Middle Jurassic Todilto Formation of northern New Mexico and southwestern Colorado: Marine or nonmarine?

D. W. Kirkland[1], R. E. Denison[1], and R. Evans[2]

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D. W. Kirkland', R. E. Denison', and R. Evans[2]
'Programs in Geosciences, The University of Texas at Dallas, Richardson, Texas 75083;
'Mobil Exploration Production Technical Center, PO. Box 650232, Dallas, Texas 75265

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Abstract

For more than 40 years there has been a controversy about the origin of the Jurassic (Callovian) Todilto Formation, an evaporitic limestone and gypsum unit in northern New Mexico and southwestern Colorado: Is it marine or nonmarine? The unit typically consists of a basal laminated limestone 5-20 ft (1.5-6.1 m) thick, a transition zone of laminated limestone with gypsum nodules, and a thicker upper zone of nodular and crudely laminated gypsum. Over wide areas, the gypsum has been dissolved, leaving a residuum of limestone breccia. Laminae in the micritic carbonate are alternately calcite and organic matter with small amounts of silt. The varve couplets are generally <0.7 mm thick. The Todilto Formation rests directly upon the eolian Entrada Formation and is overlain by the Summerville Formation, which is apparently both marine and nonmarine. The Todilto Formation is equivalent but apparently not connected to the marine Curtis Formation, a unit deposited during invasion of the Jurassic Sundance Sea.

Fossil aquatic insects (Hemiptera) are rare at several localities in the laminated limestone, but abundant in a basal clastic bed of the Todilto. The prolific localized occurrence probably represents a remnant of a small body of brackish water between Entrada dunes. Three genera of fish have also been described from Todilto sediments: marine *Hulettia* and *Caturus,* and *Todiltia* which may have been nonmarine. Nonmarine ostracodes have been found sporadically around the margin of the Todilto basin. Several marginal localities have produced calcareous algae, including dasyclad algae in the Grants area, New Mexico.

Values of carbon isotopic ratios have been used to argue for a marine origin of the Todilto, but are equally compatible with nonmarine or mixed water. Values of strontium isotopic ratios do not match those of sediments deposited from normal marine Callovian sea water, and calculations of the effect of mixing show that the values probably result from influx of large volumes of riverine water into sea water. Values of sulfur isotopic ratios appear to be compatible with Middle Jurassic marine water, but calculations of the effect of mixing show that the large volumes of river water essential to explain the strontium ratios would not remove the sulfur values from the marine range. Interpretations from all three elements are compatible.

The Todilto Formation was deposited in a coastal body of saline water (a salina) adjacent to the Sundance Sea. After an initial flooding by marine water, the salina was maintained by inflow of fresh water from streams, mostly intermittent, and by influx of sea water by seepage through or over-topping of physiographic barriers. The arid climate promoted evaporation, which led to precipitation of laminated carbonates and nodular gypsum. Reconstruction of the Todilto paleoenvironment as a salina reconciles all apparent conflicts in interpretation of the paleontology, stratigraphy, sedimentology, and chemistry.

Introduction

The Todilto Formation can be seen in widely distributed, conspicuous outcrops in northern New Mexico and southwestern Colorado. It consists of a Limestone Member typically 5-20 ft (1.5-6.1 m) thick and a Gypsum Member typically 30-100 ft (9.1-30.5 m) thick (Fig. 1). The distribution of the latter is areally more restricted, but where it is absent a Breccia Member (the residue of gypsum dissolution) may be present. The approximate deposition extents of the Todilto Limestone and Todilto Gypsum Members are shown in Figure 2.

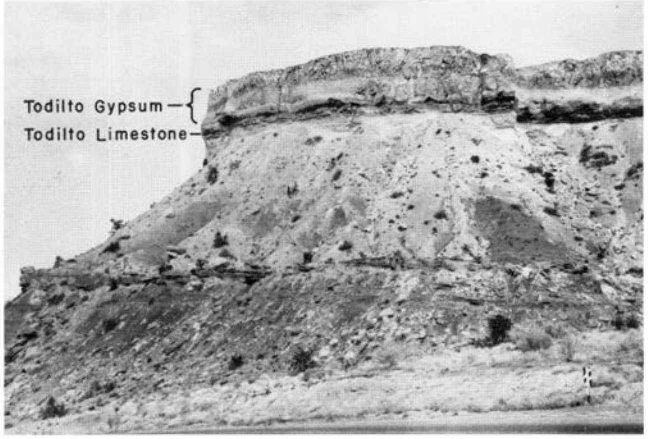

FIGURE 1—Todilto Formation, Entrada Sandstone (Jurassic) directly beneath Limestone Member and Chinle Formation (Triassic) at base; along NM Highway 44, about 8 mi west and north of San Ysidro, Sandoval County, New Mexico (sec. 12, T16N, R1W), viewed from southeast.

For more than 40 years there has been a controversy about the environment of deposition of the Todilto Formation: Was it marine or nonmarine? Among advocates of a lacustrine environment are Silver (1948), Rapaport et al. (1952), Anderson & Kirkland (1960), and Tanner (1970); and among those favoring a marine setting are Baker et al. (1947), Imlay (1952), Harshbarger et al. (1957), and Ridgley (1983; who changed her position from the one she held in 1977, when she stated: "The Todilto Limestone in the southwestern part of the Chama Basin was deposited in a lacustrine environment."). Other workers (Lucas et al., 1985; Anderson & Lucas, 1992) believe that the Todilto originated in a salina isolated from the sea; technically a lake, but one that received a substantial influx of marine water.

In this paper we combine isotopic, paleontological, and stratigraphic information in an attempt to determine the environment of deposition of the Todilto Formation. Much of this information is new, including all the values for strontium isotopes, and many of the values for carbon and sulfur isotopes. Particularly the strontium isotopic data provide us with a new approach to resolving the question of the original depositional setting, an approach that can be used for other deposits of carbonates and evaporites for which the environment is unknown. Also new are data on the distribution of fossil insects and, in part, of fossil fish. Many of the individual pieces of evidence may be equivocal, but when viewed together they lead us to only one conclusion in our attempt to resolve this protracted controversy.

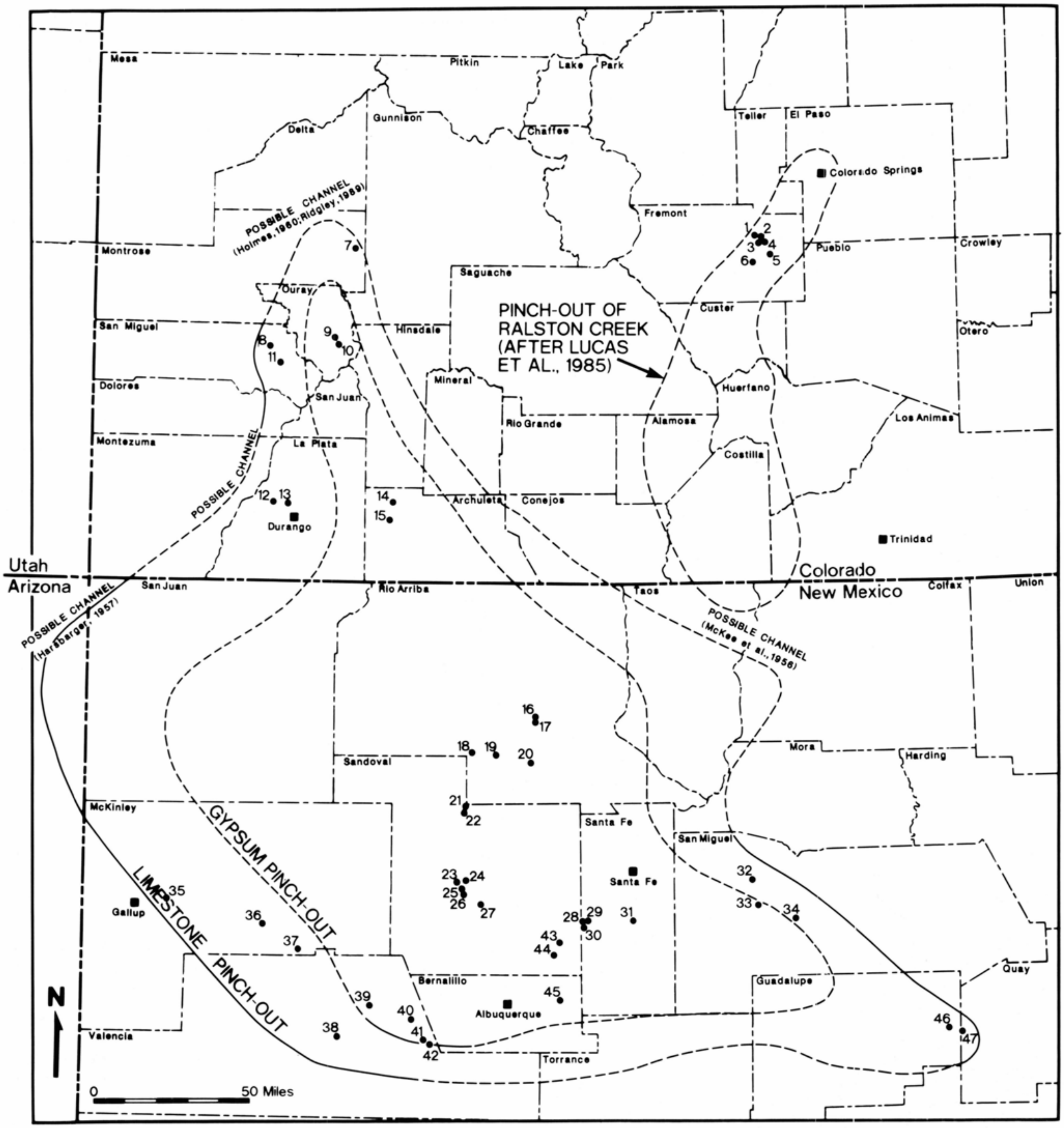

FIGURE 2—Approximate depositional limits of Todilto Limestone Member and Todilto Gypsum Member, and approximate limits of Ralston Creek Formation. Also shown are the general location of possible channels connecting the Todilto Basin with other waterbodies, and sample localities and sample identification numbers (see Tables 1–3 for specific locations).

The Todilto Formation is an evaporitic sequence, but there is no direct or indirect evidence that salts other than calcium sulfate and calcium carbonate were precipitated. Much of the limestone probably originated inorganically, although algae may have aided its precipitation (Anderson & Kirkland, 1960), and for an extended interval brine within the Todilto waterbody was in a salinity range that allowed gypsum to precipitate.

Evaporite units such as the Todilto are often indiscriminately considered to be marine despite an absence of paleontological evidence usually used to make a distinction between a marine and a nonmarine origin. In a seminal paper, Hardie (1984) advocated that for each individual evaporite deposit we should ask: Were the parent waters marine or were they nonmarine? As is clear from Hardie's excellent discussion, this distinction is not always easy to make, and a variety of different types of information may be needed before we can arrive at an answer. It is Hardie's approach that we take herein to an investigation, which is the outgrowth of a long-time interest in the paleoenvironment of the Todilto Formation.

Acknowledgments

J. P. Bradbury and T. K. Lowenstein reviewed the manuscript. We acknowledge their help. In an early phase of the study, **J.** P. Bradbury contributed substantially to our understanding of the Todilto environment and devoted many hours of field work to the endeavor. J. T. Polhemus allowed us to use data from his manuscript on the Todilto insects. M. A. Rooney helped interpret the carbon isotopic data from the Todilto. W. K. Blank made the strontium separations, and A. Fletcher determined many of the strontium-isotope ratios, R. N. Donovan generously collected four of the Ralston Creek samples. S. A. Northrop brought our attention to the paper of Cockerell and provided initial exposure to the paleoenvironmental problems of the Todilto. P. L. Kirkland helped with preparation of the manuscript. R. Y. Anderson, whose contagious enthusiasm for understanding the Todilto paleoenvironment has endured for 35 years, reviewed the section on strontium isotopes, brought our attention to the recent paper of 0. J. Anderson and S. G. Lucas, and made several useful and perceptive recommendations. Initial work on this project was done while the authors were employed by Mobil Research and Development Corporation.

Nature of Todilto Formation

Petrology

In the following discussion, we use descriptions of our own samples (92 of which were examined petrographically), as well as observations from several published descriptions of the Todilto (Anderson & Kirkland, 1960; Reese, 1984; McCrary, 1985; Lucas et al., 1985; Ridgley, 1986). Away from the margins of the basin, four primary rock types can be distinguished: a laminated limestone, a limestone with nodular gypsum, a gypsum with minor calcite, and a limestone breccia.

The laminated limestone facies is the basal unit of the Todilto; its contact with the underlying Entrada Sandstone is usually sharp, the transition from sandstone to limestone occurring within a few centimeters. In a few places, a thin (1-8 cm) shalt' zone separates the sandstone from the limestone. At some localities laminae are so thin and so well-defined that the rock is a "paper" limestone, analogous to a paper shale. More than 90% of each sample of the laminated limestone examined in our study are composed of calcite, which occurs in distinctive laminae 0.1-0.7 mm thick and separated by concentrations of silt and brown-to-black organic matter (Fig. 3). The calcite is of variable crystallinity—in some laminae exceptionally fine-grained micrite, and in others microspar (0.05-0.1 mm) which is particularly common in the axes of larger folds and in limestone associated with microfolding and microfaulting (Kirkland & Anderson, 1970). As a generalization, the limestone that is finely laminated is micritic and the laminae of organic matter have a wavy appearance in thin section.

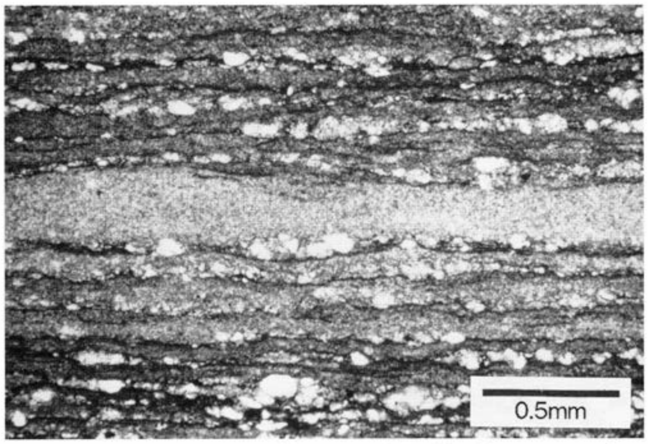

FIGURE 3—Thin section of laminated Todilto limestone, plain light; dark laminae are predominantly organic matter; silt grains (white) are probably wind-blown and are associated with the organic laminae; the bulk of the sample is calcite; abandoned quarry, Tijeras Canyon, Bernalillo County, New Mexico (sec. 1, T10N, R5E).

The terrigenous component of the laminated limestone is mostly silt and fine sand typically occurring as scattered grains within and on top of laminae of organic matter (Anderson & Kirkland, 1960; Fig. 3). Although quartz is the major constituent, plagioclase, K-feldspar, calcite, muscovite, tourmaline, zircon, glauconite, opaque minerals, dolomite grains, and metamorphic and granitic rock fragments occur in trace amounts. Clay minerals are not a major terrigenous component, except in samples from the lowermost Todilto at the major insect locality (Loc. 23 of Fig. 2); all of our XRF analyses of the limestone showed less than 2% $A1_20_3$ and most were less than 0.5%.

Todilto limestones from near the pinchout of the unit are nonlaminated or poorly laminated and some contain lenses of calcite-cemented fine-grained sandstone. The sand grains are randomly distributed and the content of organic matter is low.

Ostracodes, phosphatic material, and insect parts were the only fossils identified in the limestone samples. Ostracodes were common in samples from two localities (Locations 13 and 36 of Fig. 2). The fragments of phosphatic material are probably fish bones. The laminated limestone contains only minor magnesium, generally less than 0.5 wt.% MgO, and this was never observed as recognizable dolomite rhombs. Only one sample that we investigated was dolomite—a sample from the Ralston Creek Formation (Loc. 2 of Fig. 2). Twenty-one samples of laminated limestone (of the 92 analyzed) have unusual concentrations of two trace elements. The mean for strontium is 302 ± 75 ppm and the mean for manganese is 494 ± 206 ppm. Compared to fine-grained carbonates deposited in a normal marine environment, these mean values are low for strontium and high for manganese.

The stratigraphically lowest occurrence of gypsum in the Todilto is as pod-shaped nodules in the upper part of the laminated limestone. Below the first recognizable gypsum nodules, the laminated limestone may contain small pods of calcite spar interpreted as former gypsum nodules that have been dissolved and replaced by spar. In the transition zone from limestone to gypsum (Fig. 4) the proportion of micritic carbonate is progressively reduced until it is finally relegated to the "wire" in chicken-wire gypsum or to crude laminae therein. The laminae in the transition zone have scattered silt and carbonaceous material, as do the underlying limestone laminae. A few samples from the transition zone at Tongue Arroyo (Loc. 43 of Fig. 2) contain chalcedony spherulites, 0.3-0.5 mm in diameter, along some micritic laminae. Thin veinlets of gyp-

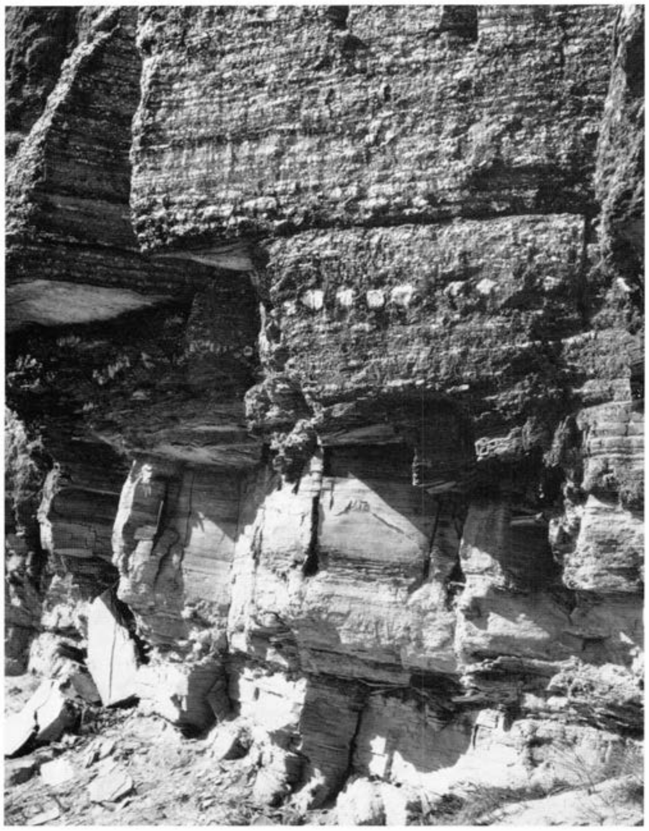

FIGURE 4—Todilto Limestone Member (below) and Todilto transition zone; cliff along NM Highway 44 approximately 9 mi north of San Ysidro, Sandoval County, New Mexico.

sum connecting nodules occur parallel to bedding, and others cut across calcite laminae (Figs. 5, 6).

Because the base of the interval in which nodular gypsum is intercalated with limestone laminae is not always clearly defined, and because the top of that interval is gradational, precise thickness determinations of the unit that we designate the transition zone are difficult to make. For the same reason it is difficult to determine the exact boundary between the Limestone and Gypsum Members. [Tentatively we define the base of the Gypsum Member as the oldest gypsum nodules, or field evidence of their prior existence, and include the transition zone as the basal part of the Gypsum Member.] At Tongue Arroyo (Loc. 43 of Fig. 2), Kelly & Northrop (1975) measured 22 ft (6.7 m) of the transition zone, the appearance of part of which is shown in Figure 7. We estimate that the transition zone at the Gallina locality (Loc. 18. of Fig. 2) is about 15 ft (4.6 ft) thick, of which the lower 3 ft (0.91 m) contain only scattered gypsum nodules.

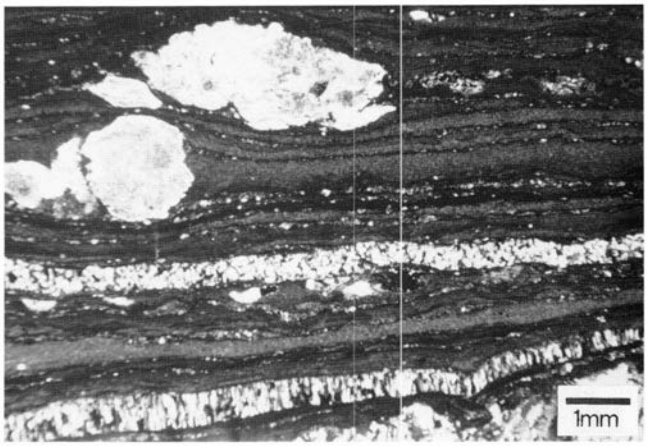

FIGURE 6—Thin section of gypsum nodules and bands of bedding-parallel satin spar in a dark, laminated, micritic matrix; San Felipe Quarry, Tonque Arroyo, Sandoval County, New Mexico (SW¼ sec. 1, T13N, R5E).

The gypsum unit proper may be crudely laminated, or may have a poorly- to well-defined chicken-wire appearance. There is minor carbonate in the form of dust-like calcite particles evenly distributed through the rock or concentrated to form laminae or to delineate nodules in otherwise homogeneous gypsum. The gypsum has a variety of textures, but it is generally composed of fine anhedral crystals that may show preferred orientation. Porphyroblasts scattered sporadically throughout the gypsum range in maximum dimension from less than one millimeter to many centimeters. Anhydrite relicts are common in the coarse porphyroblastic crystals; they were not identified in the finer matrix, but in the deep subsurface the calcium-sulfate phase is anhydrite.

