Clastic Pipes of Probable Solution-Collapse Origin in Jurassic Rocks of the Southern San Juan Basin, New Mexico

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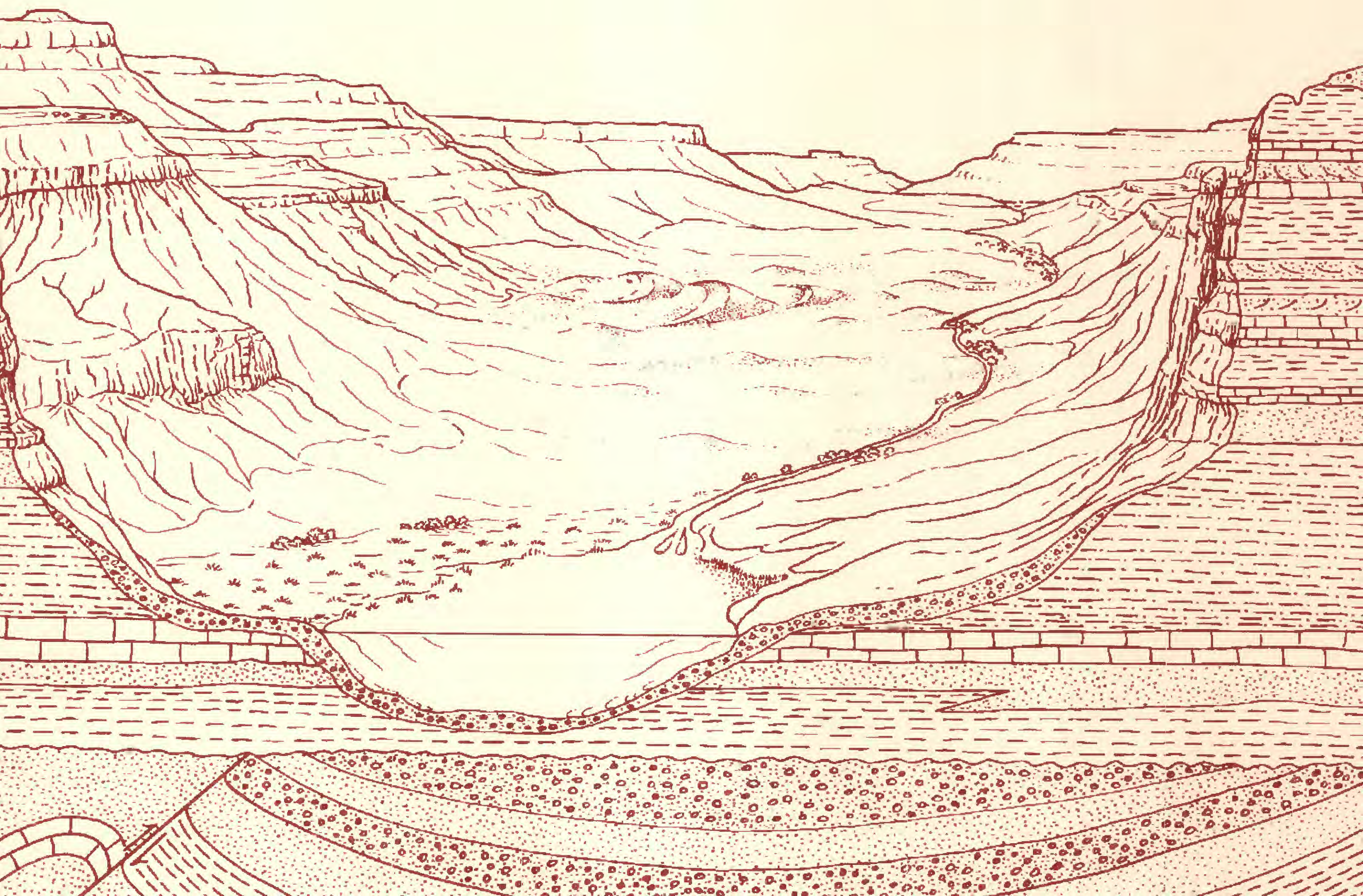

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Chapter L

Clastic Pipes of Probable Solution-Collapse Origin in Jurassic Rocks of the Southern San Juan Basin, New Mexico

By RALPH E. HUNTER, GUY GELFENBAUM, and DAVID M. RUBIN

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1992

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Library of Congress Cataloging-in-Publication Data

Hunter, Ralph Eugene
Clastic pipes of probable solution-collapse origin in Jurassic rocks of the southern San Juan Basin, New Mexico / by Ralph E. Hunter, Guy Gelfenbaum, and David M. Rubin.
p. cm. — (Evolution of sedimentary basins—San Juan Basin ; ch. L) (U.S. Geological Survey bulletin ; 1808–L)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:1808–L
1. Clastic pipes—San Juan Basin (N.M. and Colo.) 2. Geology, Stratigraphic—Jurassic. 3. Geology—San Juan Basin (N.M. and Colo.). I. Gelfenbaum, Guy. II. Rubin, David M. III. Title. IV. Series. V. Series: U.S. Geological Survey bulletin ; 1808–L.
QE75.B9 no. 1808–L
[QE611.5.U6]
557.3 s—dc20 91–4320
[552'.5] CIP

