. CO_2 in Action, McCarty No. 1: sec. 34, T18N, R31E.
52. Trauger and Bushman (1964, p. 22): sec. 5, T11N, R31E.
53. Dobrovolny et al. (1946, section 3): sec. 31, T11N, R31E; Trauger and Bushman (1964, p. 17): sec. 31, T11N, R31E.
54. Dobrovolny et al. (1946, section 4): sec. 29, T10N, R30E.
55. Dobrovolny et al. (1946, section 8): sec. 36, T9N, R30E.
56. Dobrovolny et al. (1946, section 9): sec. 18–19, T9N, R31E.
57. Dobrovolny et al. (1946, section 10): sec. 27–34, T8N, R32E.
58. Mankin (1958a, section 57-10): sec. 5, T9N, R34E.
59. Baldwin and Muehlberger (1959, section 22): sec. 27, T26N, R32E.
60. Amerada Hess Corporation, State No. 1: sec, 17, T20N, R32E.
61. Humble Oil and Refining Company, Cherokee Federal No. 1: sec. 3, T19N, R32E.
62. Amoco Production Company, Heimann No. 1: sec. 3, T19N, R33E.
63. Amoco Production Company, Heimann No. 6: sec. 28, T19N, R33E.
64. Humble Oil and Refining Company, Humble "CL" State No. 1: sec. 13, T17N, R32E.
65. Baldwin and Muehlberger (1959, section 25): sec. 2, T23N, R33E.
66. Baldwin and Muehlberger (1959, section 20): sec. 25, T27N, R36E.
67. Baldwin and Muehlberger (1959, section 23): sec. 34, T26N, R35E.
68. Baldwin and Muehlberger (1959, section 26): sec. 26, T23N, R35E.
69. Baldwin and Muehlberger (1959, section 24): sec. 2, T24N, R36E.
70. Baldwin and Muehlberger (1959, section 27): sec. 29, T21N, R36E.
71. Baldwin and Muehlberger (1959, section 28): sec. 30, T20N, R36E.
72. Baldwin and Muehlberger (1959, section 3): sec. 21, T31N, R29E.
73. Baldwin and Muehlberger (1959, section 17): sec. 3, T29N, R29E.
74. Baldwin and Muehlberger (1959, section 5): secs. 2–23, T31N, R29E.
75. Cooley (1955, section 3): sec. 22, T31N, R30E.
76. Cooley (1955, section 7): sec. 30, T31N, R30E.
77. Cooley (1955, section 2): sec. 24, T31N, R30E.
78. Cooley (1955, section 4): secs. 3–9, T31N, R31E.
79. Cooley (1955, section 1): sec. 20, T31N, R32E.
80. Cooley (1955, section 6): sec. 12, T31N, R32E.
81. Baldwin and Muehlberger (1959, section 11): sec. 12, T31N, R32E.
82. Cooley (1955): sec. 20, T32N, R34E.
83. Baldwin and Muehlberger (1959, section 13): sec. 1, T31N, R34E.
84. Cooley (1955, section 8): sec. 32, T35N, R36E.
85. Baldwin and Muehlberger (1959, section 15): sec. 31, T31N, R36E.
86. Baldwin and Muehlberger (1959, section 16): sec. 34, T31N, R36E.