Where the gypsum is completely dissolved there is a limestone breccia, which is a distinctive rock-type formed

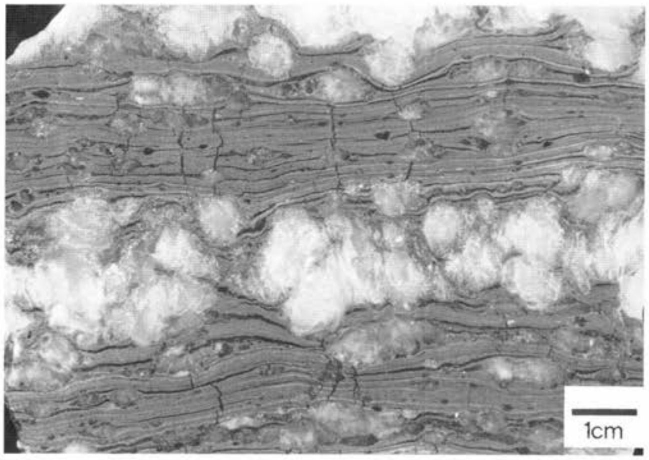

FIGURE 5—Polished slab of Todilto transition zone showing layers of gypsum nodules within laminated limestone; from cliff face along NM Highway 44 approximately 9 mi north of San Ysidro, Sandoval County, New Mexico.

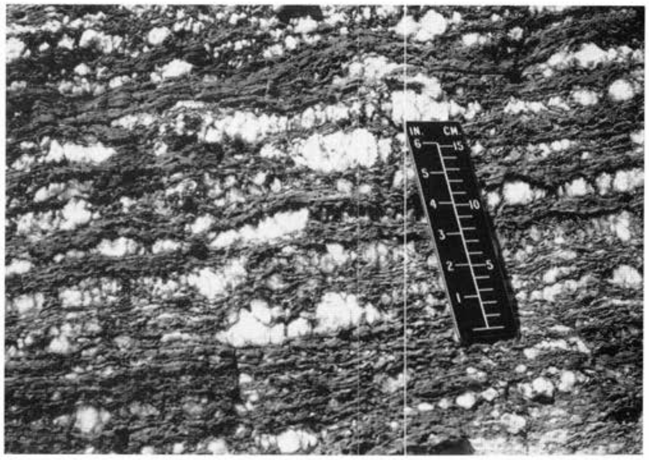

FIGURE 7—Laminated limestone with gypsum nodules, transition zone between laminated limestone and nodular gypsum; San Felipe Quarry, Tonque Arroyo, Sandoval County, New Mexico (SW¼ sec. 1, T13N, R5E).

as a residuum (Burbank, 1930; Holmes, 1960; Stapor, 1972). The gypsum unit per se is thicker than the transition zone, but it is much poorer in calcite, so that more of the breccia fragments probably came from the transition zone than from the gypsum unit. The breccia varies considerably in appearance and scale. Intralaminated breccia zones as thin as 1.5 mm are enclosed in undisturbed laminated limestone. Some samples contain breccia clasts that appear to have been soft when forming, whereas others must have been brittle. Individual clasts range from fractions of a millimeter to several centimeters, and their shape is controlled by the morphology of the original laminations. In most clasts the length is twice the width, and in some ten times the width. The space between the clasts is filled by sparry calcite and lesser amounts of insoluble material of largely uncertain composition (Fig. 8). Sand and silt are uncommon and in some samples completely absent. This supports the petrographic observation that the gypsum contains little terrigenous material. In the Ouray mining district of southwestern Colorado the fragments composing the breccia rarely exceed two inches (5.1 cm) and are usually much smaller and sharply angular (Burbank, 1930). Where the formation is unaltered, "a minimum of cementing matter" is present and the breccia is extremely porous (Burbank).

The bituminous character of the laminated limestone becomes clear from the analysis of 28 outcrop samples for total organic carbon (TOC). The distribution of values is shown in Figure 9. Eight samples had TOCs of <0.2%. Although samples appeared fresh, some weathering may have occurred and may in part explain these low TOCs. Six samples had TOCs between 0.8 and 1.3%. There was no geographic or stratigraphic pattern to the results. Furthermore, there is no relationship between the TOC and insoluble residue. The Todilto Limestone Member is the source rock for seven small (<1,000,000 bbls) oil fields in the underlying Entrada Sandstone (Ross, 1980; Vincelette & Chittum, 1981). The source-reservoir relationship is clear; oil from the Media field (Ostrander, 1957) (NW¹/4SW¹/4 sec. 14, T19N, R3W, Sandoval County, New Mexico), for example has a $\delta\ ^{13}C_{PDB}$ of -27.0‰ as compared to 6 $^{13}C_{FDB}$ values of -27.2 ‰ and -27.5 ‰ for bitumen extracted from two samples of Todilto limestone from locality 25 in Figure 2. The composition of the oil from the Media field is unusual. It has a low pristane/phytane ratio (0.86) and an even-carbon predominance (a carbon preference index of 0.91) (Ross, 1980, fig. 8). These characteristics are typical of carbonate source rocks deposited in association with evaporites, and indicate generation of oil from organic matter derived from algae and bacteria. However, the oil also has a correlation-index curve (Vincelette & Chittum, 1981, fig. 10) that suggests a higher content of paraffins than in Pennsylvanian and Cretaceous oils from the San Juan Basin, a high pour point (90°F = 32°C), and a high boiling point (205°F = 96°C). The sample of oil from the Media field analyzed by Vincelette and Chittum appears to have lost much of its volatile fraction, which might account for its high pour and boiling points. If the Todilto oils are indeed waxy, the original source of the waxes would generally be attributed to waxes covering leaves and other green parts of terrestrial plants (Eglinton & Hamilton, 1967), but it could also be attributed to algae (e.g. Moldowan & Seifert, 1980) or bacteria (e.g. Harwood & Russell, 1984).

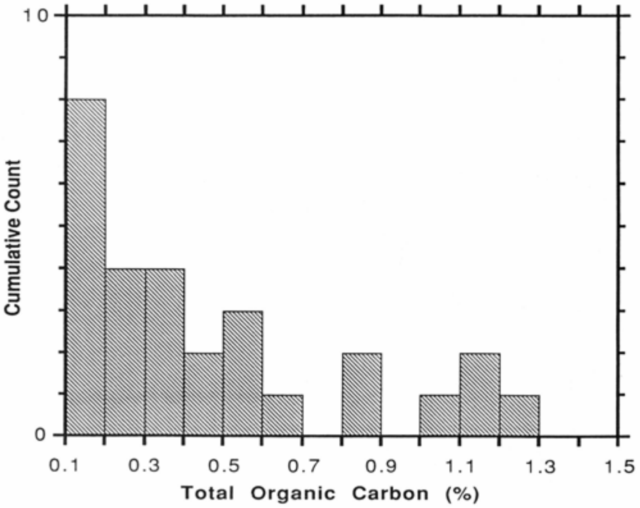

FIGURE 9—Distribution of total organic carbon (TOC) in Todilto Limestone (various localities, northwestern New Mexico).

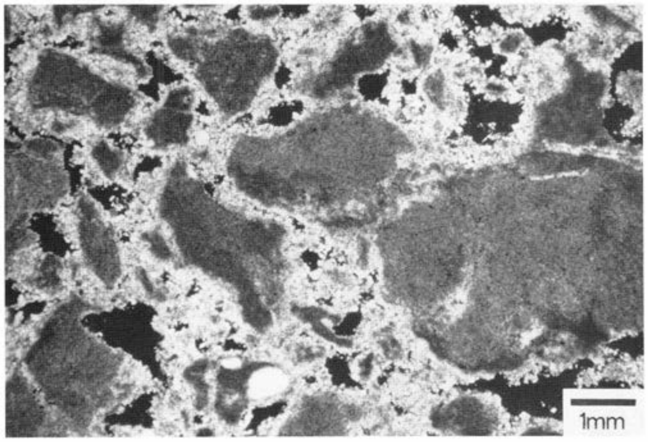

FIGURE 8—Thin section (polarized light) of typical limestone breccia derived from dissolution of Todilto Gypsum Member (probably mainly a remnant of the transition zone); Gallisteo dam locality, Rio Arriba County, New Mexico (sec. 17, T14N, R7E).

Stratigraphy

General stratigraphy of Todilto Formation

The name Todilto Formation was given by Gregory (1917) to outcrops of a distinctive limestone at Todilto Park, McKinley County, New Mexico, located about 30 mi (48.2 km) northwest of Gallup near the southern end of the Chuska Mountains and about 5 mi (8 km) east of the Arizona-New Mexico boundary. Subsequently, what is now the Limestone Member was found to extend throughout northwestern New Mexico, part of southwestern Colorado, and part of east-central New Mexico (Fig. 2). Current usage of the term Todilto (e.g. Smith et al., 1961) includes two members, a thick Gypsum Member that overlies the Limestone Member. The areal extent of the Todilto Gypsum Member, including the extent of its residual accumulation called the Todilto Breccia Member, is smaller than that of the Limestone Member (Fig. 2). The Todilto has been considered a member of the Morrison Formation (Baker et al., 1936), of the Entrada Sandstone (Hoover, 1950), and of the Wanakah Formation (Baker et al., 1947; Pipiringos & O'Sullivan, 1976, pl. 1, section C-C'; Condon & Huffman, 1988), but for the past 40 years most workers, at least in New Mexico, have granted it the status of a formation. In southwestern Colorado the Todilto Limestone and Gypsum have usually been designated as the Pony Express Limestone Member and the Gypsum Member of the Wanakah Formation.

The Todilto Limestone Member can be as much as 40 ft (12.1 m) thick, but through much of its extent ranges from 10 to 20 ft (3.0-6.1 m) (Ash, 1958, fig. 4; Hilpert, 1969, pl. 3; Kamin, 1968, fig. 3). Near its depositional edge in some parts of its southwestern, northwestern, and northern extent the thickness of the Limestone Member increases considerably (e.g. Silver, 1948; Holmes, 1960, p. 92). The reason for this local thickening is uncertain.

As mentioned above, the Limestone Member is transitional upward into the Gypsum Member and the proportion of calcite decreases progressively as the proportion of gypsum increases. In the transition zone, gypsum occurs principally as sporadic-to-abundant nodules in a limestone matrix. In some outcrops, nodules have been removed by dissolution, leaving vugs. The Gypsum Member is generally 50-100 ft (15.2-30.5 m) thick (Weber & Kottlowski, 1959, p. 12) and contains intercalated calcite laminae that are commonly distorted. The gypsum is both nodular (Fig. 10) and poorly laminated (Fig. 11).

The thickness of the Gypsum Member in New Mexico is highly variable, ranging from about 80 to 0 ft (24.4-0 m) over less than about 0.2 mi (0.32 km). An excellent example of this rapid lateral transition from a thick section of gypsum to a section in which gypsum is represented only by a porous residual deposit can be seen near Youngsville, New Mexico (sec. 32, T23N, R4E). [In southwestern Colorado, Holmes (1960) describes the breccia zone as being "loosely packed and extremely permeable. The residual deposit, which is present where the Gypsum Member is thin or absent, is designated a solution breccia (Burbank, 1930; Holmes, 1960; Stapor, 1972). In the Chama Basin, Rio Arriba County, New Mexico, the solution breccia ranges from 3 to 23 ft (0.91-7 m) (Stapor, 1972). In southwestern Colorado, Holmes (1960) reports that the "breccia unit ranges in thickness from a few feet to over fifty feet within a few hundred feet along strike." Burbank (1930) reports that [these units] "...range in thickness from one foot to 60 or 70 ft, but are commonly from 8 to 15 feet thick." [The maximum thickness of the breccia unit in southwestern Colorado suggests that the Gypsum Member here was originally substantially thicker or that it contained a much greater carbonate fraction than the Gypsum Member in northwestern New Mexico.] Although genetically related to the Gypsum Member, the breccia unit is a distinctive and mappable unit, and following the convention of Stapor (1972), we refer to it as the Todilto Breccia Member.

FIGURE 10—Characteristic nodular gypsum, Todilto Gypsum Member; San Felipe Quarry, Tonque Arroyo, Sandoval County, New Mexico (SW¼ sec. 1, T13N, R5E).

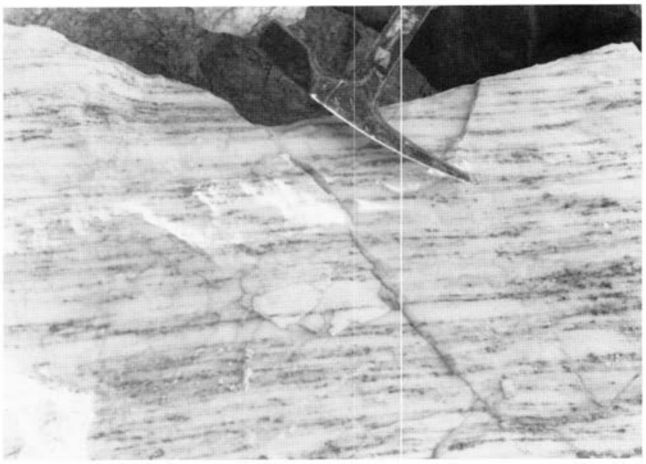

FIGURE 11—Laminated gypsum, Todilto Gypsum Member; east wall of San Felipe Quarry, Tonque Arroyo, Sandoval County, New Mexico (SW¼ sec. 1, T13N, R5E).

In Ouray County, southwestern Colorado, the Todilto Breccia Member is extensively mineralized. Orebodies containing gold and silver have been developed in a number of mines including the Wanakah, Pony Express, and Newsboy (Irving, 1905; Burbank, 1930). The porosity of the breccia unit probably contributed to localization of the ore. The breccia is widely present in Ouray County. Most of the Gypsum Member in this area had been dissolved before Late Cretaceous or early Eocene times. Burbank (1930) was able to establish this temporal relationship because dikes of porphyry and also fissures of these ages cut through the limestone and the brecciated part of the formation "without showing evidence that the thick gypsum deposit was present *at* the time of their formation." The gypsum, however, may *not* have undergone significant solution during Summerville deposition. The Bilk Creek Sandstone Member (Goldman & Spencer, 1941) of the Wanakah Formation (now the Summerville Formation) lies directly on the smooth or undulating surface of the breccia, and fine quartz grains of the sandstone member do not penetrate pores in the underlying breccia (Holmes, 1960). This may indicate that solution of gypsum occurred after compaction of the overlying sandstone (Holmes, 1960). The breccia probably formed, as Burbank speculates, during deposition of the Morrison Formation. Interestingly, in a local area 6 mi (9.7 km) north of the city of Ouray (sec. 36, T45N, R8W) on Baldy Peak, the Todilto Breccia Member is absent, and 52 ft (15.9 m) of original Todilto gypsum crops out (Burbank, 1930; Kamin, 1968).

General stratigraphy of the Pony Express Formation and its relationship to the Todilto Formation

In southwestern Colorado a limestone with thickness, lithology, stratigraphy, age, and fossil fauna similar to those of the Todilto Limestone Member was designated the "Pony Express beds of the Wanakah Member of the Morrison Formation" by Burbank (1930, p. 171). The Pony Express beds lie just above the Entrada Sandstone and constitute the base of Burbank's Wanakah Member. Goldman & Spencer (1941, p. 1755) elevated the Pony Express beds of Burbank to member rank, and Eckel (1949, p. 29) elevated the Wanakah Member of the Morrison to the rank of formation and included the Pony Express in the Wanakah as the basal member. Like the Todilto Limestone, the Pony Express Limestone is overlain in places by a gypsum bed that is usually much thicker. Like the Todilto Limestone, where the gypsum unit is absent a limestone breccia usually directly overlies the Pony Express Limestone. The areal extent of this breccia unit plus the areal extent of the genetically associated gypsum unit are more restricted than the areal extent of the Limestone Member (Kamin, 1968, p. 18).

South of the San Juan Mountains in Colorado, with few relatively short interruptions, the Pony Express Limestone can be traced along exposures and by well penetrations into the Todilto Limestone (Kamin, 1968, p. 11). Both the Todilto and the Pony Express were obviously deposited from the same waterbody. The two units, each of which has been formally designated, are clearly the same strati-graphic unit.

Although the term Pony Express Limestone is well entrenched in the geologic literature, in this paper, following the lead of Holmes (1960) and Anderson & Lucas (1992), we use the name Todilto Formation for the Pony Express Limestone as well as for its closely associated gypsum and breccia units. We do not recommend that the term "Pony Express" be completely abandoned; it has long been used as a miner's term in the San Juan Mountains (e.g. Purington, 1896), and its usage in this capacity should continue. Unlike Baker et al. (1947), Imlay (1952), Condon & Huffman (1988), and Ridgley (1989), we use Todilto Formation instead of Pony Express member of the Wanakah Formation. Our reasons are as follows:

(1) The Todilto Limestone and the Pony Express are the same stratigraphic unit.

(2) The name Todilto Limestone (Gregory, 1917) takes precedence over the name Pony Express Limestone (Burbank, 1930).

(3) The carbonate and sulfate lithologies of the Todilto Formation (and the Pony Express Limestone of Burbank) are clearly distinct from the overlying, predominantly siliciclastic units of the Wanakah Formation. Thus, as in New Mexico, the Pony Express (now Todilto) of southwestern Colorado is a mappable unit distinct from the overlying elastic beds and should have a formation rank instead of a member rank. Furthermore, the name Wanakah is preoccupied (Grabau, 1917) and should not be used for a Jurassic lithostratigraphic unit (Anderson & Lucas, 1992). We concur with Anderson & Lucas that the name Summerville should replace the name Wanakah.

Vertical relationship of the Todilto to stratigraphically adjacent units

The Todilto Formation is everywhere underlain conformably by the Middle Jurassic Entrada Formation and, throughout much of its extent, is overlain conformably by the Middle Jurassic Summerville Formation (e.g. Anderson & Lucas, 1992, fig. 2). The Entrada is a massive, extensively crossbedded, chiefly eolian sandstone, whereas the Summerville is a thinly bedded sandstone with "interbedded gypsiferous siltstone, sandy siltstone, or mudstone" (Anderson & Lucas, 1992). The thin-bedded Summerville probably resulted from deposition in large shallow lakes and marine tidal flats. Throughout northwestern New Mexico and southwestern Colorado, the Summerville is commonly overlain by eolian sandstones including the Junction Creek Sandstone, Bluff Sandstone, and Zuni Sandstone.

The evaporitic carbonate and sulfate of the Todilto Formation appear out of place in the otherwise thick siliciclastic section, which throughout much of its distribution includes the Upper Triassic Chinle Formation (predominantly shale) and Entrada Sandstone below, and the Summerville, Upper Jurassic Morrison Formation, and Upper Cretaceous Dakota Formation (predominantly sandstone) above.

Although fossil evidence is rare, the Summerville Formation appears to have both marine and nonmarine facies. In the Chama Basin, north-central New Mexico, the Wanakah Formation (now the Summerville Formation of Anderson & Lucas, 1992) occurs above the Todilto and below the Morrison. In the Chama Basin, New Mexico, Ridgley (1989) found at a number of localities in the Summerville Formation the nonmarine mollusk *Vetulonaia* sp., ostracodes, charophytes, and, in the upper unit, the trace fossils *Rhizocorallium*, *Thalassinoides*, and *Arenicolites.* From this assemblage she infers that during the middle and upper Callovian time a "large lake covered the southern part of the Chama basin." The trace fossils, which are in beds overlying those containing *Vetulonaia* and underlying those containing ostracodes and charophytes, would normally indicate marine conditions, but they are interpreted by Ridgley to indicate lacustrine conditions. About 10 mi (16.1 km) west of Delta, west-central Colorado (secs. 9 and 10, T51N, R13W), in limy siltstones of the Summerville Formation, Holmes (1960) found specimens of the marine pelecypod *Mytilus* (identified by J. B. Reeside, Jr.), which indicates that marine waters were present in this area. The beds at this locality probably represent marine tidal flats.

Lateral relationship of the Todilto to stratigraphically equivalent units

The last major marine invasion of the Western Interior by Jurassic seas, referred to as the Sundance Sea, took place in the Middle Jurassic. As we will show, the origin of the Todilto Formation is related to this marine invasion. Stratigraphic units that either represent this invasion or are related closely to it include the Sundance, Swift, Summerville, Curtis, Todilto, Junction Creek, Bluff Sandstone, Zuni Sandstone, and Ralston Creek. In the following paragraphs we discuss two of these units, the Curtis and the Ralston Creek, both of which have direct bearing on understanding the origin of the Todilto Formation.

The Todilto Formation correlates stratigraphically with the Curtis Formation (Imlay, 1952). In northwestern Colorado, where it is chiefly a carbonate, the Curtis Formation contains a variety of marine invertebrates (Gilluly & Reeside, 1928); these belong to the well-known fauna of the upper part of the Sundance Formation (Baker et al., 1936). The Curtis also contains 21 species of foraminifera and 10 species of ostracodes (Eicher, 1955). It covers northwestern Colorado and extends southeastward in a well-defined lobe as far as Aspen, Colorado. Marine fossils were found as far south as the town of Burns, Eagle County, Colorado (Holmes, 1960). In this area the Curtis is underlain by the Entrada Sandstone and overlain by the Summerville, or where the Summerville is missing by the Morrison (Holmes, 1960). Throughout parts of northern New Mexico, the Todilto is also underlain by the Entrada Sandstone and overlain by the Summerville Formation.

The southernmost extent of the Curtis Formation in northwestern Colorado and the northernmost extent of the Todilto Formation in southwestern Colorado are shown in Figure 12. The shortest distance between the Curtis and the Todilto is about 60 mi (96.6 km). Imlay (1952) states,

> Direct marine connection of the Wanakah formation of southwestern Colorado with the Curtis formation farther north near Snowmass Canyon, Wolcott, and State Bridge seems improbable because the two areas are separated by a positive mass on which the Morrison formation overlaps onto Precambrian rocks.