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Clastic Pipes of Probable Solution-Collapse Origin in Jurassic Rocks of the Southern San Juan Basin, New Mexico

By Ralph E. Hunter, Guy Gelfenbaum, *and* David M. Rubin

Abstract

Pipes that contain downdropped strata are locally common in Jurassic rocks above the Todilto Limestone Member of the Wanakah Formation in the southwestern part of the San Juan Basin, New Mexico. The pipes are elongate, vertical, roughly cylindrical structures 0.1–40 m in diameter. They are similar in form and stratigraphic position to pipes previously studied in the southeastern part of the San Juan Basin but differ in that they commonly contain intact strata identical to the host strata, whereas pipes in the southeastern part of the basin typically consist of breccia and homogenized material. Where the sense of movement of material within the pipes relative to the host strata can be determined by correlation of beds or by drag along the ring faults bounding the pipes, material within the pipes has consistently been downdropped.

Downdropped but otherwise little disturbed strata are so common within pipes in the southwestern part of the basin that the fluid-escape or spring-vent origin advocated previously for pipes in the southeastern part of the basin seems implausible. Gradual collapse following the localized dissolution of evaporites probably is the primary cause of the pipes rather than a subsidiary cause as previously suggested. Neither the cylindrical form nor the large height-to-width ratios of the pipes is evidence against a solution-collapse origin, because such features are common in collapse structures of diverse origin, including those formed experimentally. The evaporite unit at the top of the Todilto in the southeastern part of the basin most likely extended farther west originally, and its early dissolution at discrete points probably caused localized collapse of the overlying sediment. Evaporite dissolution may also be the primary cause of pipe formation in the southeastern part of the basin and of Jurassic folding and faulting throughout the southern part of the basin.

Manuscript approved for publication April 19, 1991.

INTRODUCTION

Clastic pipes are elongate, roughly cylindrical structures composed of clastic sedimentary material. Most if not all were oriented roughly vertically at the time of their formation. Although they are rare or absent in most sedimentary rocks, they are locally common, as in several Jurassic formations of the southern San Juan Basin, New Mexico (fig. 1). Pipes in the southeastern part of the San Juan Basin have been studied in considerable detail because some of them are sites of uranium mineralization (Hilpert and Moench, 1960; Clark and Havenstrite, 1963; Granger and Santos, 1963; Schlee, 1963; Wylie, 1963; Megrue and Kerr, 1965; Moench and Schlee, 1967; Hilpert, 1969). In this paper we describe relatively little studied pipes in Jurassic rocks of the southwestern and south-central parts of the San Juan Basin.

Clastic pipes can form by the diapiric rise of plastic sediment, by fluid (water or gas) escape and associated slurry intrusion or foundering, by collapse accompanying or following the removal of underlying material, and by the filling of pipe-shaped cavities. Water-escape pipes (Allen, 1961; Lowe, 1975; Bailey and Newman, 1978) include spring-vent pipes (Hawley and Hart, 1934; Gabelman, 1955; Dionne, 1973) and pipes that may underlie earthquake-induced sandblows (Sieh, 1978; Obermeier and others, 1985). Gas-escape pipes include cryptovolcanic pipes (Gabelman, 1957; Wylie, 1963) and pipes that may underlie sea-floor pockmarks formed by the escape of hydrocarbon gases (Hovland and Judd, 1988). Collapse-induced pipes include those formed by the dissolution of buried evaporites (Landes, 1945; Christiansen, 1971; Anderson and others, 1978; Anderson and Kirkland, 1980) and carbonate rocks (Dietrich, 1953; Keys and White, 1956; Barrington and Kerr, 1963; Hawley and others, 1965;