The locations of the place names mentioned by Imlay are shown on plate 1 of Baker et al. (1936). The basal member of the Wanakah Formation (using Imlay's nomenclature) is the Pony Express Limestone, which we have designated the Todilto Limestone. The positive mass referred to by Imlay is the Uncompahgre uplift, which was a low-lying positive area during the Todilto time. It was subsequently covered by the Upper Jurassic Morrison Formation and Cretaceous marine strata.

Most of the area separating the southernmost Curtis and northernmost Todilto outcrops is covered by post-Jurassic sedimentary rocks and post-Jurassic intrusives. An exception is an outcrop of limestone about 4 ft (1.2 m) thick in Gunnison County, Colorado (sec. 32, T125, R86W). Holmes (1960, p. 99) identified this exposure as Todilto (his Gothic section) and wrote that the middle bed (0.4 ft = 0.12 m thick) is "very similar to Pony Express limestone of the Telluride District." If Holmes' identification were correct, known exposures of Todilto Limestone and marine Curtis Limestone would be separated by less than 25 mi (40.2 km). The two formations would be so close that a strait connecting the Curtis and Todilto waterbodies might have existed in this area. A strait at the northern end of the Uncompahgre uplift, as shown in Figure 2, is inferred by Holmes (1960, figs. 25, 29) and Ridgley (1989, fig. 9).

The basal part of the Ralston Creek Formation of south-central Colorado is equivalent to the Todilto Formation (e.g. Johnson, 1962), and the upper part is probably equivalent to the Summerville Formation (of Anderson & Lucas, 1992). In south-central Colorado the Ralston Creek Formation occurs directly above the Entrada Formation and directly beneath the Morrison Formation. As we discuss in detail below, two species of fossil fishes, *Hulettia americana* and *Todiltia schoewei*, have been found in both the Todilto and Ralston Creek Formations. This helps to establish that the two formations are stratigraphically (and probably temporally) correlative, and it leads to the conclusion that the two waterbodies might have been connected, however briefly. In the Canyon City area, Colorado, the Ralston Creek Formation consists principally of from 30-170 ft (9.1-51.8 m) of gypsum, conglomerate, sandstone, and shale, with gypsum forming the major part of the section (Frederickson et al., 1956). In the Raton Mesa area of south-central Colorado, near the New Mexico border, the formation consists of 16-69 ft (4.9-21 m) of sandstone, siltstone, gypsum, and limestone, with siliciclastics predominating (Johnson, 1962).

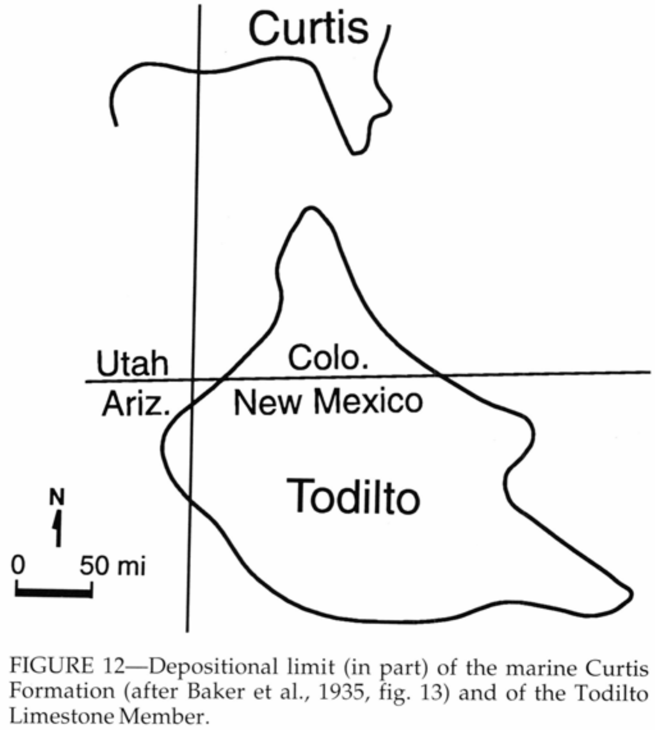

FIGURE 12—Depositional limit (in part) of the marine Curtis Formation (after Baker et al., 1935, fig. 13) and of the Todilto Limestone Member.

Imlay (1952) used the term Wanakah (= Summerville) in south-central Colorado for what is now called Ralston Creek Formation (Van Horn, 1957). In that same work, Imlay reported that *Vetulonaia* was Found at the type section of the Ralston (= Ralston Creek) Formation. This is the same nonmarine genus of mollusk that Ridgley (1989) subsequently found in the Wanakah Formation (now Summerville) of the Chama Basin. This mollusk also occurs in the overlying Morrison Formation (Imlay, 1952).

The Ralston Creek Formation is characterized by anhydrite, gypsum, and limestone. These facies comprise much of the formation in the Denver Basin and southward to the New Mexico boundary (McKee et al., 1956). Anhydrite beds also occur in the subsurface of western Kansas (Merriam, 1955) in a unit Merriam correlated with the Sundance of Wyoming, equivalent to the Ralston Creek Formation. But were the waterbodies that deposited the Todilto and Ralston Creek connected? McKee et al. (1956) state:

> Whether the evaporite basin in northeastern New Mexico and eastern Colorado was once connected to the south with the basin that extends westward across New Mexico is not known. No data are available from the critical area north of Santa Fe, part of which has not been penetrated and part of which contains only pre-Jurassic rocks.

Subsequent to the investigation of McKee et al. (1956) some new data have been generated. Griggs & Northrop (1956) reported that "...very distinctive, thinly laminated Todilto limestone... has been noted at Joyce dome in Colfax County" (southeastern part of T27N, R25E). (We have not personally verified the identification of this outcrop as Todilto and have not included the locality within the paleogeographic limits of the Todilto Limestone.) Typical Todilto limestone, thinly laminated and less than 5 ft (1.52 m) thick, has also been found in the Moreno Valley near Eagle Nest, Colfax County, New Mexico (SW part of T27N, R17W) (Wanek & Read, 1956). Here it overlies the Ocate Sandstone, a name which is synonymous with the Entrada (Lucas et al., 1985), and is overlain by the "Wanakah Formation," about 25 ft (7.6 m) thick in this area. These Todilto outcrops are about 50 mi (80.5 km) due north of Todilto outcrops at Sapello near Las Vegas, New Mexico, and less than 40 mi (64.4 km) south of well-exposed outcrops of Ralston Creek Formation in southwestern Las Animas County, Colorado (Johnson, 1962). The Ralston Creek outcrops in the Raton Mesa area do not contain a basal limestone, but consist of "alternating beds of sandstone, siltstone, and limestone with very thin interbeds of claystone, gypsum, and jasper" (Johnson, 1962). The presence of a distinctive Todilto limestone facies in west-central Colfax County, New Mexico, increases the probability that there was a connection, possibly ephemeral, of the Todilto evaporite basin with the Ralston Creek evaporite basin in Colorado and Kansas.

Tectonic setting and paleogeography

The tectonic setting of the Todilto depositional basin is shown in Figure 13. A broad, generally east-west-trending high extended from central Arizona through central New Mexico (Dobrovolny et al., 1946; Silver, 1948; Smith, 1951; Rapaport et al., 1952; McKee, 1956; Harshbarger et al., 1957). Another low positive area, the Uncompahgre uplift, was present northeast of the basin (McKee, 1956; Holmes, 1960).

The large positive element to the south of the Todilto Basin (Fig. 13) greatly affected Jurassic sedimentation. This positive element, called the Navajo Highland by Smith (1951), the Zuni Highland by Rapaport et al. (1952, p. 15), and the Mogollon Highland by Harshbarger et al. (1957), developed in Triassic time. The Mogollon Highland, as we refer to it, remained prominent throughout Late Jurassic and Cretaceous times (Harshbarger et al., 1957).

South of Laguna, New Mexico, each of the members of the Entrada Sandstone and of the Morrison Formation become thinner and coarser southward, and progressively overlap the positive area in that direction (Silver, 1948). Other evidence of the Mogollon Highland is the pinch-out of the Todilto Limestone Member to the south, as well as pinch-outs of fine-grained clastic beds intercalated within the Jurassic section (Rapaport et al., 1952, p. 16). In Jurassic exposures of the modern Zuni uplift, Rapaport et al. (1952, p. 16) found that the majority of foreset beds dip northward, indicating that erosion of the Mogollon Highland provided the bulk of Jurassic sediments in this area. The tectonic evolution of this uplift is described by Kelley (1967).

The Uncompahgre uplift, a Precambrian element of the Ancestral Rockies, was active during the late Paleozoic. The uplift, which extends into north-central New Mexico, was still influencing sedimentation during Jurassic time. The Entrada in the area of the Black Canyon of the Gunnison, for example, pinches out against the southwestern flank of the uplift, but reappears in the central basin of Colorado (Holmes, 1951, 1960). Similarly, for a distance of probably 100 mi (161 km) or more, the Todilto and the Wanakah (now Summerville) Formations apparently pinch out against the southwestern flank of the Uncompahgre uplift (Fig. 13) (Holmes, 1960). The youngest Jurassic formation in southwestern Colorado, the Morrison, was the first to definitely cover the Precambrian rocks (Imlay, 1952). [The thickness of the Morrison over the crest is reduced by about 40% (Holmes, 1960).] The uplift plunges northwestward at about the same latitude as the northernmost extent of the Todilto Formation (Fig. 13). It is for this area that a possible connection with the Curtis (Sundance) Sea has been proposed (Fig. 12).

Based on an absence of clastic material (other than wind-borne silt) in the Todilto limestone and gypsum, neither the Uncompahgre uplift nor the Mogollon uplift could have been very high-standing during Todilto time. In addition to the low relief, arid climate was probably also partially responsible for the dearth of clastic material.

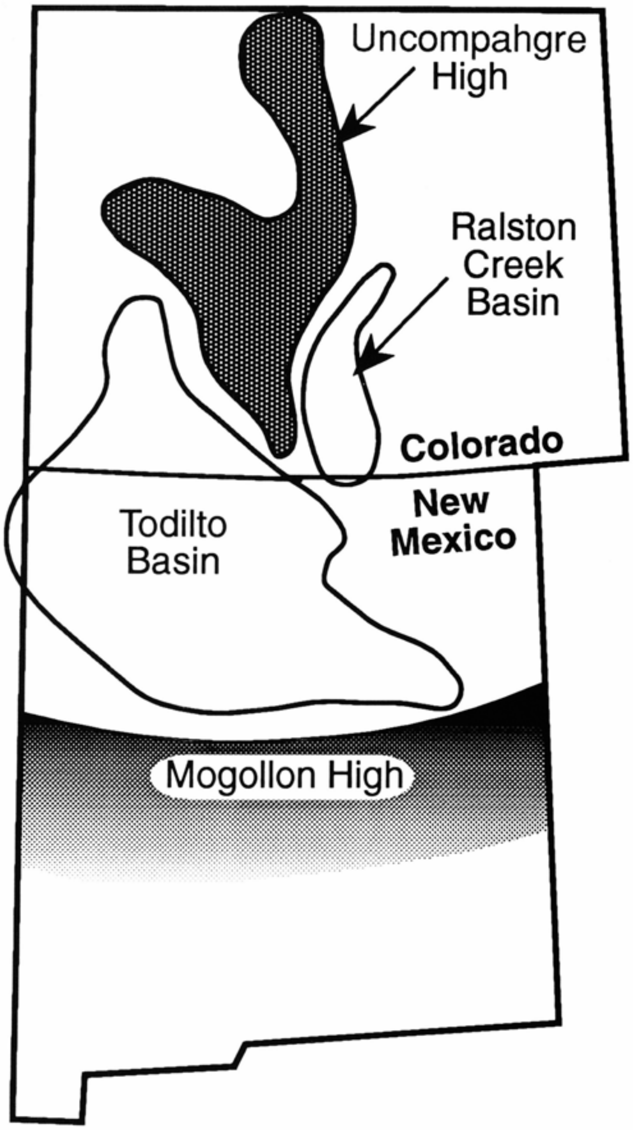

FIGURE 13—General location of positive areas (low hills) during Callovian (Middle Jurassic) time in relation to the Todilto and Ralston Creek depositional basins (modified from McKee et al., 1956).

Our reconstruction of the paleogeography of the Todilto Formation incorporates all readily available data and is shown in Figure 2, in which the extent of the Todilto limestone and gypsum facies is not too different from that in paleogeographic reconstructions of others (McKee et al., 1956, pl. 9, fig. 5; Ash, 1958, figs. 3, 4; Anderson & Kirkland, 1960, fig. 7; Hilpert, 1969, fig. 3; Lucas et al., 1985, fig. 7; Condon & Huffman, 1988, fig. 5a; Ridgley, 1989, fig. 10). In reconstructing the paleogeography of the Todilto in southwestern Colorado, we have included the investigations of Holmes (1960, fig. 29) and Kamin (1968, fig. 3).

Three possible channels or straits have been suggested: between the Todilto and Curtis in west-central Colorado (Holmes, 1960; Condon & Huffman, 1988; Ridgley, 1989), between the Todilto and Ralston Creek in northeastern New Mexico (McKee et al., 1956), and between the Todilto and Summerville in northwestern New Mexico (near the Four Corners area) (Harshbarger et al., 1957) (Fig. 2). Of the three proposed Todilto channels, only that through west-central Colorado would have definitely connected the Todilto waterbody with normal marine water. Whether the others would have connected the Todilto with marine, modified marine, or nonmarine-derived water is conjectural.

We suggest a fourth possibility, that a channel may have existed in southwestern Colorado between the Todilto depositional basin and the Summerville depositional basin as defined by Baker et al. (1936). This possible channel in Montezuma County, Colorado, is shown in Figure 2. The Summerville Formation (of Baker et al., 1936) in this area appears to virtually border the western pinchout of the Todilto limestone (Fig. 14). To the west beyond the limits of Todilto and Curtis deposition, the basal part of the Summerville (the lower silty facies) was probably in part contemporaneous with these carbonate units (see Baker et al., 1936, fig. 16; Harshbarger et al., 1957). Imlay (1957), for example, indicated that the Summerville grades into "a thinner, more calcareous facies ... characterized at its base by the Todilto limestone..." As mentioned above, Holmes (1960, pp. 92, 107) reported that in west-central Colorado he found *Mytilus* and possible tubes of serpulid worms in thin limy siltstones of the Summerville. These marine fossils occur less than 20 mi (32.2 km) from the center of the narrow Todilto Basin. If the elastic unit bordering the western pinch-out of the Todilto Limestone in southwestern Colorado were truly marine, and if this unit and the Todilto were truly contemporaneous, marine waters probably would not have been entirely blocked from entering the basin.

Age

A Middle Jurassic age is well-delimited for the Todilto Formation and for the Ralston Creek Formation. The age of these units is considered by most workers to be Callovian (Imlay, 1980; Kocurek & Dott, 1983; Schultze & Enciso, 1983; Lucas et al., 1985; Ridgley, 1989), more specifically middle Callovian (e.g. Lucas et al.; Ridgley). The proposed correlation of the Todilto with the chronostratigraphic scale is shown in Figure 15.

Schaeffer & Patterson (1984) proposed that the age of the Todilto and members of the Sundance Formation of Wyoming that bear similar fish fossils is not middle Callovian but late Bathonian to early Callovian ("...last half of the Bathonian to about the middle of the Callovian..."). The principal fish-bearing unit in the Sundance Formation, the Hullett Sandstone Member, lies directly above two members (the Canyon Springs Sandstone and the Stockade Beaver Shale) that do not contain fish fossils. The age of these two lower members has recently been defined as late Bathonian on the basis of ammonites (Imlay, 1980). According to Schaeffer & Patterson (1984), the Hullett Sandstone Member is in the zone of *Kepplerites maclearni*, a characteristic ammonite of the western interior of the United States. They contend that this zone may also be Bathonian (based on pers. comm. from J. H. Callomon, 1982). Imlay (1980, pp. 69-75), however, considers the *Kepplerites maclearni* zone, which he originally designated as middle Callovian (Imlay, 1957), to be early Callovian.

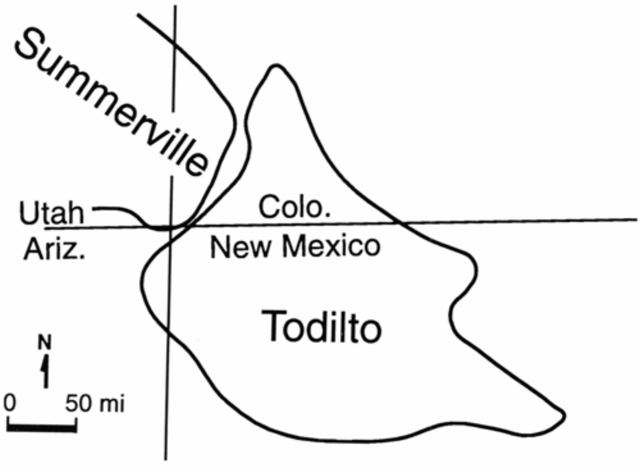

FIGURE 14—Depositional limit (in part) of Summerville Formation (after Baker et al., 1935, fig. 13) as compared with depositional limit of Todilto Limestone Member.

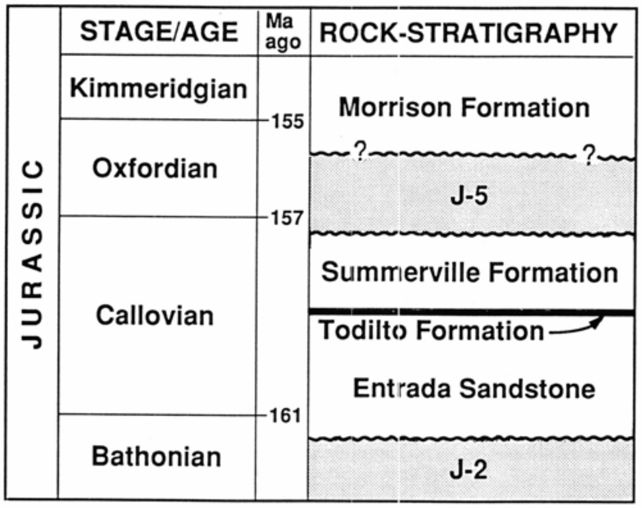

FIGURE 15—Jurassic strata of northwestern New Mexico correlated with the time scale of Harland et al. (1989). The Todilto Formation is estimated to have been deposited in 30,000–100,000 years. On the time scale, the positions of the time boundaries assigned to formations and to unconformities are imprecise chiefly due to limited faunal control. The unconformities are identified according to the scheme of Pipiringos & O'Sullivan (1978).

In much of the Rocky Mountain region the Entrada Sandstone, which directly underlies the Todilto, is early and middle Callovian (Imlay, 1980). In northern New Mexico and southwestern Colorado the age of the Entrada is not as well-established as in other parts of the Rocky Mountain region. Some think it may possibly be in part Bathonian (e.g. Schaeffer & Patterson, 1984, fig. 2). The overlying Todilto /Ralston Creek Formations, however, probably are of lower or middle Callovian age. As Lucas et al. (1985) pointed out, the Todilto Formation is possibly slightly younger than the members of the Sundance (particularly the Hulett Sandstone Member with which it has been correlated based on the fish fossils.

In terms of absolute time, the Todilto waterbody probably existed as an ephemeral event of 30,000-100,000 years (see Anderson & Kirkland, 1960) over approximately 4 my, from about 161 to 157 my ago (based on the chronology of Harland et al., 1989). The accuracy of this age is sufficient for our needs, but as we will show below, a reasonably well-established age is required in order to use the ^{87}Sr/^{86}Sr and ^{32}5 /^{34}5 data as aids in determining whether the Todilto depositional environment was marine or lacustrine.

Depositional environment

Laminae of calcite and organic matter characterize much of the Limestone Member except near its depositional edge. These laminae could not persist with remarkable regularity for distances of at least several miles (e.g. Fig. 16) if macrofauna inhabited the floor of the basin.

Macrofauna would have been eliminated if the salinity were too high or if the concentration of oxygen in the water were too low. The near absence of a benthic fauna (whether marine or lacustrine) in the Todilto depositional environment was probably related to the waterbody being persistently stratified through much of its extent, probably as a result of salinity—a layer of less saline water overrode a layer of more saline water. [Stratification resulting from temperature might have been superimposed on, and possibly coincidental with, the stratification resulting from salinity.] Stratification of the waterbody would have prevented oxygen in near-surface water from being easily transported to the bottom, and it would have resulted in anoxic water at the bottom. During deposition of the carbonate unit, Todilto fishes (at least *Hulettia)* probably lived in the surface waters, which would have had sufficient oxygen for respiration and low enough salinity not to cause desiccation.

As a consequence of the stratification, the waters near the bottom of the basin would have been quiet, with strong currents seldom, if ever, reaching the bottom. The depth of water would have to be sufficient for stratification to develop and persist. Based on the assumed stratification of the waterbody, its large areal extent, its ephemeral nature, the total thickness of the Todilto Formation, its position at the southern end of the Sundance Sea, the height of remnant Entrada dunes, and a consideration of regional tectonics, we estimate that the Todilto waterbody was probably less than 300 ft (91.5 m) deep.