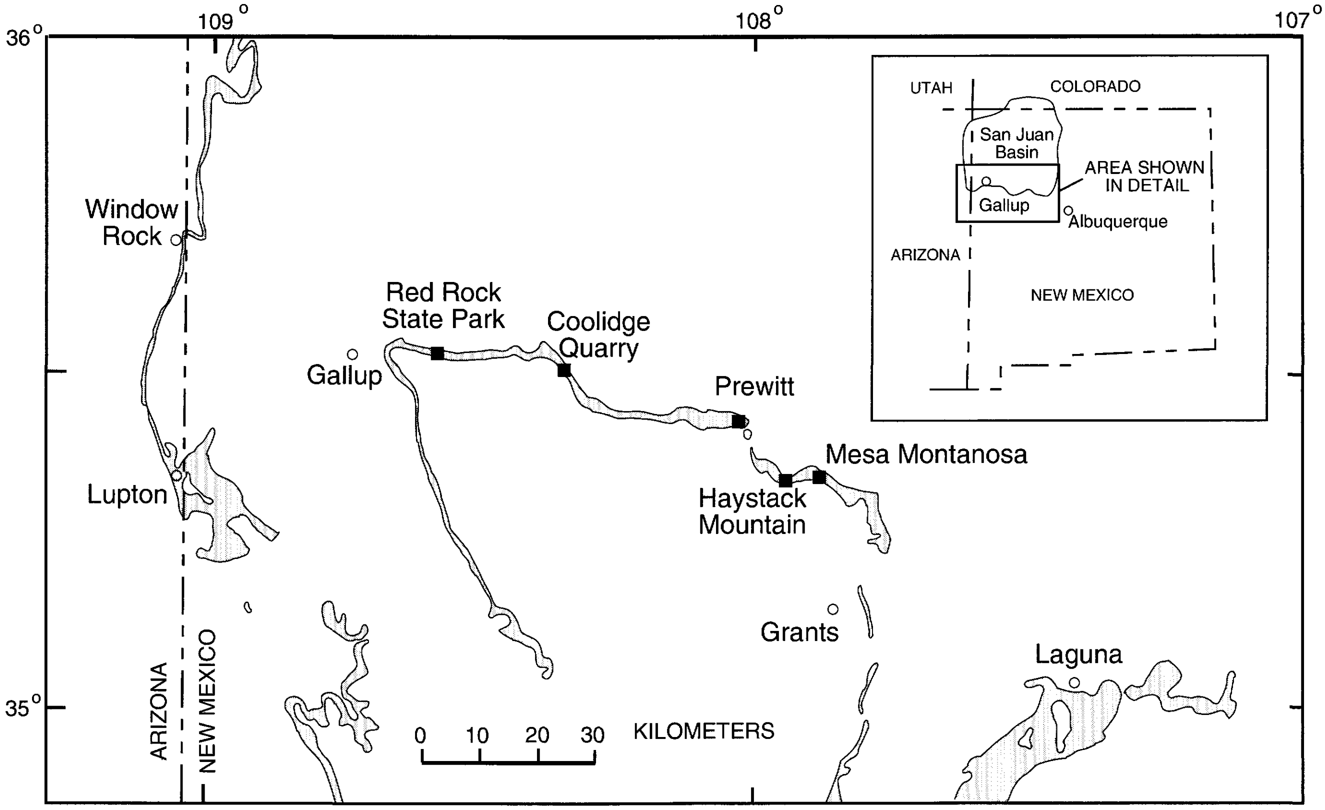

Figure 1. Study locations (solid squares) and outcrops of the San Rafael Group and approximate equivalents (screened pattern) in the southern San Juan Basin, New Mexico and Arizona.

Gornitz and Kerr, 1970; Wenrich, 1985; Krewedl and Carisey, 1986; Wenrich and others, 1988), those formed by the melting of subsurface ice (McDonald and Shilts, 1975), and those formed by other volume-reduction processes (Wisser, 1927). Cavities of pipelike form, which may be filled later to form pipes, can form by the localized dissolution of an evaporite or carbonate body at the ground surface or sea floor, by the erosion of potholes by flowing water, and by the decay of tree trunks that were buried while standing. Pipe-shaped biogenic structures, which include vertical burrows and root structures, should probably not be called pipes.

In their studies of the southeastern San Juan Basin, Schlee (1963) and Moench and Schlee (1967) interpreted the pipes as spring-vent structures, although they recognized that collapse due to gypsum dissolution may have played a subordinate role in forming the pipes. In this paper we present evidence that the pipes in the southwestern and south-central parts of the basin formed by solution collapse. Although we have not extensively studied the pipes in the southeastern part of the basin, we consider a solution-collapse origin to be the most reasonable explanation for all the pipes in the southern San Juan Basin.

GEOLOGIC SETTING

The stratigraphy of Jurassic rocks in the southern San Juan Basin has been discussed in detail by Condon and Peterson (1986), and recent changes in stratigraphic nomenclature have been discussed by Condon and Huffman (1988) and Condon (1989). Stratigraphic units pertinent to this study are in the interval from the Wanakah Formation to the Morrison Formation (fig. 2). The Wanakah Formation, which overlies the Entrada Sandstone and underlies the Morrison, consists of the Todilto Limestone Member, formerly accorded formational status, the overlying Beclabito Member, formerly called the Summerville Formation, and the Horse Mesa Member at the top. The Horse Mesa Member, formerly called the lower part of the Bluff Sandstone (Moench and Schlee, 1967) or informally called the lower part of the sandstone at Mesita (Condon and Peterson, 1986), has not been recognized in the southwestern San Juan Basin, where the Cow Springs Sandstone occupies the same stratigraphic position. The Todilto pinches out a short distance west of Red Rock State Park, and the Beclabito apparently grades into the Cow Springs in the subsurface between Gallup and Lupton. At

Lupton, the Cow Springs occupies the entire interval from the top of the Entrada to the base of the Morrison.

The Todilto Limestone Member of the Wanakah Formation consists of a thin (0–9 m), widespread limestone unit and an overlying thicker (0–37 m), geographically more restricted gypsum-anhydrite unit. The gypsum-anhydrite unit, which consists entirely of gypsum at the surface and predominantly of anhydrite in the subsurface, crops out in the southeastern part of the basin but is absent in outcrops farther west. The Todilto has been interpreted as probably lacustrine by some workers (Anderson and Kirkland, 1960; Tanner, 1970; Rawson, 1980) and as probably marine by others (Harshbarger and others, 1957; Ridgley and Goldhaber, 1983; Ridgley, 1984, 1986). In either case, the water body was hypersaline by the time the gypsum-anhydrite unit was deposited.

The Beclabito Member of the Wanakah Formation is 9–49 m thick and consists mainly of silty sandstone and siltstone with mudstone and claystone partings. Most of the beds are reddish in color, although some sandstone beds are very light colored or white. The bedding is predominantly flat. Lamination and other small-scale sedimentary structures are generally absent or indistinct. The Beclabito Member was deposited close to the margins of a shallow water body that, like the water body in which the Todilto was deposited, was either shallow marine or lacustrine. Some of the Beclabito was probably deposited within the water body, but much of the unit was probably deposited on a sabkha that bordered the water body (Condon and Peterson, 1986). Swirled vestiges of lamination, which are visible on well-exposed outcrops, indicate intense small-scale deformation. The small-scale deformation was probably caused by a variety of penecontemporaneous processes including bioturbation, physical processes such as loading and liquefaction, and chemical processes such as intrastratal evaporite precipitation and dissolution. A few sandstone beds that have preserved cross lamination can be identified as eolian on the basis of structures formed by climbing wind ripples (Hunter, 1981).

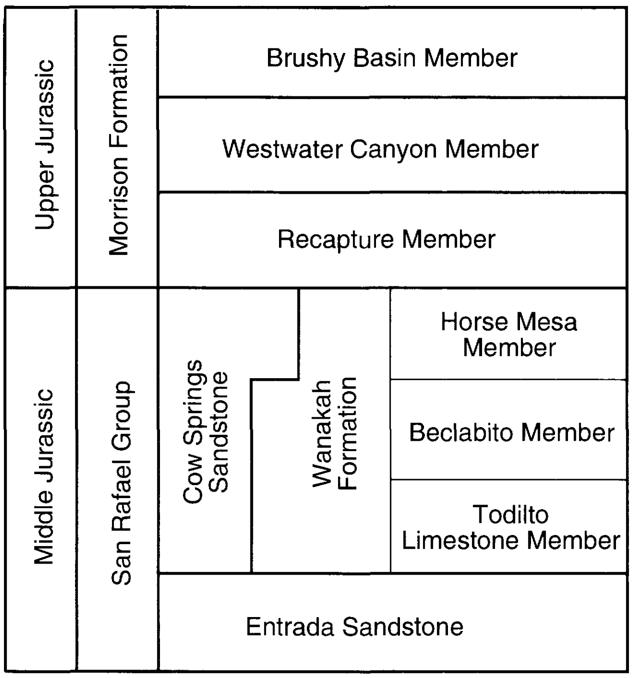

Figure 2. Stratigraphy of Jurassic rock units in the southern San Juan Basin. The stratigraphy of the interval between the Entrada Sandstone and the Morrison Formation differs geographically; in the extreme southwestern part of the basin (around Lupton, fig. 1) the Cow Springs Sandstone occupies the entire interval, whereas at Haystack Mountain and farther east the Wanakah Formation occupies the entire interval. In the area between Lupton and Haystack Mountain the Cow Springs Sandstone overlies the Beclabito Member of the Wanakah.

The Cow Springs Sandstone and the Horse Mesa Member of the Wanakah Formation are similar in character, thickness, and stratigraphic position. Both are light-colored to reddish, fine- to medium-grained sandstones that are 40–100 m thick along the southern side of the San Juan Basin. Cosets of cross-strata are interbedded with sets of thin, flat beds. Most of the sets of cross-strata are less than 1 m thick. The Cow Springs has been interpreted as eolian dune and interdune deposits (Condon and Peterson, 1986). The Horse Mesa has been interpreted as probably fluvial (Moench and Schlee, 1967; Maxwell, 1982) or as eolian (Condon, 1989). We concur with an eolian interpretation for both the Cow Springs and the Horse Mesa, mainly on the basis of structures formed by climbing wind ripples (Hunter, 1981).