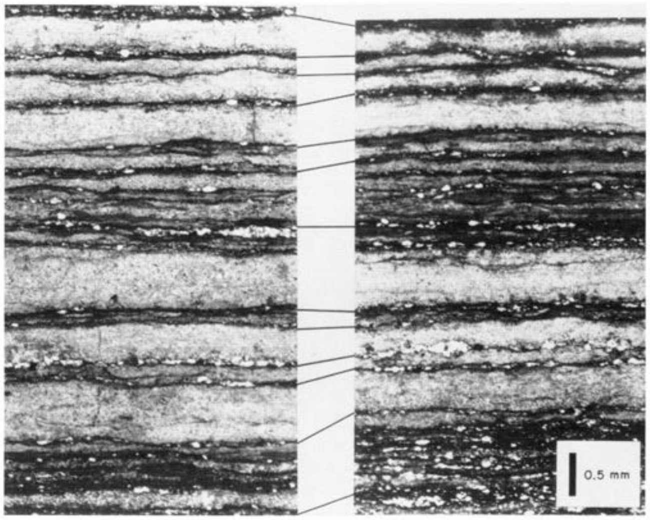

FIGURE 16—Correlative thin sections (plain light) of calcite and kerogen (dark) laminae; localities F (left) and H (right) of Anderson & Kirkland (1966), Sandoval County, New Mexico, separated by 1.4 mi (2.3 km).

Paleontology and paleoecology

Paleoenvironmental reconstructions are usually based primarily on fossils, which can be used to infer whether an environment were well or poorly oxygenated, hypersaline or brackish, marine or nonmarine. Because this is the standard way to proceed with a paleoenvironmental reconstruction, in this instance to determine whether Todilto waters were either marine or nonmarine, we have devoted considerable effort to an investigation of the array, albeit sparse, of fossil species in the Todilto Formation.

Insects

Discovery and current investigation

A fossil insect was discovered in the Todilto Limestone Member by Cockerell (1931). He described "a very perplexing, not very well preserved" insect from a locality 35 mi (56.3 km) east of Santa Rosa, New Mexico. This is probably the Bull Canyon locality (Quay County) at which Lucas et al. (1985) and Bradbury & Kirkland (unpublished) independently rediscovered fossil insects (Loc. 46, Fig. 17). Cockerell named the fossil insect *Xiphenax jurassicus,* and he reported that it occurred in the same interval as the fossil fish *Pholidophorus americanus* (now *Hulettia americana).* Some specimens collected by Bradbury & Kirkland (1966) from Sandoval County, New Mexico, look like the specimen illustrated by Cockerell. The single peculiar insect found by Cockerell is possibly the same species as other insects found more recently in the Todilto, but it may have undergone more decomposition than most of those found by Bradbury & Kirkland.

Bradbury & Kirkland (1966) found abundant fossil aquatic Hemiptera in the Todilto Formation in Sandoval County, New Mexico (latitude 106.906° N, longitude 35.561° W), on what then was the Ojo del Espiritu Santo Grant and now is part of the Zia Indian Reservation (Loc. 23, Fig. 17). The locality is several miles west of a series of warm springs along the front of the Nacimiento Mountains, and about 1 mi west of an abandoned well-casing of a warm spring 100-150 ft (30.5-45.7 m) east of N.M. Highway 44. For many years a spa and a cafe existed at the roadside "spring," but little evidence of the buildings now exists. Bradbury & Kirkland (1966) designated the site the "Warm Springs locality." Specimens from this locality are currently being investigated by J. T. Polhemus, University of Colorado Museum, Englewood, Colorado. He reports **(J.** T. Polhemus, in prep.) that they belong to the family Naucoridae (creeping water bugs) and most closely resemble the modern genus *Aphelocheirus* known only from the Old World. Specimens of the principal species (Fig. 18) have an oval body about 12 mm long and 6 mm wide.

Stratigraphic and geographic distribution

At the Warm Springs locality, most insects are found on bedding planes of a 3-inch (7.6 cm) zone of laminated silty shale and laminated calcareous shale near the base of the formation. At this locality the overlying limestone and gypsum units have been eroded back from the cliff edge of the Todilto, allowing easy access to the shale (Fig. 19). Fossil insects occur in abundance (more than 400 specimens have been collected). About one-third of the collection is suitable for taxonomic investigation (J. P. Bradbury, pers. comm. 1969). The fish *Hulettia americana* was rarely encountered with the insects (Bradbury & Kirkland, 1966). This is significant, since *H. americana* is thought to have had marine affinities (Schaeffer & Patterson, 1984, p. 12). Fishes *(H. americana, Todiltia schoewei)* and insects are rare in the overlying Limestone Member.

Fossil Hemiptera occur elsewhere in the basal Todilto exposures at the southern end of the Nacimiento Mountains. However, if not covered, the basal beds usually crop out in a recess formed by removal of the less resistant Entrada Sandstone beneath a cliff of Todilto limestone and gypsum (Fig. 1), which makes collecting both difficult and often hazardous.

Fossil insects have been found at 9 other localities in the Todilto Formation (Fig. 17) (Cockerell, 1931; Bradbury & Kirkland, unpublished; Kirkland, unpublished; Lucas et al., 1985). The localities extend east—west for about 160 mi (257.5 km) from near Laguna (Loc. 39) to Bull Canyon (Loc. 46), and north—south about 120 mi (193.1 km) from Suwannee Peak (Loc. 41) to near Echo Amphitheater (Loc. 17). Preservation of fossil insects at these localities is poor. At the Bull Canyon locality (Loc. 46, Fig. 17), some poorly preserved insects are associated with fossil fish; they occur in a laminated limestone unit, and also near the base of an underlying calcareous, sandy, gray shale (Lucas et al., 1985, fig. 9).

Paleoecological deductions

The vast majority of modern aquatic insects inhabit fresh water (Pennak, 1953, p. 492); only a few species have

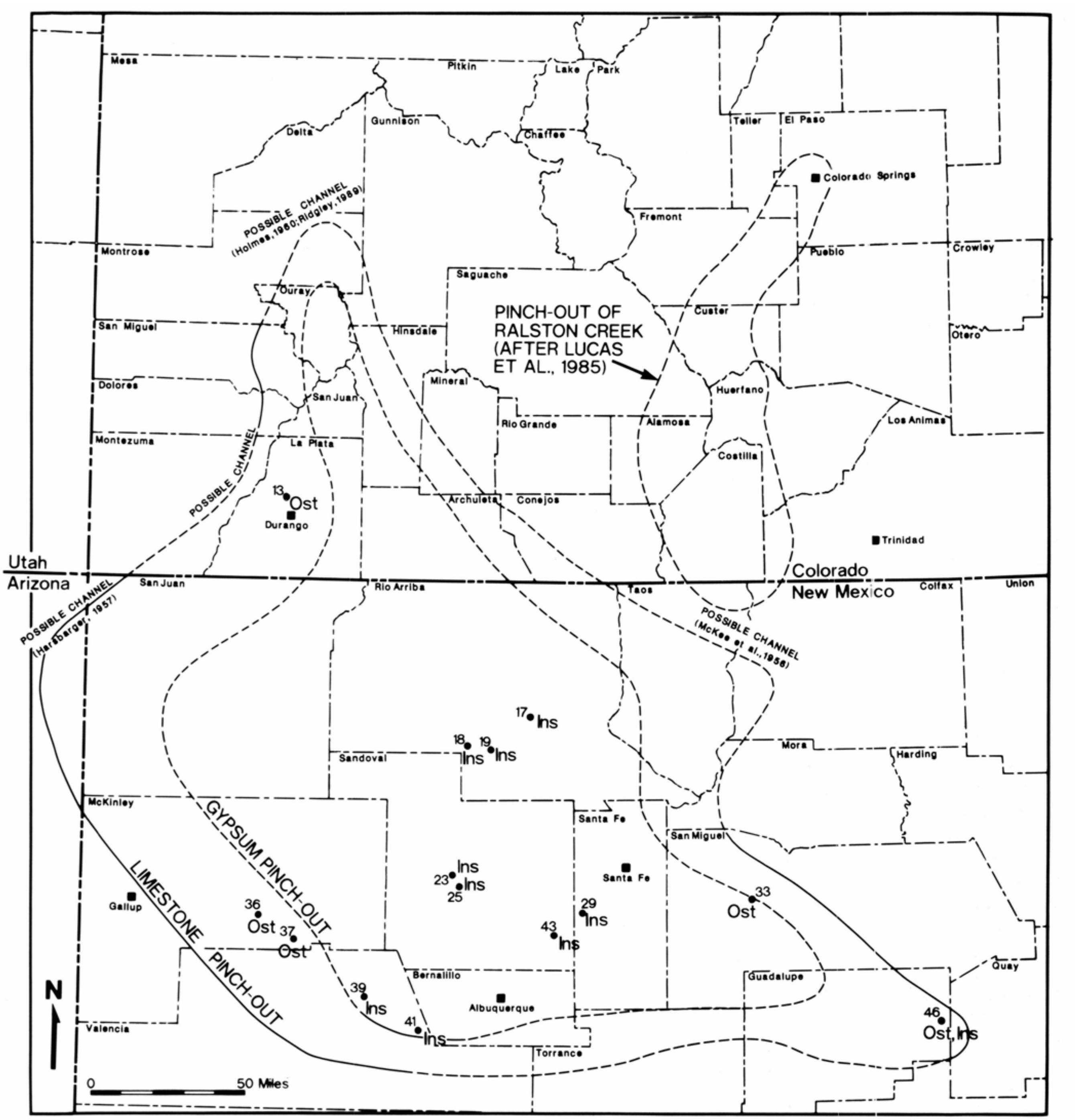

FIGURE 17—Fossil insect (Ins) and ostracode (Ost) localities, Todilto Limestone Member, northern New Mexico and southwestern Colorado. Insect localities: **17–19**, **25–29**, **39**, **41**, **43** found by J. P. Bradbury and/or D. W. Kirkland, previously unreported; **23**, Bradbury & Kirkland, 1966; insect and ostracode locality **46**, Cockerell, 1931 and Lucas et al., 1985; ostracode locality **13**, Bush et al., 1959, and McCrary, 1985; **33**, McCrary, 1985; **36**, Swain, 1946; **37**, McCrary, 1985, and this report.

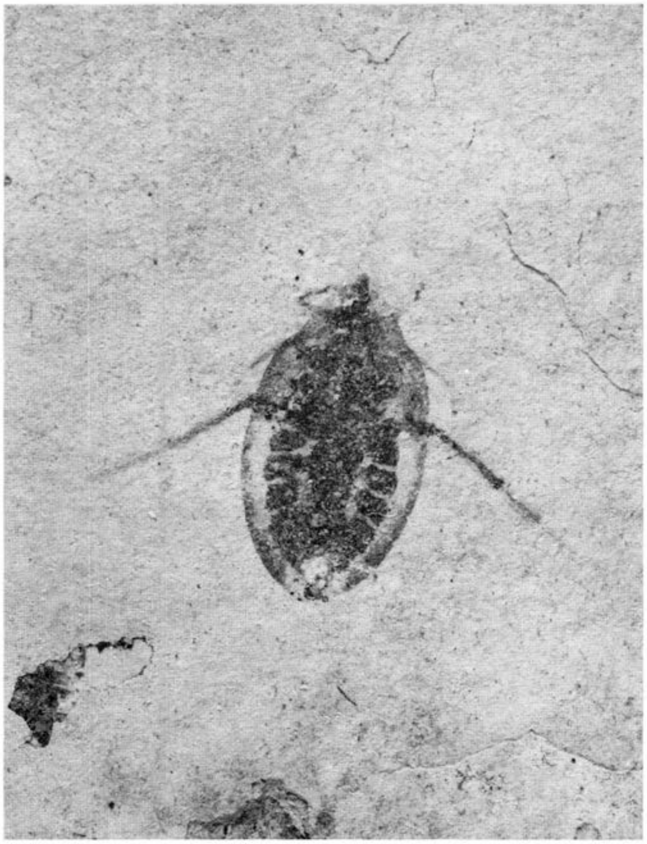

FIGURE 18—Fossil aquatic Hemiptera from the base of Todilto Formation; Zia Indian Reservation, Sandoval County, New Mexico (latitude 106° 54' 22"N, longitude 35° 33' 38"W). Length 1.2 cm.

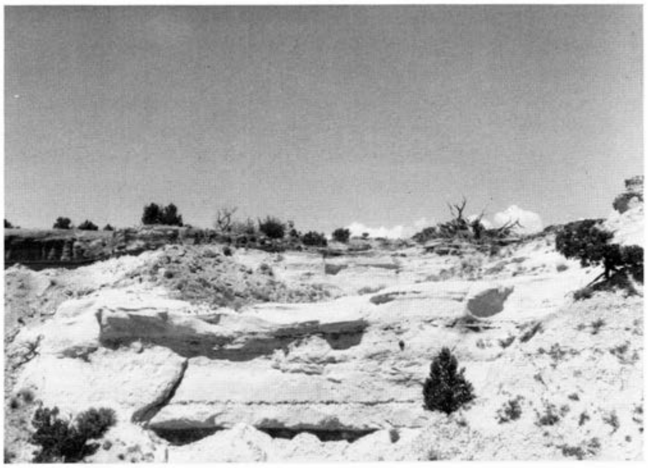

FIGURE 19—Principal fossil-insect locality, basal Todilto Formation; Zia Indian Reservation, Sandoval County, New Mexico (latitude 106° 54' 22"N, longitude 35° 33' 38"W). The Todilto Formation has been markedly eroded so that only the basal insect-bearing section lies conformably on the Entrada Sandstone.

invaded marine and brackish waters. A species of the same suborder as the Todilto insects, for example, inhabits the brackish Baltic Sea (J. T. Polhemus, pers. comm. 1990). Also, R. L. Usinger (pers. comm. 1966) reports belostomatids (giant water bugs) in tidal pools along the California coast. Insects are almost unknown in normal marine water except for a hemipteran group of water striders, namely the genus *Halobates* (Scheltema, 1968). Nor does evidence from the fossil record support past inhabitation of the marine environment by aquatic insects. Thus, if the insects inhabited the Todilto waterbody near where their fossil remains are now found, we would infer that the water was not normal marine. But did the insects actually inhabit the waterbody?

Hemipteran fossils are rare in the laminated-limestone facies. Judging from the stratigraphic relationship of the limestone unit to the overlying gypsum unit, the low diversity of invertebrate and vertebrate fossils in the limestone unit, and the characteristic microstratification in the limestone, we can infer that the salinity of the water from which calcium carbonate was deposited was certainly at least brackish, and possibly more saline than modern sea water. Tracheids and fibers derived from terrestrial plants occur in organic laminae (Anderson & Kirkland, 1960, fig. 2). Many of these plant fossils were probably transported into the basin by streams. Insects are rare and poorly preserved on limestone bedding planes, and possibly the fauna represent a thanatocoenosis. The insects may have inhabited nearshore areas of the Todilto waterbody or may have been brought there by streams. *Todiltia schoewei* is considered by Schaeffer & Patterson (1984) to be a fresh-water fish, which may have been washed into the hypersaline waterbody from the fresh-or brackish-water environments. This supports our theory that the insects represent a thanatocoenosis.

But what of the basal shaly unit at the Warm Springs locality? Does it represent a thanatocoenosis? Here fossil Hemiptera are present in abundance. About one-third of the fossil insects are moderately to well-preserved, suggesting that they did not endure long transport. Neither the remains of terrestrial plants nor of terrestrial insects were observed on the many square feet of bedding plane exposed in a search for insect specimens. In the basal zone only the fossil *fishHulettia americana* and a possible worm track were encountered in association with the fossil insects. These facts do not support a thanatocoenosis of insects transported by streams or from nearshore areas into a saline(?) waterbody. More likely the insects were living in the water in which the calcareous shale originated. [One modern genus of the family Naucoridae, to which the Todilto forms belong, is permanently aquatic and does not depend on atmospheric oxygen. An ultramicroscopic hairpile consisting of 2 million hairs per square millimeter serves as a gill, absorbing dissolved oxygen from water (Thorpe, 1950; Usinger, 1957).]

Data derived from both drilling for oil in the Entrada Sandstone and from seismic surveys in the southern San Juan Basin allow us to infer the nature of the Entrada surface in this area at the beginning of Todilto deposition. This was about the time of deposition of the insect-bearing calcareous shale at the southern end of the Nacimiento Mountains. At that time just west of this area in San Juan, McKinley, and Sandoval Counties, New Mexico, a series of elongated sand ridges extended in a northeast direction; some were up to 15 mi (24.1 km) long, 2.0 mi (3.2 km) wide, and 114 ft (34.8 m) high. They show as systematic seismic anomalies that Vincelette & Chittum (1981) interpreted as topographic highs formed by reworking of the dunes by waves and currents of a transgressing waterbody (Fig. 20).

At the initial stage of Todilto deposition, relief of the dunes was of course greater than after transgression of the Todilto waterbody. In the basal shale, the fish *Hulettia americana* suggests that the transgressing waters were marine. The thin, insect-bearing shale at the southern end

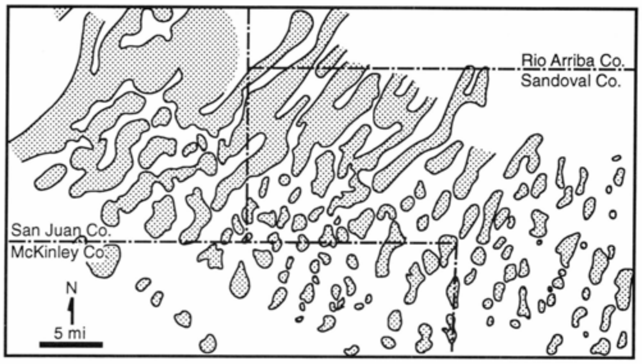

FIGURE 20—Orientation and general distribution of topographic ridges (stippled), top of the Entrada Sandstone, northwestern New Mexico. These ridges, which may have present relief of >100 ft, represent modified eolian sand dunes (after Vincelette & Chittum, 1981).

of the Nacimiento Mountains may represent an accumulation of clay and calcareous clay in an isolated or nearly isolated, probably brackish waterbody in a low between Entrada sand-highs. The waterbody, which would have been close to the shore of the transgressing Sundance Sea, probably received considerable meteoric water as seepage from surrounding dunes.

Fossil fish

Taxa, general localities, relative abundances, and distribution

The fossil fish of the Todilto Limestone, Ralston Creek Formation, and Sundance Formation have been used to support both a marine (e.g. Baker et al., 1947; Imlay, 1952; Harshbarger et al., 1957) and a nonmarine (e.g. Ash, 1958; Tanner, 1970; Schultze & Enciso, 1983) origin for the Todilto Formation. Three principal works have been written on these fossils by Schaeffer & Patterson (1984), Schultze & Enciso (1983), and Lucas et al. (1985). Schaeffer & Patterson considered the taxonomy, distribution, and paleoenvironment of fish taxa within the Todilto and Sundance Formations; Schultze & Enciso investigated the distribution, associations, and age of fossil fish in the basal Ralston Creek Formation north of Canyon City, Colorado; and Lucas et al. investigated the taxonomy, distribution, taphonomy, and paleoenvironment of fossil fish in the Todilto, particularly at localities near the small town of Ima, Quay County, New Mexico.

The fossil fish of the Todilto have been renamed by Schaeffer & Patterson (1984). The species previously called *Pholidophorus americanus* is now *Hulettia americana* (Eastman), and that called *Leptolepis schoewei* is now *Todiltia schoewei* (Dunkle). A third species, *Caturus dartoni* (Eastman), was recently discovered in the Todilto (Schaeffer & Patterson, 1984). It is much rarer than the other Todilto species and has been found only at Bull Canyon, Guadalupe County, New Mexico (Loc. 46, Fig. 21). *H. americana* and *T. schoewei* are illustrated in Figure 22. *Hulettia* is much more abundant than *Todiltia* (Lucas et al., 1985; and personal observation). *Hulettia* has a maximum length of about 12 cm, *Todiltia* a maximum length of about 8 cm with a mean length of about 5 cm (Lucas et al., 1985), and *Caturus* a standard length (from nose to caudal cleft) of about 30 cm (Schaeffer & Patterson, 1984).

In the Todilto Limestone and Ralston Creek Formation fossil fishes have been found at 19 localities, which are shown on Figure 21 and include those reported in the literature and those known to the authors. The specimens occur chiefly in the laminated limestone, except in Fremont County, Colorado, where they are found in very fine-grained laminated sandstone of the basal Ralston Creek Formation. In the Todilto Limestone Member the localities span about 200 mi (322 km) east-west across New Mexico and about 150 mi (241.5 km) north-south in western New Mexico and western Colorado (Fig. 18). The fish occur near the edge of the depositional basin as well as near its center (Fig. 18). Insects and ostracodes are associated with the Todilto fish, and a conifer strobilus, twig impressions, and palynomorphs are associated with the Ralston Creek fish.

Principal fossil-fish localities

At many of the fossil localities in Figure 21, only one or two specimens of fossil fish, usually *Hulettia americana,* have been found. In one other instance scales and gill arches were collected, and at six other localities fish were found but not identified to genus. At five additional areas, one of which is in Crook County, Wyoming, more extensive collections, including both *H. americana* and *T. schoewei,* have been made. These areas are described briefly in the following sections.

Bull Canyon/Luciana Mesa locality—The first specimens of Todilto fish were found in. 1929 near Ima, Quay County, New Mexico, by L. D. Kessler, a petroleum geologist (Northrop, 1961), and were identified as *H. americana* by Koerner (1930). Dunkle (1942) identified *Todiltia schoewei* from the Bull Canyon area, and Schaeffer & Patterson (1984) identified *Caturus dartoni.* In this part of New Mexico there are now two closely associated collecting localities, Bull Canyon and Luciana Mesa (Locs. 46 and 47, Fig. 21) (Lucas & K ietzke, 1986). At these localities, which are near the edge of the depositional basin, the limestone is less than 2 m thick and contains a significant amount of elastic material (Lucas & Kietzke, 1986). The number of specimens collected is exceptional when compared with the other Todilto and Ralston Creek localities. At Bull Canyon the fossil fish "...have a decided preference for the limestone pinchouts on the northwest 'shores' of the northeast-to-southwest-trending interdune fingers of the Todilto waterbody..." (Lucas et al., 1985). Lucas et al. infer that the large numbers of fish in this marginal area may represent an assemblage of individuals that died following spawning. About 30% of the specimens of *Hulettia* at these localities, are curled. Based on this observation, Lucas et al. (1985) infer that many specimens of *Hulettia* floated after death.

New Mexico Highway 4 locality--Fossil fish have been found in the Todilto Limestone cliffs along N.M. Highway 4, 7-12 mi (11.3-19.3 km) north of San Ysidro, Sandoval County (Bradbury & Kirkland, 1966; Schaeffer & Patterson, 1984) (Locs. 23, 25, and 26, Fig. 21). Ninety percent of the 30 or so specimens collected here are *Hulettia americana.* They were found mainly during an assiduous search for fossil insects and during an attempt to correlate Todilto laminae. Specimens of *Hulettia* occur both in the blocky limestone and in the underlying laminated shalt' unit directly above the contact with the Entrada Sandstone. In the basal shale, as previously mentioned, some specimens of *H. americana* are associated with water bugs. The several specimens of *T. schoewei* are restricted to the blocky limestone facies. During the death and burial of *T. schoewei* at this locality, the Todilto shoreline was probably at least several tens of miles away. Based upon both the unexpected discovery of fossil fish at this locality and on the wide distribution of fossil fish (Fig. 21), the possibility exists that sporadic fish bodies occur laterally and vertically throughout much of the Limestone Member, and that a diligent search will result in the discovery of fossil fishes at Todilto localities elsewhere.

Piedra River locality—In exposures along the slopes of the Piedra River valley and in the area of Weminuche Creek, both north of the small town of Piedra, Archuleta County, Colorado, specimens of *Hulettia americana* and *Todiltia schoewei* have been collected from the Pony Express Limestone (now Todilto Limestone) (Cross & Larsen, 1935, p. 40; Read et al., 1949; Schaeffer & Patterson, 1984). The general area is shown as locality 14 in Figure 21. The specific localities, in a forest and commonly on steep slopes at elevations of 8000-9000 ft (2439-2744 m), are not easily accessible.

Canyon City locality—Both *Todiltia schoewei* and *Hulettia americana* were found in the Ralston Creek Formation, Fremont County, Colorado, one year after their discovery at Bull Canyon, New Mexico (Schoewe, 1930). The specimens were identified by Dunkle (1942). The fish-bearing horizon in the Canyon City embayment (Locs. 1,

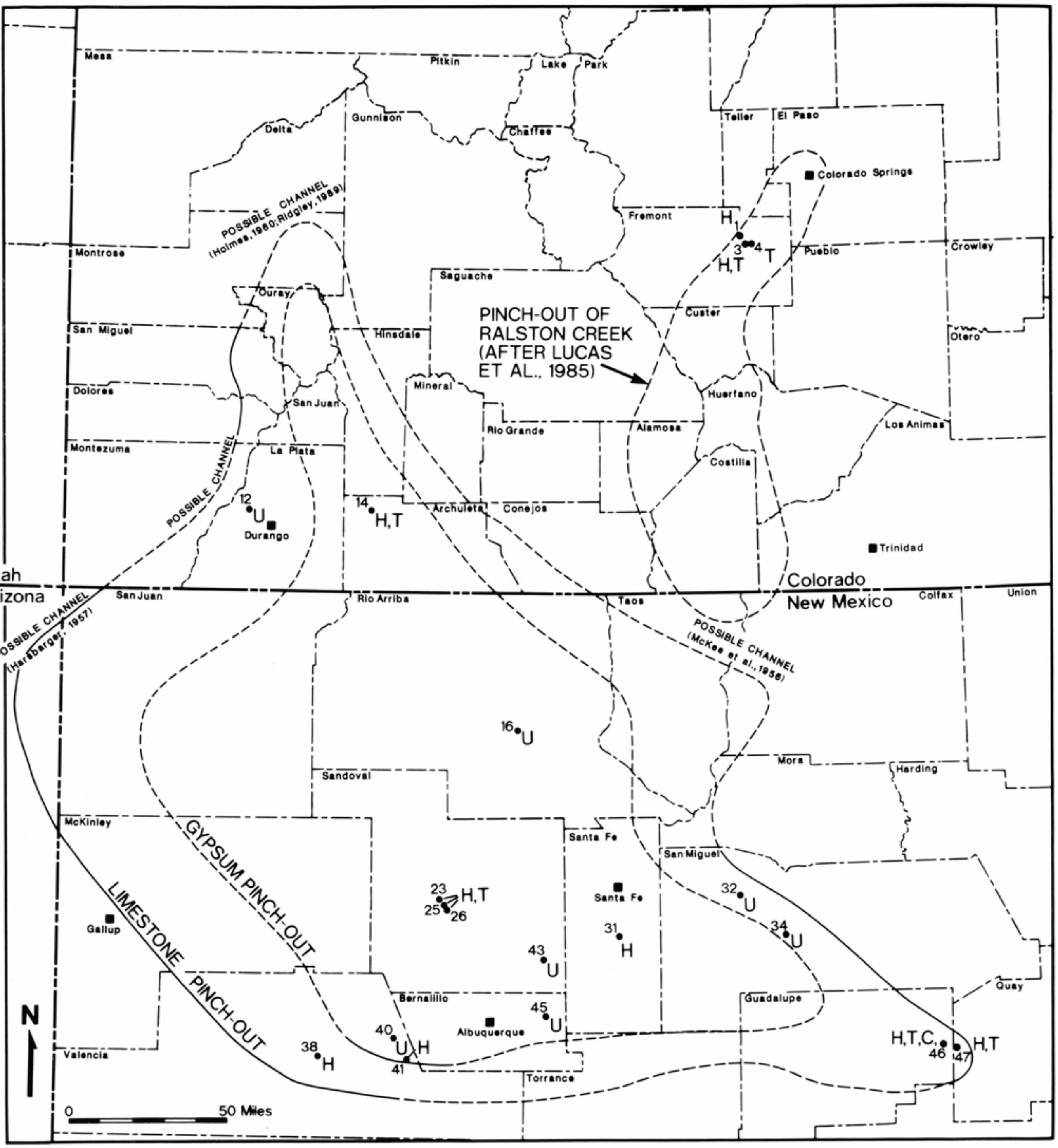

FIGURE 21—Fossil-fish localities, Todilto Limestone Member, northern New Mexico and southwestern Colorado: **47**, Schaeffer & Patterson, 1984; **46**, Koerner, 1930, Lucas et al., 1985, Schaeffer & Patterson, 1984; **45**, J. P. Bradbury, previously unreported; **43** and **40**, D. W. Kirkland, previously unreported; **38** and **41** (H), Northrop, 1961; **34**, Tanner, 1970; **32**, Baltz & Bachman, 1956; **31** (H), Colbert, 1950, Northrop, 1961; **23**, **25**, **26** (H, T), Bradbury & Kirkland, 1966; **16**, Tanner, 1970; **14**, Cross & Larson, 1935, Read et al., 1949; **12**, Eckle, 1949. Fish-fossil localities, Ralston Creek Formation, Fremont County, Colorado: **1** and **4**, Schultze & Enciso, 1983; **3**, Schoewe, 1930, Dunkle, 1942. H = *Hulettia americana*, T = *Todiltia schoewei*, C = *Caturus dartoni*, and U = genus and species indet.

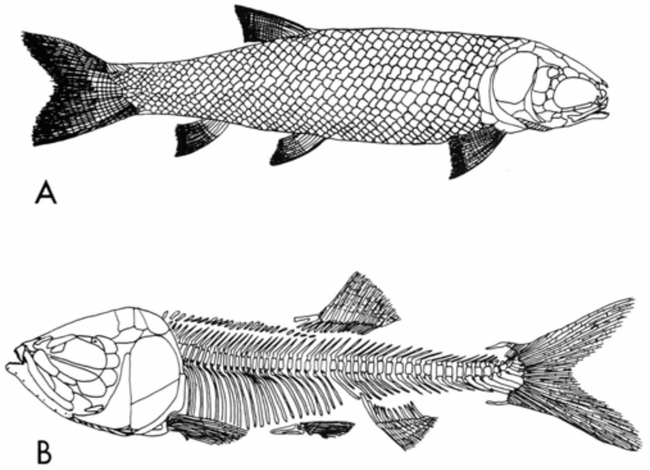

FIGURE 22—Restorations of (A) *Hulettia americana* and (B) *Todiltia schoewei* (after Schaeffer & Patterson, 1984).

3, and 4, Fig. 21) has been studied by Schultze & Encisc (1983). Plant remains were collected from the same horizon and in the vicinity of the fossil-fish locality. They are discussed in a following section.

As noted above, the nonmarine bivalve *Vetulonaia faberi* has also been found in the Ralston Creek Formation (Imlay, 1952), probably in the upper part. This species has also been found in the nonmarine Morrison Formation (Imlay, 1952) and in the upper member of the Wanakah (= Summerville) Formation in the Chama Basin, New Mexico (Ridgley, 1989).

Sundance localities—Hulettia *americana* and *Caturus dartoni* were found by N. H. Darton and described by Eastman (1899a, b) from the Canyon Springs Sandstone Member of the Sundance Formation near Hot Springs, South Dakota. *Hulettia americana* has since been reported from the Todilto, Ralston Creek, and Sundance Formations, whereas *Caturus dartoni* has been reported only from the Todilto and Sundance Formations. *(Todiltia schoewei is* known only from the Todilto and Ralston Creek Formations.) Darton (1899) found the fish in the "sandy layers" at the base of 21 ft (6.4 m) of green, sandy shale. Above the sandy shale is a limestone filled with *Ostrea,* and several feet below the shale is a red-bed sequence. The fossil fish probably occur in the upper part of the Canyon Springs Sandstone Member of the Sundance Formation (Schaeffer & Patterson, 1984), which along with the partly contemporaneous Stockade Beaver Member was deposited in shallow marine water (Imlay, 1980).

The primary collecting locality in the Sundance Formation is a laminated calcareous siltstone of the basal Stockade Beaver Member that unconformably overlies the Gypsum Springs Formation. The fossil-bearing siltstone is about 3 ft (0.91 m) thick and occurs about 6.5 mi (10.5 km) north of Hulett, Crook County, Wyoming (Schaeffer & Patterson, 1984), which is about 100 mi (161 km) northwest of Hot Springs, South Dakota. Of 800 fish specimens about 90% are *Hulettia.* Schaeffer & Patterson (1984) found no direct criteria to identify the habitat of the fish, but a massive siltstone directly above the fish zone contains marine pelecypods and *Lingula,* and the basal Stockade Beaver Member contains marine invertebrates to the north, south, and west of the fish locality.

Paleoecological deductions

By comparison with various European Jurassic assemblages, the Sundance fish assemblage may be regarded as marine (Schaeffer & Patterson, 1984, table 3). Two taxa from the Sundance fish assemblage *(Hulettia* and *Caturus)* are present in the Todilto Formation. Schaeffer & Patterson (1984) concluded that "there is reason for suggesting that these fishes entered the Todilto Basin from the western interior ('Sundance') sea." They further concluded that *Todiltia schoewei,* found in the Todilto and Ralston Creek but not in the Sundance, may have been a fresh-water form.

Lucas et al. (1985) argued that if the Todilto Basin were flooded by normal marine water, a normal marine fauna of fish and invertebrates would be expected. S. Northrop (pers. comm. 1963) used a similar argument. The restricted fish fauna and absence of normal marine invertebrates have been the primary evidence in support of a lacustrine origin. A restricted fish fauna could result, however, if the Todilto waterbody were connected by a channel with the Sundance Sea. This situation might have ensued if the salinity in an elongated strait were to progressively increase due to evaporitic conditions. The progressively increasing salinity in the channel and the adjoining embayment might have acted as a barrier preventing marine fish and invertebrates from migrating into the main part of the basin. Small numbers of marine forms might have drifted into the basin, however. Only if the Todilto Basin were to have had a channel analogous to that of the modern Karabogas-Gol (e.g. Dzens-Litovskiy & Vasil'yev, 1962), could large numbers of fish have been swept into the basin. Marine vertebrates and invertebrates would of course also have been prevented from entering the Todilto waterbody if the sea water seeped into the basin through sand of an Entrada dune field, an idea proposed by Lucas et al. (1985).

Hulettia americana and *Caturus dartoni* are closely associated with marine fossils, particularly near Hulett, Wyoming, and show affinity to marine Jurassic fish assemblages in Europe (Schaeffer & Patterson, 1984). Thus, although marine fossils have not been found on the same bedding planes as *Hulettia americana* and *Caturus dartoni,* these two species appear to have marine affinity and their presence gives considerable support to advocates of a marine origin of the Todilto Formation.

Fossil ostracodes

Original discovery

Swain (1946) described a new species of "nonmarine" ostracode, *Metacypris todiltensis,* from outcrops of the Todilto Formation 6 mi (9.7 km) north of Thoreau, New Mexico, adjoining state highway 56 (Loc. 36, Fig. 17). These small ostracodes occur only in the lower part of the Todilto Limestone and "primarily in the zone of intertonguing where they occur both in the limestone beds and in the intervening elastic layers" (Ash, 1958). Swain (1946) stated, "The species...is close to unisulcate representatives of M. *whitei* Jones (1886), from the Morrison formation of Colorado." *Metacypris* is known only from lacustrine sediments (Swain, 1946; Jones, 1956, p. 285). The genus *Metacypris* has since been synonymized with *Theriosynoecum* by Markhoven (1963). *Theriosynoecum* was considered by Sohn (1956) to be confined to the Morrison Formation, of which he probably considered the Todilto to be a basal member.

Additional discoveries

Since the original discovery of ostracodes at the Thoreau locality by R. H. Wilpolt and J. B. Reeside, Jr., specimens have been reported from five widely scattered localities (Fig. 17), all of them close to the pinchout of the Todilto Limestone. J. B. Reeside *(in* Bush et al., 1959) reported ostracodes from the Pony Express Limestone (now Todilto Limestone) along the Animas River. McCrary (1985) reported *Metacypris todiltensis* from outcrops of the Todilto Limestone along Trimble Lane, Durango, Colorado (Loc. 13, Fig. 17) (see her fig. 25), where they occur in the upper 2.5 —3.5 m of the unit. She stated that ostracodes also occur rarely in her informally designated "Crinkly and Upper Breccia" units of the Todilto Limestone near Las Vegas, New Mexico (Loc. 33, Fig. 17) and at the Poison Canyon Locality near Grants, New Mexico (Loc. 37, Fig. 17). We, too, have seen ostracodes at the latter locality (Fig. 23), and A. K. Armstrong (pers. comm. 1990) relates that other localities exist in the Grants area. Lucas et al. (1985) reported that several poorly preserved ostracodes were found in the Todilto at the Bull Canyon locality (Loc. 46, Fig. 17).

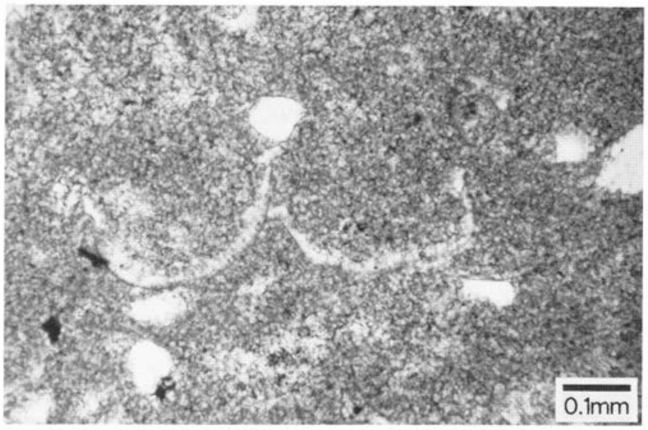

FIGURE 23—Thin section showing ostracode valves [*Theirosynoecum* (*Metacypris*) *todiltensis*] in nonlaminated calcite matrix with randomly distributed silt grains; Poison Canyon mine, McKinley County, New Mexico (sec. 30, T13N, R9W).

Paleoecological deductions

The ostracodes occur close to the shoreline of the Todilto waterbody during its maximum extent. All specimens may be the same species, but *Metacypris todiltensis* has been identified only from the Thoreau and Durango localities. M. *todiltensis* is similar to M. *whitei* from the Morrison Formation, which accumulated in a fluvial and fresh-water environment. This evidence suggests that M. *todiltensis* was a nonmarine form, but not necessarily from a lacustrine environment. All of the ostracodes have been found near the ancient shoreline, and if the waterbody were marine they may have lived in brackish water where streams or seepage freshened the surface water, or they may have been forms adapted to or tolerant of waters of higher salinity.

Plants

A single "highly corroded conifer pollen grain" was extracted by Ash (1958) from the Todilto Limestone near Toadlena, New Mexico. We found no palynomorphs in the basal calcareous shale at the primary insect locality. Ash, like Anderson & Kirkland (1960, fig. 2), found tracheids of vascular plants and plant fibers. The absence of palynomorphs is surprising. The Todilto Limestone in McKinley and Sandoval Counties, New Mexico, is apparently no more than thermally mature (Vincelette & Chittum, 1981), and pollen and spores, if present, would therefore not have been highly carbonized. Furthermore, the bottom water of much of the Todilto waterbody was probably anoxic, suggesting that wind- or water-borne palynomorphs would have been preserved. In shallow marine waters today, many palynomorphs reach the bottom as a result of being contained within fecal pellets. Nonetheless, repeated extractions of the limestone and calcareous shale samples from Sandoval County by the authors and by others have produced no well-preserved specimens.

An alga, apparently calcareous, was found by John R. Peters at Todilto Park north of Gallup, New Mexico (Northrop, 1961). This locality is near the pinchout of the Todilto Limestone. Some algal structures described from the Todilto (e.g. the "bioherms" of Perry, 1963) may be deformation features (see Rapaport et al., 1952, pp. 3841; Kirkland & Anderson, 1970). Algal oncolites occur in the Todilto (Pony Express) Limestone along the Animas River near Durango, Colorado (Kamin, 1968). They average about 2 cm in diameter. Kamin (1968) reported that they belong to the "concentrically stacked spheroid structural group" (see fig. 7). At her Trimble Lane locality, Durango, Colorado, McCrary (1985) found "digitate blue-green algal(?) stromatolites" in the lower part of the Todilto (Pony Express).

Dunkle (1942) found a gymnosperm cone (a strobilus, probably *Palissya)* in association with fossil fish in the Ralston Creek Formation, north of Canyon City, Fremont County, Colorado (Loc. 3, Fig. 2). Also in the Ralston Creek Formation several miles to the southeast of the fish localities, twig impressions of the conifer *Elatides williamsonia(?)* were reported by Frederickson et al. (1956). Palynomorphs were identified by Cramer (1962) from Locality 3, Figure 2. He identified *Classopolis* sp., *C. minor, Zonalapollenites dampieri, Monosulcites* sp., and *Caytonipollenites* sp.

In the Grants area, New Mexico, A. K. Armstrong (in manuscript) has found dasyclad algae in the Todilto Limestone (Anderson & Lucas, 1992). These green algae of the family Dasycladaceae are euryhaline and can live in fresh (<2 ppt), brackish, marine, and hypersaline water (Beadle, 1988).

Stable isotopes

Carbon

Ridgley & Goldhaber (1983) reported $\delta^{13}C_{PDB}$ measurements of 36 samples of Todilto Limestone calcite from north-central New Mexico to range from —2.5 to +1.7‰. We analyzed 19 samples of calcite from the Todilto Limestone Member in northwestern New Mexico (Fig. 24; Tables 1, 2), and the range of $8\ ^{13}C_{,B}$ values for our samples from —2.83 to +1.96‰, is similar to that reported by Ridgley & Goldhaber (1983). We also obtained a $\delta^{13}C_{CPB}$ value of —0.45 ‰ for a single sample of calcite from an abandoned gypsum quarry (Loc. 45, Fig. 2). Figure 24 shows the sample locations and Figure 25 is a frequency distribution of our $8\ ^{13}C_{pDB}$ values.

The mean $\delta^{13}C$ value for marine Jurassic limestones is +0.44 ‰ (standard deviation = 1.61 ‰; n = 21; Keith & Weber, 1964, table 1). The mean $\delta\ ^{13}C$ value for samples

TABLE 1—Carbon and oxygen isotopic values for Todilto Limestone Member from localities in northwestern New Mexico.

Locality	Location	$\delta^{13}C$‰	$\delta^{18}O$‰
17	21-25N-4E, Rio Arriba County	+0.44	−6.26
20	SWSWNW 32-23N-4E, Rio Arriba County	+0.21 +1.69	−7.14 −8.39
21	12-20N-1E, Sandoval County	+1.66	−7.94
23	NESE 26-17N-1W, Sandoval County	+1.01	−9.85
25	SESW 13-16N-1W, Sandoval County	+1.49	−5.87
26	SWSW 30-16N-1E, Sandoval County	+0.31	−9.81
29	NW 4-14N-7E, Santa Fe County	+1.09	−10.46
30	17-14N-7E, Rio Arriba County	−0.75	−6.09
33	SESE 16-15N-16E, San Miguel County	+1.15	−7.46
35	7-15N-16W, McKinley County	−0.29	−6.39
36	19-14N-12W, McKinley County	+1.53	−7.86
40	8-9N-3E, Valencia County	−1.20	−7.49
41	13-8N-3W, Valencia County	−1.64	−8.79
42	19-9N-2W, Valencia County	−1.21	−10.32
44	1-10N-5E, Bernalillo County	+0.59	−5.84
46	7-8N-27E, Quay County	−2.83	−9.35

of fresh-water Jurassic limestone is —3.59 ‰ (standard deviation, 1.75 ‰; n = 26; Keith & Weber, 1964, table 1). The mean of our data set is +0.04 ‰ (standard deviation = 1.46 ‰; n = 16). This value is well within one standard deviation of the mean δ "C value reported for *marine* Jurassic limestones. Ridgley & Goldhaber (1983) also reported that their values fall within the range for limestones deposited in marine environments. These data appear to support the argument put forth by Ridgley & Goldhaber, that isotopic data indicate a marine origin for the Todilto. But is this conclusion justified?