The Morrison Formation is a complex sequence of nonmarine sandstone, siltstone, mudstone, and claystone that is divided into several members (fig. 2). It is 70–190 m thick along the southern margin of the San Juan Basin. Depositional environments represented in the formation include fluvial, lacustrine, and eolian. Eolian sandstones are restricted to the Recapture Member, the lowest member of the Morrison (Condon and Peterson, 1986; Condon, 1989). The eolian sandstone now assigned to the lower part of the Recapture in the southeastern part of the basin (Condon, 1989) was formerly assigned to the upper part of the Bluff Sandstone (Moench and Schlee, 1967).

DESCRIPTION OF PIPES

Pipes are present in outcropping Jurassic rocks along the southern margin of the San Juan Basin from near Gallup eastward to the Laguna district (fig. 1). Pipes are most common in the Beclabito and Horse Mesa Members of the Wanakah Formation and in the Cow Springs Sandstone. A few pipes are in the Morrison Formation (Hilpert and Moench, 1960; Clark and Havenstrite, 1963; Granger and Santos, 1963; Schlee, 1963; Wylie, 1963; Megrue and Kerr, 1965; Moench and Schlee, 1967; Hilpert, 1969); we have seen pipes in the Recapture Member of the Morrison as far west as the Coolidge area. No pipes have been observed above the Morrison Formation, in the Todilto Limestone Member of the Wanakah Formation, or below the Todilto.

The pipes tend to be clustered geographically. Small pipes are abundant in the lower part of the Beclabito in the southwestern part of the basin (fig. 3). Fifteen pipes averaging 1 m in diameter were observed in an area of 255 m^2 in the lower Beclabito at Red Rock State Park, and such concentrations are probably typical of that part of the section in an area of at least several square kilometers. Pipes are fairly common throughout the Beclabito and Cow Springs in the southwestern part of the basin and throughout the Beclabito and Horse Mesa in the southeastern part of the basin. A cluster of 60 pipes in an area of 0.5 km^2 has been mapped in the southeastern part of the basin (Schlee and Moench, 1963), and we observed a cluster of 34 pipes averaging 9 m in diameter in an area of 0.3 km^2 north of Prewitt in the south-central part of the basin. The clusters of pipes in the southeastern part of the basin are associated with belts of folds and faults that formed during the Jurassic or Early Cretaceous (Moench and Schlee, 1967).

In exposures parallel with bedding, the pipes appear roughly circular (fig. 4*A*). In exposures normal to bedding, the pipes appear elongate, roughly parallel walled, and oriented roughly normal to bedding (fig. 4*B*). Oblique sections across the pipes appear elliptical (fig. 5). Clastic pipes in the southwestern and south-central parts of the San Juan Basin are 0.1–40 m in diameter (fig. 3). The range in diameters is even greater, 0.025–60 m, in the southeastern part of the basin (Moench and Schlee, 1967). Many more large pipes are present in the southeastern part of the basin than in the southwestern part.

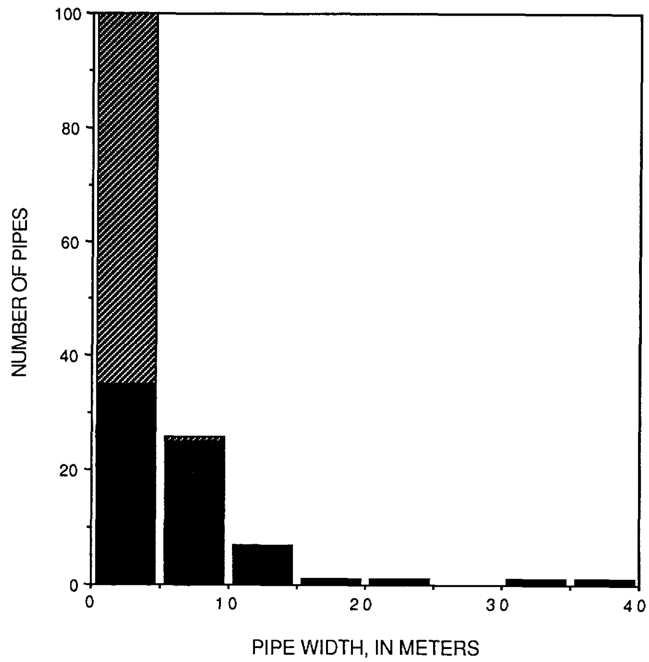

Figure 3. Histogram showing distribution of pipe widths in Jurassic rocks of the southwestern and south-central parts of the San Juan Basin. Diagonal pattern, pipes in the Beclabito member; solid, pipes in other units.