During precipitation of the Todilto gypsum, the Todilto waterbody was clearly hypersaline; it was probably hypersaline during the deposition of all but the earliest Todilto Formation. One possibility for the environment of the Todilto is that of a nonmarine hypersaline lake, and it is therefore important to ask if the limestone deposits of such a lake would be expected to show carbon-isotope values typical of fresh-water limestones (i.e. a range of $\delta\ ^{13}C_{PDB}$ of about —5.33 to —1.84 ‰). The answer seems to be no, because the hypersaline but nonmarine Pleistocene Lake Lisan, the precursor of the Dead Sea, the mean $\delta\ ^{13}C$ is —0.7‰, and 74% of 117 aragonite laminae have $\delta\ ^{13}C$ values that are more positive than a $\delta\ ^{13}C$ value of —1.85‰ (Katz et al., 1977, table 2), which is one standard deviation greater than the mean for Jurassic freshwater limestones. Without other evidence, had these values been interpreted as the Todilto data have been by Ridgley & Goldhaber (1983) (using an observed range of $\delta\ ^{13}C$ values for limestones deposited in marine environments), the sediments of Lake Lisan would be called *marine*, whereas in fact they are believed to be nonmarine (Begin et al., 1974; Katz et al., 1977). With this in mind, we can ask what processes could have occurred to produce the quasi-marine $\delta\ ^{13}C$ values for carbonates deposited from a nonmarine or not exclusively marine (but not fresh-water) Todilto waterbody, if such were the case.

If the waterbody were exclusively nonmarine and hypersaline, or if it were originally marine but modified by persistent inflow of fresh water so that the ultimate ratio of fresh to saline water was very high, the $\delta\ ^{13}C$ values of the limestone would probably not be typical of Jurassic fresh-water limestones. The $\delta\ ^{13}C$ values would probably be more positive than Jurassic fresh-water limestones and might mimic Jurassic marine $\delta\ ^{13}C$ values. Some possible reasons are:

1. The drainage basin from which streams discharged into the Todilto waterbody was probably largely a desert. If this were so, the Todilto waterbody would have received sparse stream-borne humus, which in the Jurassic had a $\delta\ ^{13}C$ value of about —26‰ In lakes, oxidation of humus is a major source of dissolved inorganic carbon. With a minor contribution of this source of isotopically light carbon, the $\delta\ ^{13}C$ of Todilto limestone, if indeed it were deposited from lacustrine waters, might have tended to mimic marine values more closely than if humus had been in abundant supply.
2. Precipitation of calcium carbonate in the Todilto waterbody may be described as follows:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_{2(g)} + H_2O$$

Several factors may have been responsible for removing carbon dioxide from the Todilto waterbody, thereby effecting precipitation of calcium carbonate. One was an increase in the temperature of surface waters during the summer, an increase that would have resulted in loss of carbon dioxide to the atmosphere. As carbon dioxide was removed, for each mole of carbon dioxide thus exsolved one mole of calcium carbonate precipitated. The net effect of this process would have beer to preferentially remove ^{12}C from the solution (as the CO_2 evolved) and to concentrate ^{13}C in the remaining $^-$bicarbonate species (Deines et al., 1974), because the isotopic fractionation between HCO_3^- and $CO_2(g)$ is considerably larger (-8.8 ‰) than that between $HCO_3^-$and $CaCO_3$ (+2.0‰) (see figure 7 of Hayes et al., 1990).

3. Photosynthesis would have also removed carbon dioxide (or bicarbonate) from the Todilto waters. As Evans & Kirkland (1988) have shown, hypersaline waters commonly support prolific algal growth. Based on earlier discussion, this appears to have been true of the Todilto surface waters during carbonate deposition. During photosynthesis by algae, carbon dioxide or bicarbonate ions containing ^{12}C would have been favored for fixing as tissue. As a result, carbonate species remaining in the Todilto waters would have become enriched in ^{13}C.
4. Kinetic isotope effects during possible exsolution would favor $^{12}CO_2$ loss and ^{13}C enrichment (Deines et al., 1974). This is because $^{12}CO_2$ is slightly more active than

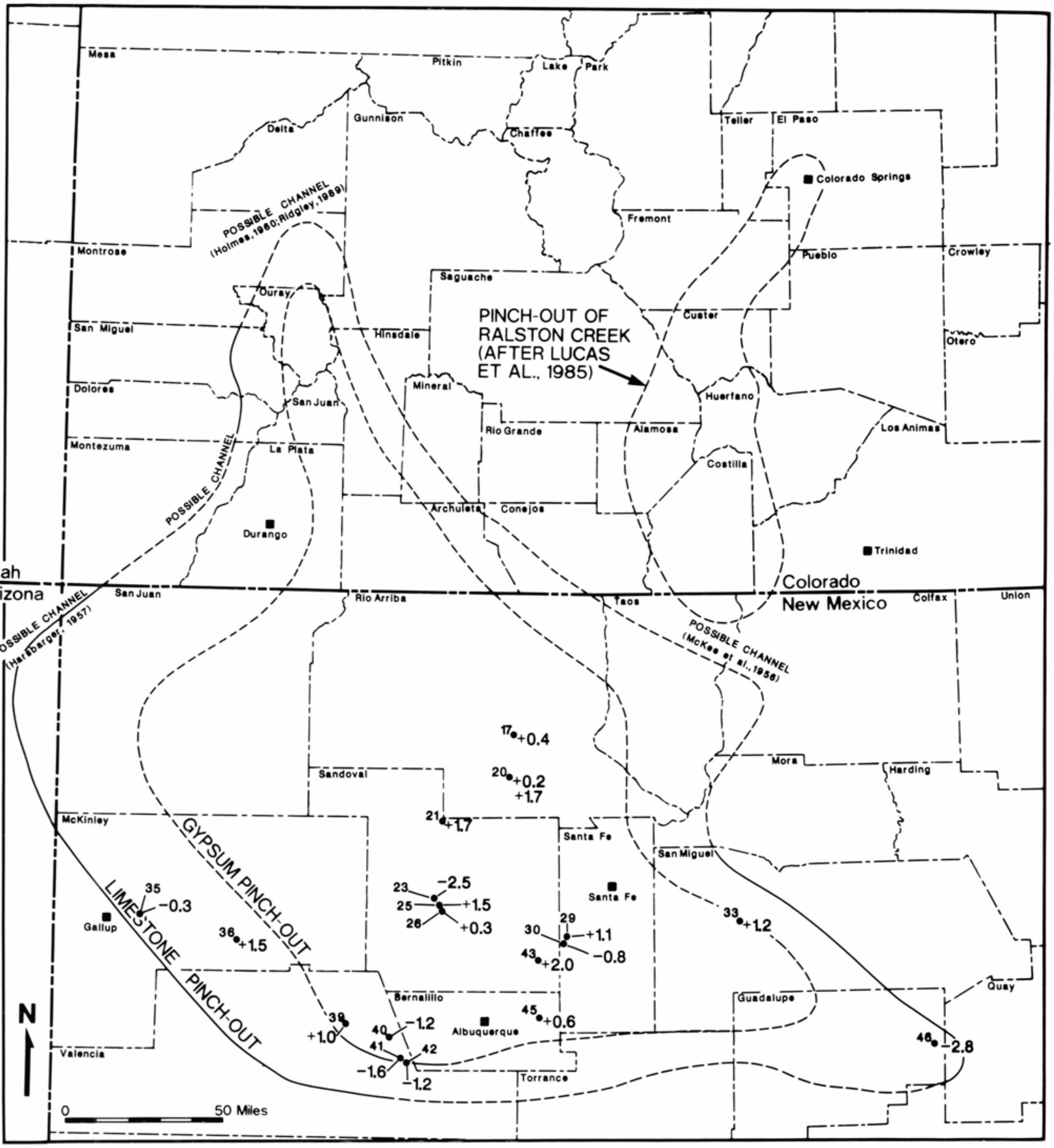

FIGURE 24—Localities sampled for carbon isotope values ($\delta^{13}C_{PDB}$‰) in the Todilto Limestone Member, northern New Mexico.

$^{13}CO_2$. This effect, however, would have probably been small relative to the effect of photosynthesis (Usdowski & Hoefs, 1990).

In summary, the carbon-isotope data cannot be used with confidence to infer a marine origin for the Todilto Limestone even though the range of $\delta^{13}C$ values is similar to that of Jurassic marine limestone. This is because several processes could have been at work in a nonmarine hypersaline waterbody, or in a mixed fresh-water/marine hypersaline waterbody, to drive the $\delta^{13}C$ values toward those of Jurassic marine limestones. Even if the Todilto waterbody were to have received only (or largely) fresh water, the Todilto $\delta^{13}C$ values cannot be expected to match values of Jurassic fresh-water limestones because of the effect of these and possibly other processes (Lazar & Erez, 1992).

Strontium

Introduction

Wickman (1948) was the first to suggest that the $^{87}Sr/^{86}Sr$ ratio of sea water had varied with time and that the variation would be recorded in precipitated calcium-bearing minerals. Measurements on ancient marine carbonates during the 1950s showed that the isotopic variation was smaller than Wickman had predicted, and it was not until development of high-resolution mass spectrometers in the 1960s and 1970s that the variation of $^{87}Sr/^{86}Sr$ ratio of sea water during the Phanerozoic could be defined (Burke et al., 1982).

TABLE 2—Strontium isotopic data from the Todilto and Ralston Creek Formations.

Locality number	Sample number	Locality name	Location	County, state	Δsw	Sample type, remarks
2	2943	Hwy 115	NESE 26-17S-68W	Fremont, CO	–112.5±2.4	Gypsum
3	8655	Canyon City	NENW 26-17S-70W	Fremont, CO	–18.0±3.1	Dolomite
4	8654	Canyon City	SW 26-17S-70W	Fremont, CO	–44.6±2.2	Gypsum
5	8656	Canyon City (Indian Springs)	SE 7-18S-69W	Fremont, CO	–189.2±1.9	Gypsum
	2942				–110.2±1.0	Gypsum
6	8657	Canyon City	NENW 32-18S-70W	Fremont, CO	–28.6±2.0	Limestone
7	8623	Black Canyon	NWNE 20-49N-6W	Montrose, CO	+48.9±3.8	Limestone
8	8626	Placerville	14-44N-11W	San Miguel, CO	–116.6±3.3	Limestone
9	10244	Ouray	NE 12-44N-8W	Ouray, CO	–57.1±6.0	Limestone breccia
	10245				–53.5±3.0	Limestone, laminated
10	8624	Ouray	8-23N-7W	Ouray, CO	+149.9±1.0	Limestone
11	8625	Telluride	8-43N-10W	San Miguel, CO	–132.9±3.9	Limestone
15	10239	Piedras River	NW 19-35N-4W	Archuleta, CO	–121.6±2.3	Limestone breccia, 5 ft above base
	10240				–132.2±2.6	Limestone breccia, near top
	10241				–129.6±3.1	Limestone breccia
	10242				–111.2±2.5	Limestone, laminated, 3.5 ft above base
	10243				–76.1±3.8	Limestone, laminated, 0.5 ft above base
16	10236	Ghost Ranch north	NW 27-25N-4E	Rio Arriba, NM	–154.3±2.5	Limestone, laminated, 3.5 ft above base
	10237				–156.4±1.4	Gypsum, near middle
	10238				–131.1±1.3	Gypsum, near top
17	8621	Ghost Ranch south	21-25N-4E	Rio Arriba, NM	–181.2±2.4	Gypsum
	8633				–154.9±2.1	Limestone
18	8627	Gallina	SE 8-23N-1E	Rio Arriba, NM	–167.0±3.1	Limestone, laminated
	10228				–186.7±1.0	Limestone, laminated, 2.2 ft above base
	10229				–160.9±1.4	Gypsum, nodular
	10232				–123.1±1.3	Gypsum, lower
	10231				–186.9±1.8	Gypsum, middle
	10230				–183.4±1.3	Gypsum, upper
19	8640	Mesa Alta	15-23N-2E	Rio Arriba, NM	–224.7±3.0	Gypsum
20	10234	Youngsville	SWSWNW 32-23N-4E	Rio Arriba, NM	–174.7±2.8	Limestone, 2.2 ft above base
	10235				–168.9±2.8	Limestone breccia
	10222				–173.0±2.0	Limestone breccia
	8634				–155.2±2.4	Limestone
	8639				-191.1±2.4	Gypsum
	10233				–147.2±1.1	Gypsum, middle
	10221				–132.6±2.1	Gypsum, top
21	8631	Señorita, mine site	12-20N-1W	Sandoval, NM	+365.4±3.2	Limestone
	8620				–29.7±4.1	Gypsum
	9898				–79.9±2.0	Gypsum
22	10227	Señorita, south	SESE 2-20N-1W	Sandoval, NM	–189.5±3.4	Limestone, laminated

TABLE 2—continued

Locality number	Sample number	Locality name	Location	County, state	Δsw	Sample type, remarks
24	10224–1	Warm Springs	NESE 26-17N-1W	Sandoval, NM	–182.6±2.4	Limestone, laminated, base
	10224–2				–174.2±1.0	Limestone, laminated, top
	9899				–225.0±2.0	Limestone, 1.4 ft above first gypsum nodules
	9899–1				–215.7±1.8	Gypsum, 1.4 ft above first gypsum nodules
	9899–2				–214.3±2.3	Gypsum, 2.2 ft above first gypsum nodules
	9899–3				–223.0±2.5	Gypsum, 3.6 ft above first gypsum nodules
	10224				–168.1±1.4	Gypsum, lower
	10225				–140.1±1.9	Gypsum, middle
	10226				–157.8±1.6	Gypsum, upper
25	2099	Warm Springs, south	NESW 13-16N-1W	Sandoval, NM	–180.5±0.8	Limestone, 1–2 inches above base
26	8636–1	Warm Springs	SWSW 30-16N-1E	Sandoval, NM	–169.2±1.5	Limestone
	8636–2				–157.9±2.1	Limestone
27	8618	White Mesa		Sandoval, NM	–181.7±2.2	Gypsum
28	10219	Kaiser quarry, west	NW 5-14N-7E	Santa Fe, NM	–169.5±1.6	Limestone, 1.5 ft above base
	10220				–186.5±1.8	Gypsum, base
	10218				–186.8±2.2	Gypsum, middle
	10217				–157.1±2.0	Gypsum, top
29	8638	Kaiser quarry	4-14N-7E	Santa Fe, NM	–168.4±2.5	Gypsum
30	8635	Gallisteo dam	17-14N-7E	Rio Arriba, NM	–89.3±1.4	Limestone
33	10214	Romeroville	SESE 16-15N-16E	San Miguel, NM	–170.1±0.9	Limestone, laminated, 2–3 ft above base
	10215				–168.7±3.1	Limestone, laminated, 3–4 ft above base
	10216				–127.0±2.5	Limestone, laminated, 4–5 ft above base
	10213				–174.7±3.2	Limestone, 8 ft above base
	10212				–174.6±2.3	Limestone breccia, top
35	2100	Gallup	7-15N-16W	McKinley, NM	–125.7±3.6	Limestone, 1–2 ft above base
36	8630	Thoreau	19–14N-12W	McKinley, NM	–173.5±2.3	Limestone
37	8628	Poison Canyon	30-13N-9W	McKinley, NM	–177.2±2.8	Limestone
	8629				–187.4±5.9	Limestone
40	2096	Microfold	8-9N-3E	Valencia, NM	–188.6±4.4	Limestone
41	8632	Suwannee Peak	13-8N-3W	Valencia, NM	–62.8±2.0	Limestone
42	2098	Mesa Redondo	19-9N-2W	Valencia, NM	–171.6±4.8	Limestone, 2–3 ft above base
43	10203	Tonque Arroyo	SW 1-13N-5E	Sandoval, NM	–171.4±1.5	Limestone, 2 inches above base
	10204				–163.7±2.9	Limestone, 3.5 ft above base
	9900–1				–183.4±2.1	Limestone, 5.1 ft above base
	9900–2				–170.9±1.9	Limestone, 5.6 ft above base

TABLE 2—continued

Locality number	Sample number	Locality name	Location	County, state	Δsw	Sample type, remarks
	9900–3				–166.8±2.0	Limestone 6.0 ft above base
	2094				–225.2±2.2	Gypsum, near base of Gypsum Member
	8637				–209.7±1.6	Gypsum
	10205				–163.7±1.4	Gypsum, 6.5 ft above base of formation
	9900–4				–168.2±2.4	Gypsum, 6.8 ft above base of formation
	9900–5				–166.7±2.2	Gypsum, 7.3 ft above base of formation
	10206				–186.9±2.1	Gypsum, 14 ft above base of formation
	10207				–164.2±2.0	Gypsum, 52 ft above base of formation
	10208				–168.6±2.7	Gypsum, 72 ft above base of formation
	10211				–185.0±2.1	Gypsum, 15 ft below top of formation
	10209				–181.0±2.2	Gypsum, 14 ft below top of formation
	10210				–153.4±2.5	Gypsum, exposed top of formation
44	2097	Placitas	34-13N-5E	Sandoval, NM	–204.7	Gypsum
45	8622–1	Tijeras	1-10N-5E	Bernalillo, NM	–224.8±4.6	Gypsum
	8622–2				–114.0±2.4	Limestone
46	8619	Bull Canyon	7-8N-27E	Quay, NM	–188.5±3.3	Limestone

The oceans carry an enormous amount of isotopically well-mixed strontium, which is removed when calcium-bearing carbonates, phosphates, and sulfates are precipitated. Depending on the mineral phase, strontium substitutes for calcium usually in the range of 100-10,000 ppm. The mineral phases contain strontium with the same isotopic ratio as sea water and, if the system remains closed, this ratio will remain unchanged in the mineral throughout subsequent geologic time.

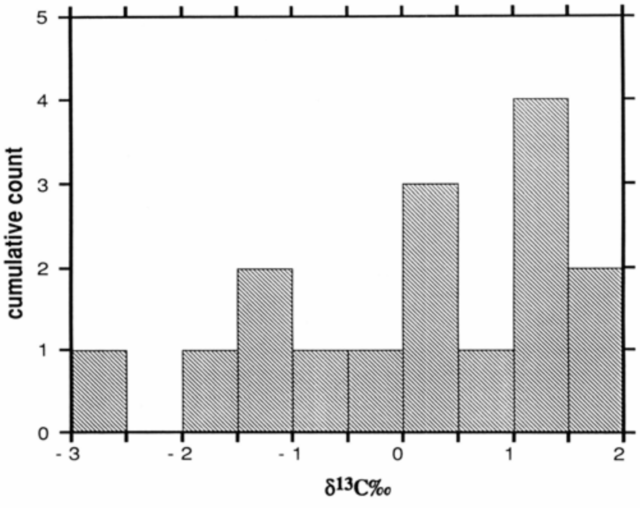

FIGURE 25—Distribution of carbon isotopic values ($\delta^{13}C_{PDB}$) in samples of limestone from Todilto Limestone Member (various localities in northern New Mexico, see Table 1) .

The ^{87}Sr/^{86}Sr ratio in sea water varies because strontium is constantly being added to the oceans from two major sources, each of which has an ^{87}Sr/^{86}Sr ratio different from that of sea water. Rivers contain small amounts of dissolved strontium derived from weathering of rocks exposed on continents, and this strontium has an ^{87}Sr/^{86}Sr ratio substantially *higher* than that of sea water. The other source is basalt, found mainly in oceanic basins. Basaltic rocks contain strontium with an ^{87}Sr/^{86}Sr ratio substantially *lower* than that of sea water, and this is added through submarine alteration of these rocks and volcanic activity. The change of the ^{87}Sr/^{86}Sr ratio of the oceans at a given time depends on which of the two sources predominates. When continental sources dominate, the ^{87}Sr/^{86}Sr ratio in sea water rises, and when oceanic sources dominate, the ^{87}Sr/^{86}Sr ratio falls. A more complete discussion of the factors controlling strontium in sea water is given by Veizer (1989).

If the present-day ^{87}Sr/^{86}Sr of a calcium-bearing sedimentary mineral is not the same as sea water of an equivalent age, the cause is either that the original ^{87}Sr/^{86}Sr ratio in the mineral phase has been diagenetically altered or that the strontium-bearing phase was not precipitated from well-mixed open-ocean water. Because the parameters that affect the $^{87}Sr/^{86}Sr$ ratio are well defined, it is possible to quantitatively evaluate the effect of the different strontium contributors and of the alteration processes.

Methods

Strontium was separated from samples using the precipitation technique of Otto et al. (1988). Gypsum samples were dissolved in water, filtered, converted to $CaCO_3$, and then dissolved in nitric acid for separation. Isotope ratios were measured using a second-order, double-focusing Nier-Johnson type mass spectrometer with a 60°, 13 inch (-33 cm) radius of curvature magnetic sector and a 91°, 15.8 inch (-40.8 cm) radius of curvature electric section. Masses 85, 86, 87, and 88 were collected simultaneously in separate Faraday cups (Burke & Hetherington, 1984). The isotope ratios were measured by comparison to the standard NBS/SRM987, for which a ratio of 0.71014 has been assumed. The $^{87}Sr/^{86}Sr$ values have been normalized to $^{87}Sr/^{86}Sr = 0.1194$ and corrected for any contribution by ^{87}Rb. The ratios are reported as the difference from modern sea water.

$$\Delta sw = ({}^{87}Sr/{}^{86}Sr_{\text{unknown}} - {}^{87}Sr/{}^{86}Sr_{\text{sea water}}) \times 10^{5}$$

Our weighed mean of modern sea water $^{87}Sr/^{86}Sr = 0.709073 \pm 3$ is based on more than 100 measurements of modern shells. The Δsw for the assumed value of NBS/ SRM987 is +106.7 ± 0.3.