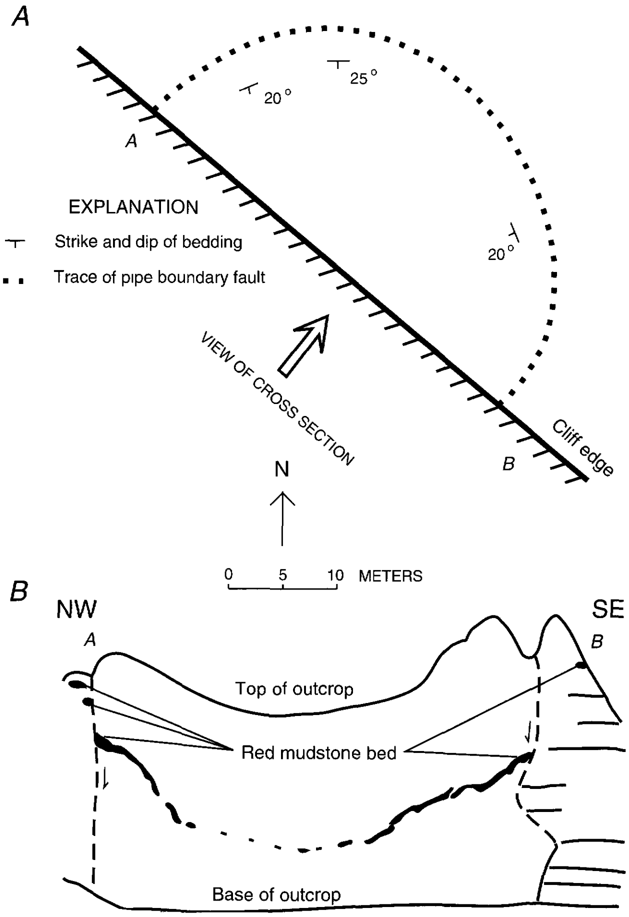

Figure 4. Sketches of a large (diameter 42 m) pipe in the Horse Mesa Member of the Wanakah Formation. South side of Mesa Montanosa (fig. 1), SE¼ SW¼ sec. 24, T. 13 N., R. 10 W., McKinley County, New Mexico. *A*, Map view. *B*, Cross section; note that red mudstone bed within pipe has dropped as much as 17 m relative to its position outside pipe.

The full vertical extent of a pipe is nowhere indisputably exposed. The original tops of almost all pipes have been removed by recent erosion, and almost all pipes extend beneath the present outcrop surface. From exposures of small pipes on almost vertical outcrops, it can be said with certainty that the small pipes are many times higher than broad, and we assume that the same is true of larger pipes. We have seen no indisputable examples of the original tops of pipes, but Hilpert and Moench (1960), Schlee (1963), and Moench and Schlee (1967) reported a few examples. In these examples, which are interpreted as pipes that extended up to the ground surface, the top flares and forms a slight depression into which the covering beds sag (see, for example, Schlee, 1963, fig. 4D). From inaccessible cliff exposures in which some pipes seem to fade out upward, we suspect that some pipes never extended

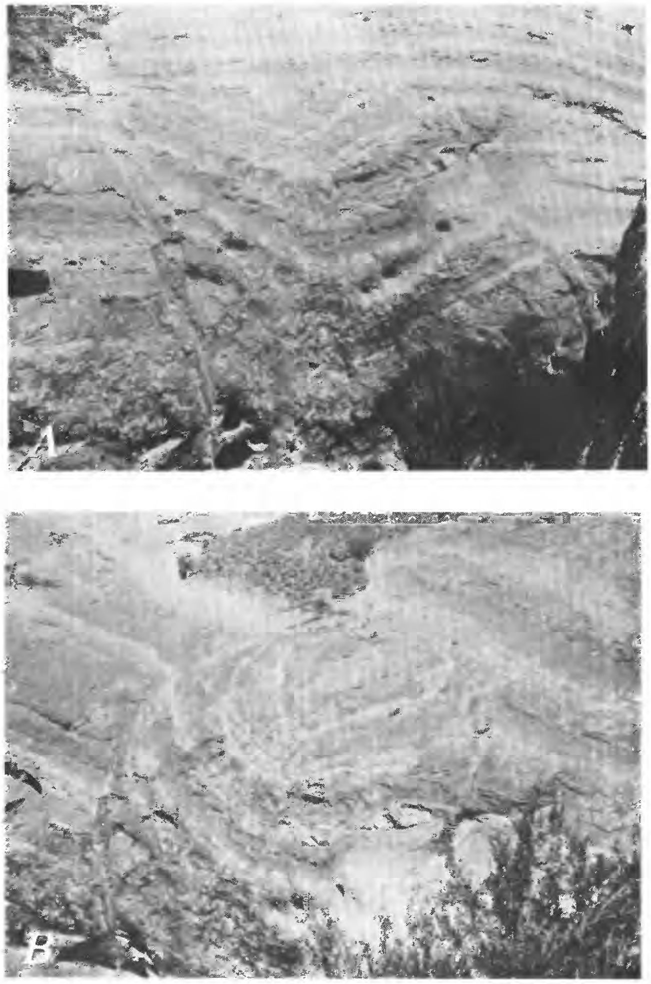

Figure 5. Oblique section through pipe in which bedding is preserved in the Cow Springs Sandstone at Red Rock State Park. The pipe is about 4 m wide. *A*, View looking horizontally at outcrop. *B*, View looking obliquely downward. Although the pipe appears in (*A*) to be truncated by flat-lying beds, it can be seen in (*B*) that the flat-lying beds above the level of the pipe outcrop are to one side of the pipe, not directly above it; the pipe extended farther upward before erosion of the outcrop.

to the surface. Indisputable examples of pipe bases are as rare as pipe tops. The character and stratigraphic level of pipe bases are critical for determining pipe origin, and we postpone a description of pipe bases until our discussion of pipe origin.