Isotopic values for the Todilto and Ralston Creek samples

We have made 85 strontium isotopic measurements (Table 2) on samples of Todilto limestone (Fig. 26) and Todilto gypsum (Fig. 27) collected from 21 localities in Colorado and New Mexico, and six measurements (Table 2) on samples of Ralston Creek dolomite and limestone (Fig. 26) and Ralston Creek gypsum (Fig. 27) from five localities in Fremont County, Colorado. The strontium isotopic values show a large variation even for samples from a single locality but, with the exclusion of several anomalous values in the vicinity of mines, the set of carbonate samples has a distinct mode at a Δsw of about -170 (Fig. 28) and the set of sulfate samples a distinct mode at Δsw of about -190 (Fig. 29).

Factors influencing the isotopic ratio of Todilto limestone and gypsum

In order to approximate the proportion of marine water to the proportion of riverine water that entered the Todilto Basin during deposition of the Limestone Member, it is necessary to determine or to approximate the parameters controlling the $^{87}Sr/^{86}Sr$ ratio during carbonate and sulfate deposition. These are: (1) The isotopic composition and concentration of strontium in sea water during Todilto time, and (2) the isotopic composition and concentration of strontium in riverine water that drained into the Todilto waterbody.

Concentration and isotopic ratio of strontium in Middle Jurassic sea water—There is no direct or reliable method of determining the concentration of strontium in Middle Jurassic ocean water. Modern seas contain nearly 8 ppm strontium on average and there is no reason to believe that the concentration of strontium in sea water was not between 6 ppm and 12 ppm throughout the Mesozoic and Cenozoic. We can, however, estimate the strontium isotopic values of sea water during Todilto time. As discussed above, paleontological and stratigraphic data indicate that the Todilto was deposited during a 30-100 ka interval within the period between 157 and 161 Ma. The best line for the $^{87}Sr/^{86}Sr$ ratio during the Callovian/latest Bathonian interval (Koepnick et al., 1990; Jones et al., 1994) indicates a Δ sw value of about -220 to -233.

Our lowest strontium values, in samples from the gypsum facies, are close to Δsw -225. These values are in accord with a Callovian age of the Todilto. There is some uncertainty as to the exact path of sea water $^{87}Sr/^{86}Sr$ during the Jurassic, and it is probably more prudent to claim that the lowest measured Todilto values, those near Δsw -225, give an age that is in agreement with the best paleontological age of samples used to determine the range of Asw values for Oxfordian, Callovian, and Bathonian sea water.

Concentration and isotopic ratio of strontium in Todilto riverine water—Neither the isotopic composition nor the concentration of the riverine-strontium contribution to Todilto waters can be determined directly. There is, however, a good understanding of strontium in modern rivers, which can be used to constrain guidelines for modeling Todilto water mixing. Palmer & Edmond (1989), in a synthesis of their own work and that of others, conclude that the mean of strontium entering oceans in river water is Δsw +270, a value that is more radiogenic than previous estimates of Δsw +190 from Wadleigh et al. (1985) and of Δsw +88 from Goldstein & Jacobsen (1987). While the use of the weighted mean of all riverine waters is valuable in some modeling, the actual range of values is great, and because the value of the weighted mean is controlled more by the contribution from the world's largest rivers, its use in attempting to understand waters in the small Todilto Basin is probably limited.

The concentration of strontium in riverine waters varies considerably, from 3 ppm (3000 ppb) to 6 ppb (Palmer & Edmond, 1989; Goldstein & Jacobsen, 1987; Wadleigh et al., 1985). Most data indicate that as the concentration of dissolved strontium increases, the $^{87}5r/^{86}Sr$ ratio decreases. With such a large range in both concentration and isotopic ratio, no single set of values for riverinestrontium input can be defended. Therefore, we modeled the mixing using three sets of values based on modern-river data: the modern mean, the least radiogenic, and the most geologically reasonable. The results from the mixing model vary widely, but they nevertheless all point to the same conclusion.

The emergent area surrounding the Todilto saliva must have been quite low. Mesozoic and Paleozoic sedimentary rocks and some Precambrian rocks formed the surface, which was probably drained by relatively small rivers and streams, many of them probably ephemeral. This geologic setting constrains the modern-river analogy for modeling the Todilto mixing; for example, data from rivers draining a Precambrian shield or a modern volcanic field are inappropriate. Goldstein & Jacobsen (1987) reported that drainages within interior lowlands contain between 55 and 350 ppb strontium with an isotopic composition between Δsw +70 and +200. This is the most reasonable range for modeling Todilto mixing.

As Figure 30 shows, the concentration of Sr has a profound effect on the calculation of riverine input. What if there were a contribution from a riverine system drain-

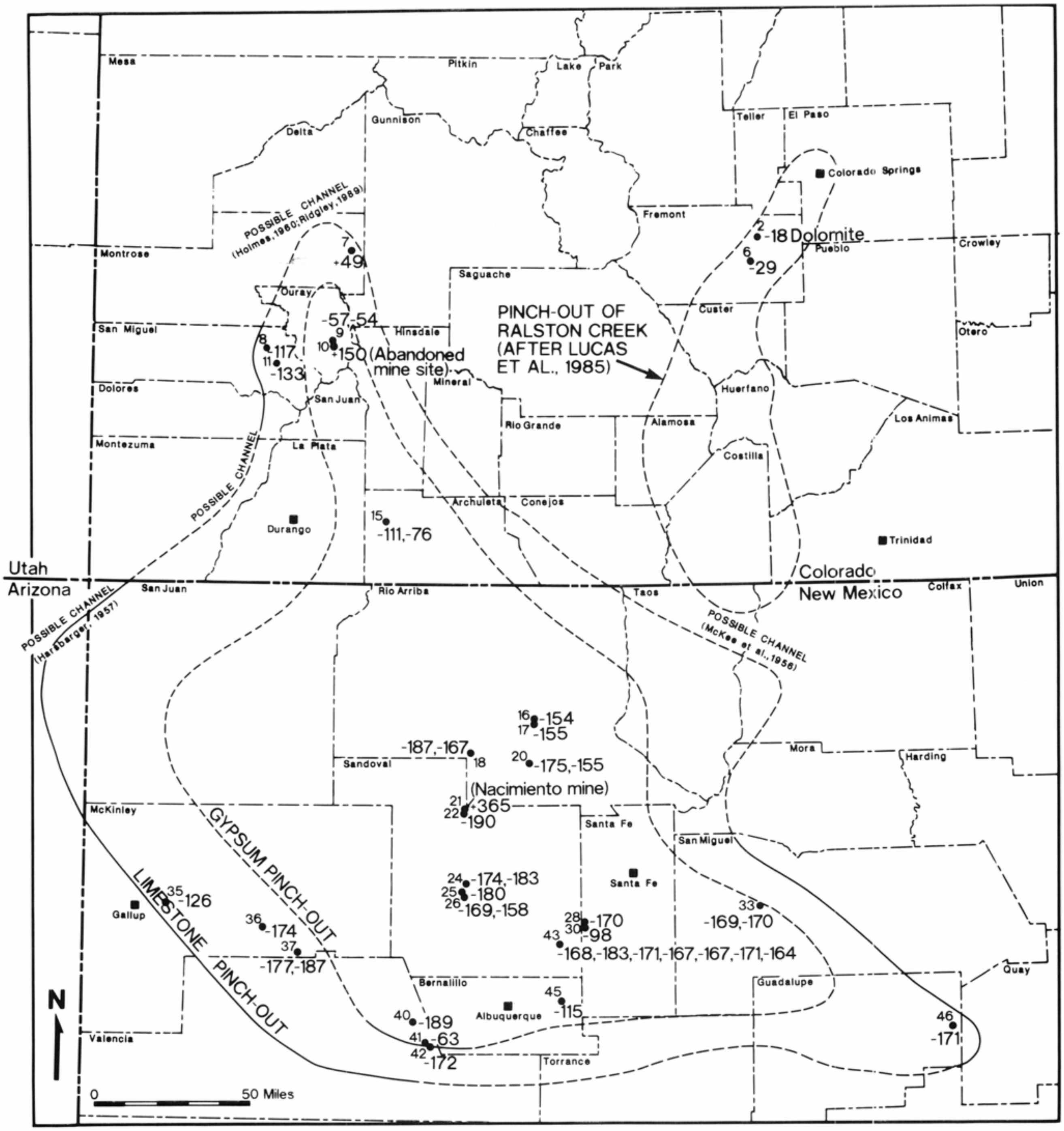

FIGURE 26—Localities sampled for strontium isotopic values ($^{87}Sr/^{86}Sr$) in the Todilto Limestone Member of northern New Mexico, and dolomite and limestone in the Ralston Creek Formation, Fremont County, Colorado.

ing an extensive evaporite sequence? Upper Permian evaporites may have been exposed in west Texas and southeastern New Mexico during Todilto deposition (see McKee et al., 1956). Substantial dissolution of these evaporites and transportation of their strontium to the salina would have had a curious effect: it would make the resulting $^{87}Sr/^{86}Sr$ values appear more marine. Upper Permian evaporites have $^{87}Sr/^{86}Sr$ values that are mostly within the range of Todilto sea water (Brookins, 1988; Denison et al., 1994), so that any contribution would be indistinguishable from a marine Jurassic signal. Therefore, a contribution from erosion of Upper Permian evaporites can be neither demonstrated nor precluded. In either case, Sr isotope results from Todilto samples record a *net* difference that is more radiogenic than contemporaneous (Middle Jurassic) sea water.

Alteration of isotopic ratio by hydrothermal waters—The effect of radiogenic strontium contributed by hydro-thermal waters is singularly illustrated by the strontium isotopic values of limestones samples in the vicinity of the Nacimiento copper mine (Loc. 21, Fig. 26) and of the abandoned gold—silver mine (Loc. 10, Fig. 26). Here Asw values are much higher than in samples from other Todilto localities because of the addition of radiogenic strontium during mild alteration of the Todilto by hydrothermal fluids associated with mineralization.

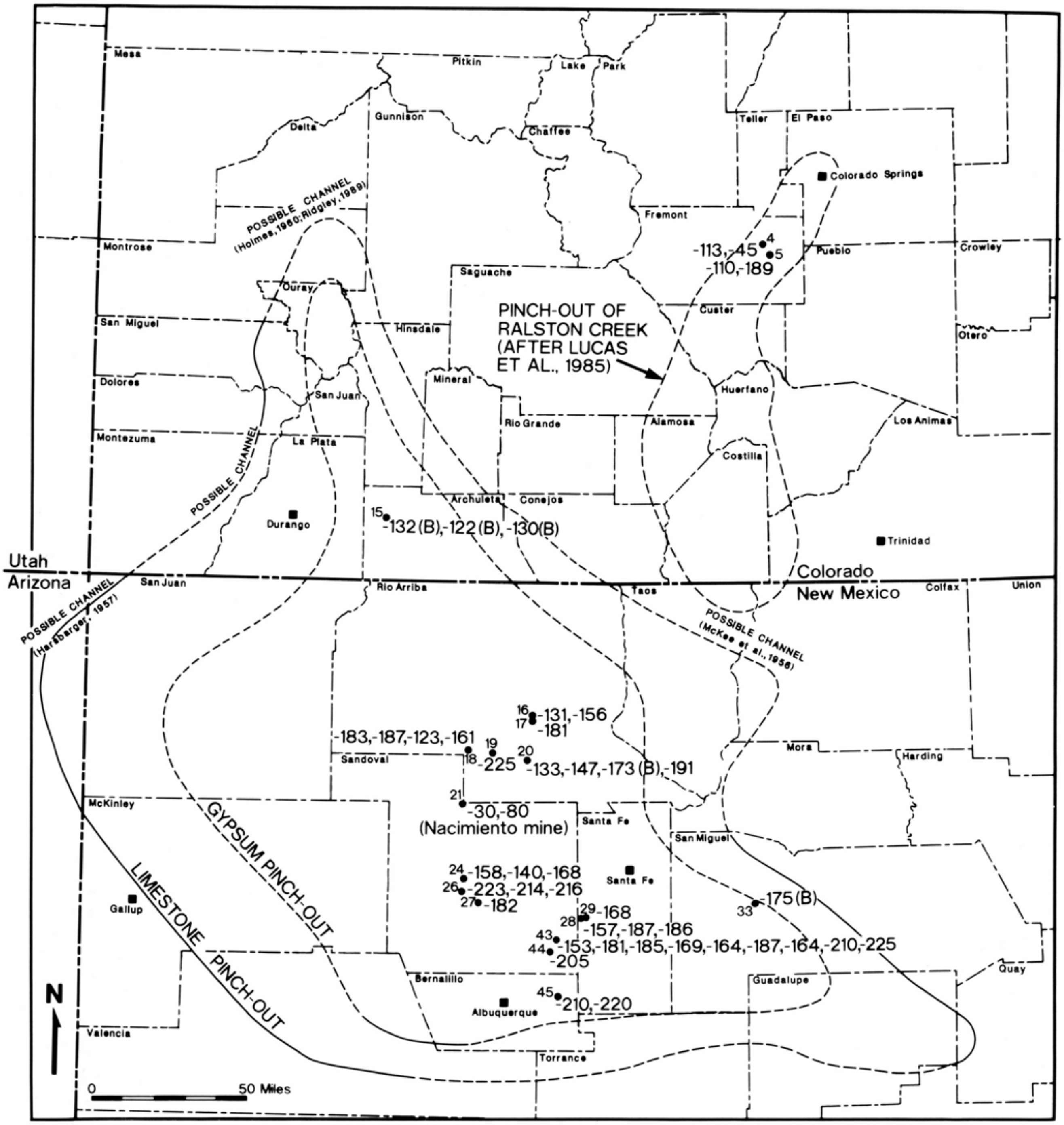

FIGURE 27—Localities sampled for strontium isotopic values ($^{87}Sr/^{86}Sr$) in the Todilto Gypsum Member of northern New Mexico and gypsum in the Ralston Creek Formation, Fremont County, Colorado.

The Δsw value of +365 in the limestone from the vicinity of the Nacimiento mine, if confirmed, would indicate that mineralization occurred in post-Middle Jurassic rather than Triassic as suggested by Woodward et al. (1974). The values for samples of Todilto gypsum in the vicinity of the mine (Δsw -30 and -80) (Loc. 21, Fig. 27) are also higher than expected, as is the $\delta^{34}S$ value of a sample of gypsum (+17.7‰) (Loc. 21, Fig. 2) from near the mine site. The localization of the anomaly is shown by results from a sample of limestone collected immediately south of the mine (Loc. 22, Fig. 26), which has a Δsw value of -190.

In addition to the limestone sample from near the gold silver mine (Loc. 10, Fig. 26), the remaining seven samples of Todilto limestone from southwestern Colorado have Δsw values that are more positive than expected for marine limestone of Callovian age. During Cretaceous and Tertiary times, Jurassic strata of the San Juan Mountains and vicinity were subjected to the intense mineralization characteristic of this area. Is it probable that during this mineralization the Todilto limestone incorporated radiogenic strontium? Probably not. The amounts of radiogenic strontium needed to be imported and indigenous strontium needed to be exported from the system are implausibly large in our opinion. Radiogenic strontium from igneous and hydrothermal

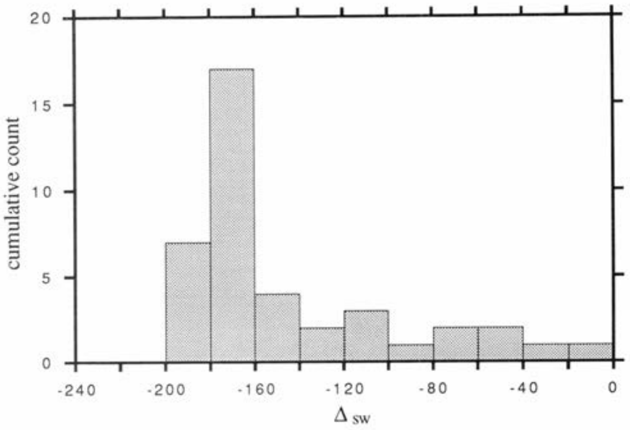

FIGURE 28—Distribution of strontium isotopic values ($^{87}Sr/^{86}Sr$) in samples of limestone from the Todilto Limestone Member (various localities in northern New Mexico and southwestern Colorado, see Table 2).

sources may have a profound local effect, but is unlikely to cause regional changes.

Application of the mixing model

The $^{87}Sr/^{86}Sr$ ratio of the Todilto waterbody changed over time with addition of riverine strontium of differing concentrations and isotopic composition. When all variables are considered, the mixing ratios show a relatively small spread. The sample localities and the strontium isotopic values for samples of Todilto limestone are shown in Figure 26. Most of the values center around Δsw -170 (Fig. 28). In order to raise the Δsw of the Todilto waterbody from -225 to -170, between 5 and 21 volumes of riverine water with values of modern interior drainage would be required for each volume of marine Todilto water originally in the basin (Fig. 30). If we perform the same calculation but use the mean value of strontium concentration for all modern-river input, and use the most radiogenic estimate of Palmer & Edmond (1989), 18 volumes of river water would be needed for each unit volume of marine water (Fig. 30). Substitute the less radio-genic mean estimates of Wadleigh et al. (1985) and Goldstein & Jacobsen (1987), and we find that between 15 and 28 river volumes would be needed (Fig. 30). This assumes normal salinity and normal strontium concentration during initial limestone deposition, both of which then increased progressively and correspondingly to a maximum during gypsum deposition. The increase in salinity requires a higher riverine input to cause the same isotopic shift. Since 7 out of 40 of the $^{87}Sr/^{86}Sr$ values for Todilto limestone samples are higher than Δsw -170 (Fig. 28), even higher volumes of fresh water would have been required.

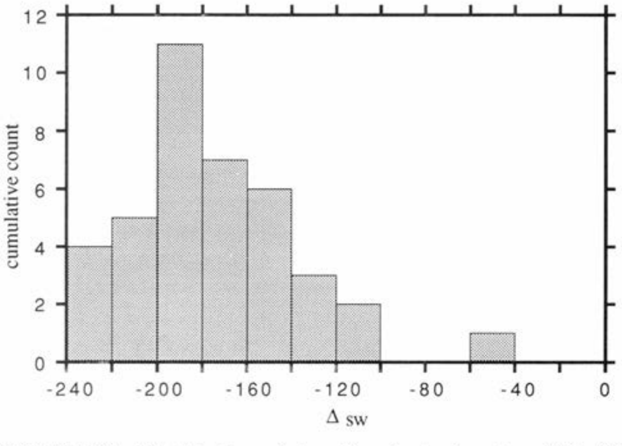

FIGURE 29—Distribution of strontium isotopic values ($^{87}Sr/^{86}Sr$) in samples of gypsum from the Todilto Gypsum Member (various localities in northern New Mexico, see Table 2).

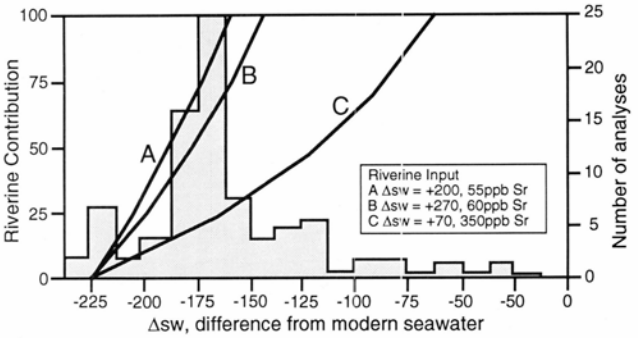

FIGURE 30—Histogram showing distribution of $^{87}Sr/^{86}Sr$ ratios (as the difference from modern sea water) in Todilto limestone and gypsum. Superimposed are mixing lines for various strontium contributions from Jurassic riverine sources into contemporaneous sea water saturated with respect to gypsum. The "Riverine Contribution" (y-axis) is expressed as unit volumes of river water to unit volume of sea water. **Line A** represents the most radiogenic model for interior drainages (Δsw +200, Sr concentration 55 ppb), a model that would require about 76 volumes of river water for every unit volume of sea water in order to raise the Δsw from a base of Jurassic gypsum-saturated sea water to a value of –175. **Line B** uses the weighed mean values of modern rivers (Palmer & Edmond, 1989) of 60 ppb Sr with a Δsw of +270 and shows that about 58 volumes of river water would be needed for every unit volume of sea water in order to raise the Δsw to –175. **Line C** is the least radiogenic case for interior drainages (Δsw +70, Sr concentration 350 ppb), a case that would require about 18 volumes of river water for every volume of gypsum-saturated Jurassic sea water in order to raise the Δsw to –175. Data from modern interior drainage, the closest modern analogy for the Todilto, are taken from Goldstein & Jacobsen (1987).

The high ratios in the Todilto Limestone in southwestern Colorado probably result from a higher influx of fresh water into this part of the basin than into the Todilto Basin in northern New Mexico. The Uncompahgre uplift (Fig. 13), which was a mountainous area during the late Paleozoic, was still a minor positive area during Middle Jurassic time (Holmes, 1951). Even though rather low, the "Uncompahgre hills" would probably have received substantially more precipitation than adjacent areas (R. Y. Anderson, pers. comm. 1993), and the narrow basin bordering the Uncompahgre uplift in southwestern Colorado may have received higher amounts of stream-borne water than did many areas to the south in New Mexico. This would result in the higher ratios observed in the limestone.

The mixing arguments used for the Todilto limestone can be used also for the Todilto gypsum. The sample localities and the strontium isotopic values for samples of Todilto gypsum are shown in Figure 27. The salinity of sea water increased by a factor of about 3.5 during gypsum precipitation, and the strontium content would have increased by a similar amount. As we pointed out, the distribution of values for the Todilto gypsum samples is more negative (i.e. closer to marine values) than the distribution of the values for the Todilto Limestone. The shift actually requires a greater contribution of stream-borne water to the basin during deposition of the sulfate facies than during deposition of the limestone facies. This is in spite of the likelihood that the deposition of gypsum commenced due to increased aridity, which resulted in a decreased stream contribution.