Pipe interiors may be structureless sedimentary rock, breccia, almost unbroken strata identical to strata surrounding the pipe, or mixtures of these three types of material. Unbroken strata within pipes are rare in the southeastern part of the basin (Schlee, 1963; Moench and Schlee, 1967) but are common in the southwestern part, where about 20 percent of the pipes have almost completely unbroken strata (figs. 5, 6) and only 10 percent have no traces of stratification. The material within the pipes is well-sorted sandstone to clayey sandy siltstone. Where the sediment of the pipe is more thoroughly cemented than the surrounding rock, the pipe may stand freely as a column. Free-standing pipes are common in the southeastern part of the basin (Schlee, 1963; Moench and Schlee, 1967) but are rare in the southwestern part.

The boundary of a pipe is a vertical ring fault or zone of closely spaced ring faults and ring fractures. Other roughly concentric ring faults that have relatively small displacements may be present within or outside a pipe (fig. 7). Where the pipe interior is stratified, the sense and amount of displacement on the boundary ring fault can be determined by correlation of strata within the pipe and surrounding strata (figs. 4, 6). Forty-eight determinations in the southwestern part of the basin all indicate downdropping of the pipe interior. The amount of downdrop is 0.4–15 m. There is a poorly defined tendency for the amount of downdrop to increase with pipe diameter. On the other hand, the ratio of downdrop to pipe diameter decreases with increasing pipe diameter; the ratio is greater than 2.0 for some pipes less than 2 m wide, less than 1.0 for pipes 2–10 m wide, and less than 0.5 for pipes greater than 10 m wide. Displacements on subsidiary ring faults outside the principal bounding fault are typically less than 0.3 m, and most of the displacements indicate downdropping toward the pipe axis (fig. 7).

The sense of displacement across the pipe boundary is commonly determinable even where beds within a pipe cannot be correlated with those outside because of a lack of distinctive beds. Beds within the pipe commonly exhibit drag, in which the beds are curved upward toward the bounding ring fault (figs. 4–6). Such drag indicates downdropping of the beds within the pipe. Drag in beds immediately outside the ring fault is not common but, where present, indicates downdropping of the pipe interior (see,

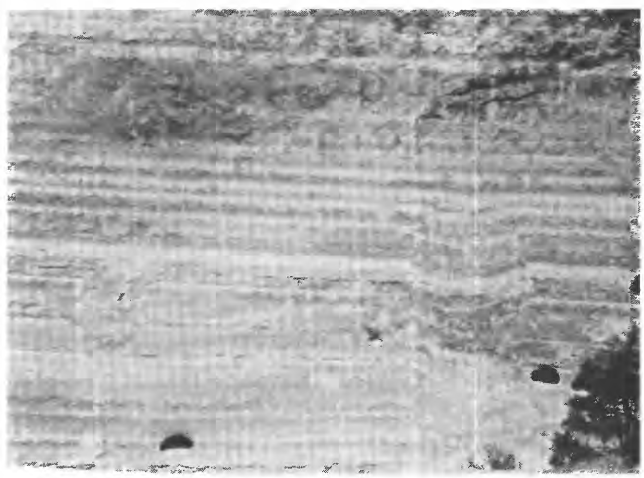

Figure 6. Two pipes with preserved, downdropped bedding in the Cow Springs Sandstone at Red Rock State Park. The pipe on the right is about 3 m wide. The outcrop slopes steeply, whereas the pipes are vertical; the pipes therefore disappear into the outcrop in a downward direction and are removed by erosion in an upward direction.

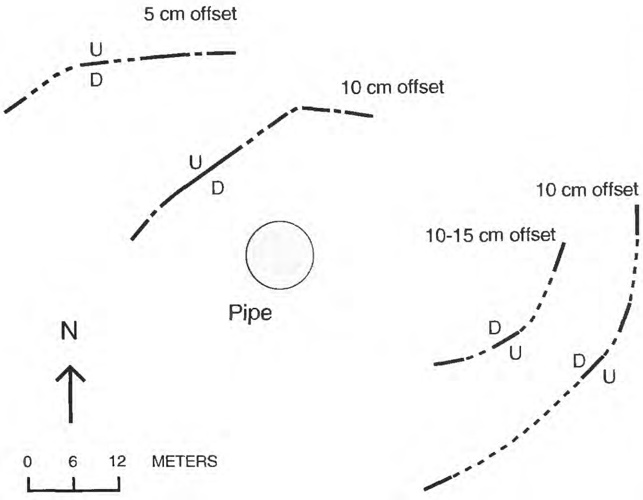

Figure 7. Faults associated with a pipe near Coolidge Quarry (fig. 1), SW1/4 sec. 28, T. 15 N., R. 14 W., McKinley County, New Mexico.