Summary

Using a range of reasonable isotopic and concentration values for riverine strontium derived from modern-river measurements, we conclude that the Todilto waterbody received far more riverine than sea water. Although this result is essentially insensitive to changes in the assumptions of original sea-water and riverine parameters, it is more sensitive to the strontium concentration than to the isotopic composition because the concentration of river water varies over a wider range (3 ppm to 6 ppb). The mixing calculations show that the large, shallow, short-lived Todilto waterbody contained a base of sea water but was volumetrically dominated by riverine water, and that the proportions of marine and riverine contributions were changing through time. For example, the data from single sites show considerable but unsystematic variation, such as the 16 analyses from the excellent exposure of 10 ft (3.0 m) of limestone and 165 ft (50.3 m) of gypsum at Tongue Arroyo (Loc. 43, Figs. 26, 27), where the values vary from Δsw -225 to -153. The Todilto saliva was probably seldom well-mixed, and the location and volume of riverine input probably varied dramatically with time.

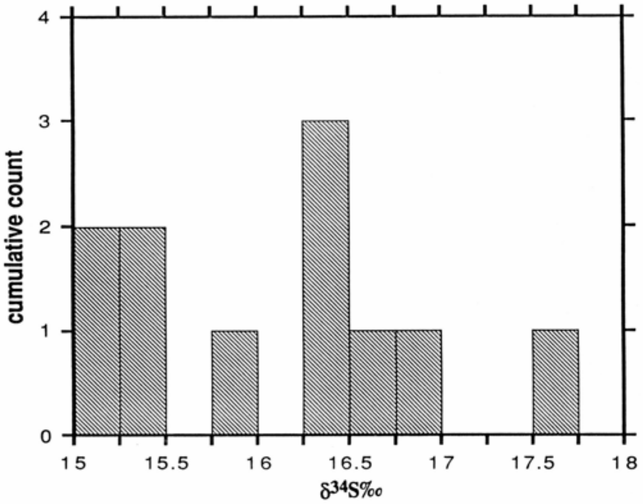

FIGURE 31—Distribution of sulfur isotopic values ($\delta^{34}S$) in samples of gypsum from Todilto Gypsum Member (various localities in northern New Mexico, see Table 3).

TABLE 3—Sulfur isotopic values for Todilto gypsum (Todilto Gypsum Member) in northwestern New Mexico, and for Ralston Creek gypsum (Ralston Creek Formation) in Fremont County, Colorado.

Locality	Location	$\delta^{34}S$‰
2	NESE 26-17S-68W Fremont Co., CO	+12.7, +13.0
5	SE 7-18S-69W Fremont Co., CO	+14.3, +14.4
17	21-25N-4E Rio Arriba Co., NM	+16.3
19	15-23N-2E Rio Arriba Co., NM	+15.1
20	SWSW 32-23N-4E Rio Arriba Co., NM	+16.6
21	12-20N-1W Sandoval Co., NM	+17.7
27	SESW 11-15N-1E Sandoval Co., NM	+15.9
29	NW 4-14N-7E Santa Fe Co., NM	+16.8
39	24-10N-6W Valencia Co., NM	+15.5
43	SW 1-13N-5E Sandoval Co., NM	+15.1, +15.4
45	1-10N-5E Bernalillo Co., NM	+16.4
49	33-13N-5E Sandoval Co., NM	+16.3

Sulfur

Superficially, the sulfur-isotope values obtained from Todilto gypsum could be used to contradict the conclusions drawn from the discussion of carbon and strontium isotopes, because the values of $\delta^{34}S$ for 11 samples of gypsum in northwestern New Mexico (Fig. 31) are mostly well within the range determined for Middle Jurassic sea water. Other analyses of sulfur isotopes have been used to support a marine origin of gypsum in the Todilto (Adler, 1974; Ridgley & Goldhaber, 1983), and therefore it might seem that no further discussion is needed. However, our interpretations of different data sets must be compatible. We can attempt to resolve the contradiction of the origin of the Todilto Formation by determining whether the marine-riverine mixing model used in the explanation of strontium-isotope ratios can also explain the sulfur-isotope values. From the model calculations it is clear that the two isotopic systems are in agreement. The apparent disparity is caused by a difference in sensitivity, because the strontium isotopes are a much more sensitive indicator of fresh-water influence on a waterbody than are sulfur isotopes. The reasons are as follows:

The same parameters that control strontium isotopic values also control sulfur: the concentration and the isotopic ratio in Jurassic sea water, and the concentration (mean) and isotopic composition of riverine input. With both sulfur and strontium there is uncertainty about the precise values assigned to the fresh-water and marine influences, but a reasonable range of values can be selected by using data on modern marine and riverine systems in conjunction with those on ancient evaporites.

Modern sea water contains about 2650 ppm SO_4^{-2} (McLellan, 1965, p. 16), and river water a mean of about

11 ppm (Livingstone, 1963). Although there is no way to prove the contention that these values are reasonably close to the values for Middle Jurassic sea and riverine water, they are the assumed values in our calculation. Even if the assumed value of 11 ppm were doubled or tripled, our conclusion would be essentially the same.

The $\delta^{34}S$ for Jurassic sea water has been reported by Claypool et al. (1980). The mean value of $\delta^{34}S$ of +16.3 ‰ ± 0.8 on 17 sulfate samples from worldwide locations is in agreement with previous results (e.g. Thode & Monster, 1965; Holser & Kaplan, 1966). The sulfur-isotope ratio of Jurassic river water feeding the Todilto waterbody cannot be accurately established. It has been argued on geologic and paleogeographic grounds that the Todilto waterbody was surrounded by a drainage basin in which streams drained mainly earlier Mesozoic and later Paleozoic sedimentary rocks with a range of about +10 to +20 ‰ of $\delta^{34}S$ for sea water during the period of their deposition. If it is assumed that most of the fresh-water sulfur would be derived from the leaching or weathering of marine rocks of that age, then the fresh water would have most likely carried sulfur with a PS of between +10 and +20 %., and such a contribution by riverine water would drive the Todilto values either higher or lower than marine $\delta^{34}S$ of +16.3 ‰ ± 0.8.

Seven of the 11 Todilto gypsum $\delta^{34}S$ values that we measured fall in a narrow range (+16.1 ‰ ± 0.7) (Table 3). The value for the gypsum sample collected from the Señorita

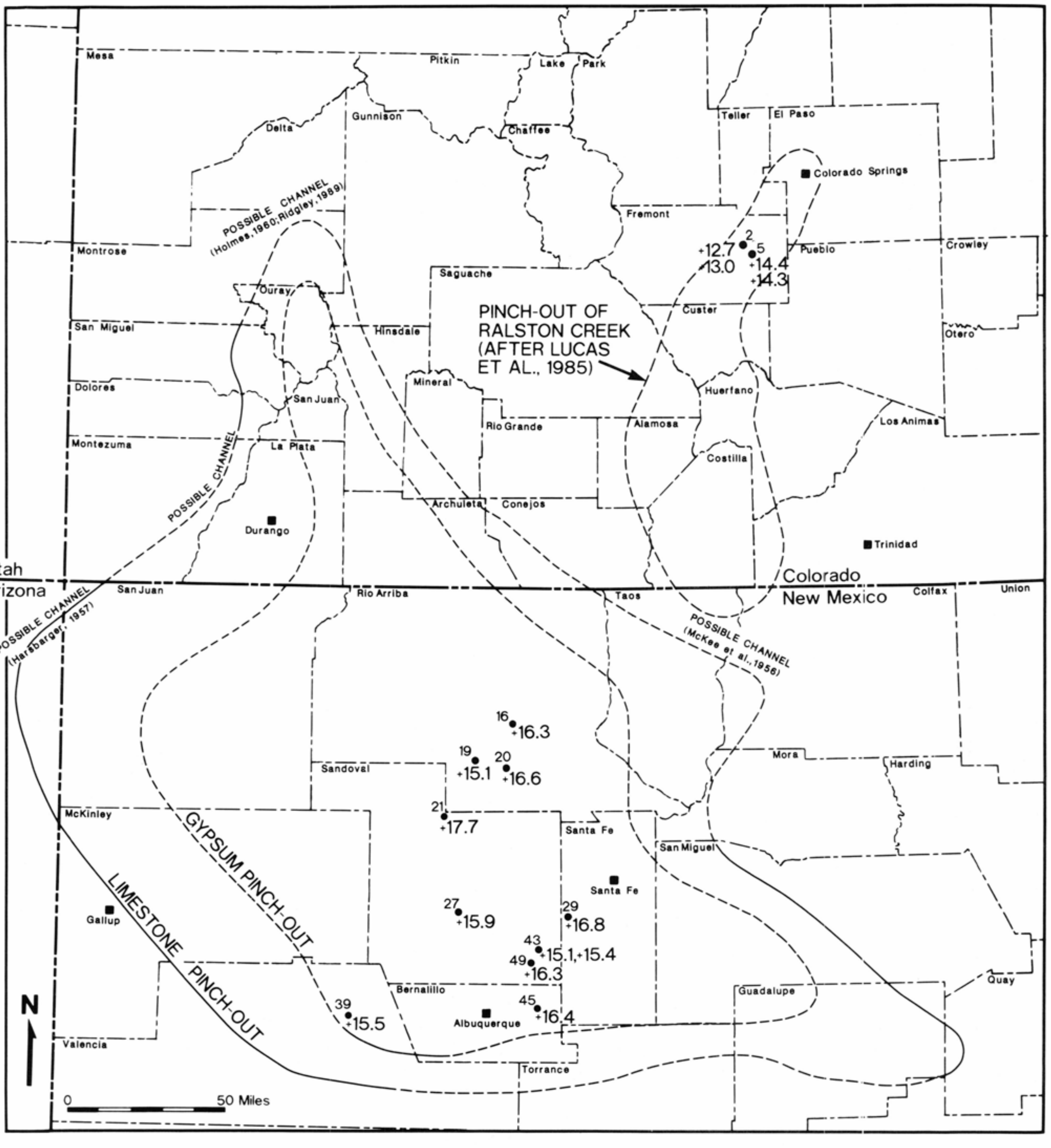

FIGURE 32—Localities sampled for sulfur isotopic values ($\delta^{34}S$) in samples in the Todilto Gypsum Member of northern New Mexico, and the Ralston Creek Formation, Fremont County, Colorado.

locality (Loc. 21, Fig. 32) is about one mil more positive than these, but the sample is from an area of known mineralization adjacent to a large sandstone-type copper deposit (Nacimiento mine), and the isotopic system was probably disturbed. Despite this anomalous value, the mean of the 11 most representative values and the mean of all the determinations (+16.2 ‰) are well within error of that determined for Jurassic sea water. $\delta^{34}S$ values for 11 samples of Todilto gypsum measured by Ridgley & Goldhaber (1983) range from +13.1 to +16.8 ‰, and all but two of their values lie within the range for marine Jurassic sulfates worldwide. The interpretation that the Todilto was marine (see references above) developed easily and naturally from data such as these (e.g. Adler, 1974), but the calculation of the effect of riverine input reveals that the interpretation may be incorrect.

At the time of deposition of the Todilto gypsum, the marine sulfate concentration would have been about 9300 ppm (gypsum saturation), and the isotopic sulfate value would have been a $\delta^{34}S$ of +16.1 ‰. Any freshwater input would have had a $\delta^{34}S$ range of +10 to +20 ‰, with an estimated sulfate concentration of 11 ppm. A change of ± 1.0 mil in the $\delta^{34}S$ value would have required an addition of 166 volumes of riverine water at +10 ‰ or 292 volumes of riverine water at +20‰ for every gypsum-saturated marine-derived volume. The +10 and +20 ‰ represent what are regarded as the extremes of isotopic variation. Calculations using these figures show that the apparently marine values of $\delta^{34}S$ could have been derived from an originally marine environment subsequently modified by inflow of nonmarine waters, the conclusion reached by an analysis of the values of carbon- and strontium-isotope ratios. There is no longer any incompatibility among the interpretations of the three isotopic ratios.

The four values of the Ralston Creek gypsum ($\delta^{34}S$ of +12.7 to +14.4 ‰) are anomalous in that they do not fall within the range of +16.3 ‰±0.8 reported by Claypool et al. (1980) for Jurassic sea water, but this gypsum was deposited from a waterbody that, although contemporaneous with the Todilto, may or may not have been connected directly to it. In fact, the relatively low values for the four Ralston Creek samples, and the different character of the two formations, could be used to argue that they were not mixed and *not* connected. Alternatively, the values might indicate that large volumes of fresh water were bringing isotopically light sulfur into this part of the basin, values far less than the estimated +16.1‰ value for Todilto water. To produce the $\delta^{34}S$ of +12.8‰ from the Ralston Creek gypsum (Locs. 2 and 5, Fig. 32) would require nearly 1000 river volumes of 11 ppm sulfate with a $\delta^{34}S$ of +10‰ if the Ralston Creek began with a base of marine sulfur (sulfate). Even if the modern mean of riverine sulfate concentrations is higher than that present at Todilto time, we would have to increase it greatly (four to six times) to change the $\delta^{34}S$ values significantly, and even then we would still need a large number of fresh-water volumes.

The conclusion is clear. Sulfur-isotope values of marine evaporitic brines are much less influenced by fresh water than are strontium isotopes and thus there is no need to reconcile the interpretations of the two isotopic systems. Both the sulfur and strontium isotopes are consistent with a Todilto waterbody that generally contained far more fresh than marine water.

Origin

During the Callovian epoch the western edge of the North American continent lay a few hundred miles west of what is now the Four Corners region and its surroundings. That part of the continent lay in the tradewind belt 15-20° north of the equator. Blowing offshore persistently from the northeast, the winds kept the edge of the continent as dry as the modern western Sahara. Desert conditions prevailed, and an extensive *erg* thousands of square miles in extent occupied the coastal regions adjacent to a shallow sea (Kocurek, 1981). The elongate dune ridges, perhaps more than 100 ft (30.5 m) high and aligned with the prevailing winds (Fig. 20), produced a low-relief topography easily susceptible to invasion from the sea to the north and west.

Minor waterbodies developed in the interdune depressions just ahead of the advancing shoreline. They were probably isolated or nearly isolated from the sea, and were probably brackish, fed by seepage of fresh water from the Entrada dunes. These small lakes, the precursors of a larger body of water from which the sediments of the Todilto Formation precipitated, were occupied by a restricted macrofauna including one or two specimens of aquatic insects and species of fish common to the Sundance Sea. The small lakes were short-lived, destined to be supplanted after an initial marine inundation of a large part of this Callovian desert. How that flooding occurred as sea level rose, whether water flowed through a strait to flood the Entrada dune field or whether nearby ocean water seeped through a barrier formed by the porous Entrada erg, is a matter for conjecture. Whatever the cause, the marine inundation produced a shallow, saline body of water at the edge of the continent, and in the arid climate that body of water soon became evaporitic and hypersaline—a salina. Throughout its 30,000 to 100,000 years existence, the Todilto salina would have had an intermittent or possibly persistent connection with the Callovian ocean via the shallow Sundance Sea to the north, a connection that determined fundamental features of the chemistry of its waters.

Several examples of Quaternary coastal salinas have been described in Australia, giving us a picture of what the Jurassic Todilto Basin may have been like (Warren, 1982; Logan, 1987). The MacLeod evaporite basin on the northwest coast of Australia developed when Holocene sea level rose higher than the floor of the nearby continental basin, thereby creating conditions in which seepage and overtopping of marine water made a saline lake out of what was previously a dry depression. In the 9000 years since the first flooding, evaporitic sediments—carbonates, gypsum, and halite—have been and continue to be deposited in a basin hundreds of square kilometers in area (Logan, 1987). In its panoply of physiographic, chemical, and biological features—barriers formed by elongate dunes, intermittent streams contributing nonmarine water, sequential deposition in the "Usiglio salt sequence," restricted fauna—the MacLeod evaporite basin could be in the Holocene what the Todilto Basin was in the Callovian.

In such a setting, it would not have taken long for the brine in the Todilto Basin to reach the concentration at which the first of the evaporitic series of minerals (calcium carbonate) would precipitate. The body of water was probably stratified, a denser brine filling in hollows in the floor of the shallow basin. Any water ingressing, saline from the Sundance Sea or fresh water from streams, would spread throughout the basin on top of the more concentrated brine beneath, but ultimately would itself become more saline under the influence of persistent evaporation. Precipitation occurred at the surface, the grains falling into the preservative brine at the bottom of the water column. Seasonal variations in the rate of evaporation, amount of rainfall, or amount of inflow from the hinterland effected a cyclical variation in the amount of sedimentation, a cyclicity that was both annual and multiannual. Laminae of evaporitic carbonate alternated with laminae of organic matter associated with traces of clastic material, giving the Todilto sediment the characteristic laminated appearance that we see in the Todilto Limestone. But however concentrated it may have been as a result of intense evaporation, the brine from which these carbonate precipitates originated was not inimical to life.

The fish *Hulettia americana*, a marine form, is distributed so widely throughout the basin that it clearly was able to survive in the saline surface waters derived from normal marine inflow from the Sundance Sea to the north, where it also lived. Calcareous algae lived near the shore, and a species of the algal family Dasycladacea, possibly an immigrant from the Sundance Sea, occurred along the southwestern margin. Fresh-water ostracodes, similar to forms from the Morrison Formation, lived in the inflow from fresh-water streams and seepage around the margin of the basin. At the concentration necessary for precipitation of carbonates, an evaporating brine is at its optimum for allowing prolific growth of algae, and the effect of this can be seen in the dark layer of the Todilto couplets that are continuous for at least several miles through a part of the depositional basin. The organic laminae are the fossilized remnants of seasonal growth of simple plant forms that could survive in hypersaline water; the laminae were preserved because waves, storms, or currents failed to disrupt stratification of the brine.

The original flooding from the Sundance Sea in the north, and the subsequent connection with the world ocean, albeit probably intermittent, gave the Todilto brine a distinctive chemistry, however much it may have been diluted by inflowing fresh water. The mixed brine in turn gave its precipitates a distinctive and indelible isotopic signature—the carbon and sulfur isotopic ratios could be interpreted as originating from marine waters, the strontium ratios as being influenced by nonmarine waters. Resolution of these apparently contradictory interpretations is possible because the environment in which the Todilto sediments were deposited was neither exclusively marine nor exclusively nonmarine. Slight changes in sea level probably resulted in an alternately flooded or isolated salina—a coastal body of saline water, so that although originally inundated by the sea, the Todilto Basin developed a lacustrine and nonmarine cast during its short existence.

As a result of both isolation and ambient climate, the brine in the Todilto Basin became even more concentrated, and precipitation of carbonate became accompanied and eventually replaced by precipitation of gypsum. Few organisms could survive the hypersalinity; fish, ostracodes, and insects disappeared. The size of the salina diminished until the inevitable supersedure of deposition by desiccation. Shallowing of the basin by deposition and regression of the Sundance Sea caused the Todilto waterbody to cease, leaving its thin accumulation of laminated carbonate and nodular gypsum as a record of its brief existence. As the Sundance Sea regressed northward during the Summerville time, thinly bedded sands and muds, as well as eolian sands, accumulated above the Todilto evaporite sequence. Shortly thereafter, during the Morrison time, uplift to the west produced a brief period of dissolution (karstification) of the exposed Todilto, accompanied by shedding of eroded material into the interior of the Jurassic continent. During these events the Todilto was buried by Middle and Late Jurassic sediments.

This description of the depositional environment of the Todilto Formation reconciles divergent opinions, interpretations, and facts. Some Todilto fish had marine affinities, whereas others were probably fresh-water. The mineralogy of the Todilto sediments could have originated in either a marine or nonmarine evaporitic setting, although the strontium isotopic ratios of those rocks are not within the range of marine Middle Jurassic sediments. Insects, which have been found at a number of localities in the Todilto Limestone, rarely inhabit the marine environment; although carbon- and sulfur-isotope ratios seem to point to marine conditions, the sediments contain nonmarine ostracodes!

Resolution of the enigma is possible only if we abandon the position that the Todilto depositional environment was either exclusively marine or exclusively nonmarine. To Hardie (1984) must go the credit for provoking us into thinking that not all ancient evaporites must be either exclusively marine or exclusively nonmarine, and Lucas et al. (1985) have to be hailed for deducing, without the isotopic data now available, that the Todilto sediments were deposited in a salina. The resolution of a scientific disagreement is accomplished by the inclusion of all relevant information into any explanation, not by ignoring facts which we may not understand. As we believe we have demonstrated by this incorporative analysis of the Jurassic Todilto Formation, circumspection is to be preferred to the narrow vision of specialization.

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TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, µm
Area		
in^{2}	6.452	cm^{2}
ft^{2}	9.29×10^{-2}	m^{2}
yds^{2}	8.361×10^{-1}	m^{2}
mi^{2}	2.590	km^{2}
acres	4.047×10^{3}	m^{2}
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^{3}	1.639×10^{1}	cm^{3}
ft^{3}	2.832×10^{-2}	m^{3}
yds^{3}	7.646×10^{-1}	m^{3}
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^{3}
acre-ft	1.234×10^{3}	m^{3}
barrels (oil), bbl	1.589×10^{-1}	m^{3}
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}
Pressure stress		
lb in^{-2} (= lb/in^{2}), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^{2})
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^{2}, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^{3})	2.768×10^{1}	gr cm^{-3} (= gr/cm^{3})
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^{3} sec^{-1}
ft^{3} sec^{-1}	2.832×10^{-2}	m^{3} sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^{2}
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^{2} sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F – 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^{2}) = 0.0929.