for example, Schlee, 1963, fig. 4B). Sagging of beds toward the pipe axis in a wide zone surrounding the pipe is fairly common in the south-central and southeastern parts of the basin (see, for example, Schlee, 1963, fig. 3A); such sagging indicates downdropping toward the pipe axis. In some of these pipes the sagging is accompanied by bed thickening toward the pipe axis, which indicates that the downdropping occurred while the beds were being deposited.

Even in the southeastern part of the basin, where strata are rarely preserved within the pipes, Schlee (1963), Megrue and Kerr (1965), and Moench and Schlee (1967) concluded that the material within the pipes had moved downward. This conclusion was based partly on drag and sagging of beds surrounding the pipes and partly on a petrographic comparison between structureless sandstone within the pipes and bedded sandstone surrounding the pipes. In a few pipes, a vertical change in the composition of pipe breccia could be correlated with a stratigraphic change outside the pipe, and the correlations indicate downdropping of the pipe interiors (Hilpert and Moench, 1960; Megrue and Kerr, 1965).

ORIGIN OF PIPES

Time of Origin

Whatever the origin of the pipes, several types of evidence indicate a relatively early origin during the Jurassic, before the beds were lithified. The preserved tops of a few pipes within Jurassic units indicate that the pipes reached the ground surface during the Jurassic (Hilpert and Moench, 1960; Schlee, 1963; Moench and Schlee, 1967). An origin contemporaneous with the pipe-bearing beds is also indicated by the bed thickening associated with bed sagging around some pipes. We have seen such thickening around a pipe in the Recapture Member of the Morrison near Haystack Mountain, and Schlee (1963) mentioned changes in bed thickness interpreted as indicative of pipe formation during deposition of what is now called the Horse Mesa Member of the Wanakah.

A prelithification origin of the pipes is suggested by the fact that drag folding of beds adjacent to the ring faults bounding the pipes involves considerable stretching and thinning of beds. Convolute folding of beds within a few pipes also implies that the sediment was unlithified. Although the faulting and brecciation of beds within many pipes indicates cohesiveness of the material, no great degree of lithification is necessarily indicated. We interpret the three types of pipe material (unbroken beds, breccia, and homogeneous structureless rock) as stages in a sequence that developed with increasing downdrop and deformation of relatively unlithified sediment. By this interpretation, the pipes in the southwestern part of the basin, which commonly contain relatively intact beds, represent a less advanced stage of pipe formation than those in the southeastern part of the basin, which typically are composed of breccia or homogeneous rock.

Although considerable evidence exists for relatively early pipe formation, we have seen little evidence to support the conclusion of Schlee (1963) and Moench and Schlee (1967) that the pipes in what is now called the Wanakah Formation formed contemporaneously with Wanakah deposition. They cited thickness changes in beds adjacent to pipes in the Horse Mesa Member of the Wanakah as suggesting deposition in sags around pipes, but the evidence of that type that we have seen is restricted to the Morrison Formation. Contacts of sets of crossbeds in the Horse Mesa Member of the Wanakah Formation and in the Cow Springs Sandstone are, for the most part, remarkably even and parallel and do not suggest local sagging of the depositional surface contemporaneous with pipe growth. Probably most of the pipes formed during Morrison time.

A Comparison of Hypotheses

Most conceivable explanations of clastic pipes are easily ruled out for the pipes in the southern San Juan Basin. The overwhelming evidence of downward movement within the pipes rules out a diapiric origin or an origin by slurry intrusion from below. The presence of strata within many pipes identical to surrounding strata rules out an origin by the infilling of tubular cavities. The presence of unbroken, downdropped strata within pipes is incompatible with an origin by the sudden or explosive escape of water or gas. A cryptovolcanic gas-escape origin, which has been favored by a few workers (Gabelman, 1957; Wylie, 1963) for clastic pipes in the Colorado Plateau, including those in the southeastern part of the San Juan Basin, is further ruled out by the absence of pipes in stratigraphic units below the Beclabito Member even in areas where pipes are abundant in the lower part of the Beclabito Member. Collapse due to the melting of ice is ruled out by the low-latitude, warm to hot climate of the area during Jurassic time (Kocurek and Dott, 1983).

The two remaining possible explanations for the pipes are gradual water escape, for example through spring vents, and collapse induced by dissolution of underlying soluble rocks. Any collapse must have accompanied gradual dissolution rather than occurring suddenly by roof failure of large, previously formed cavities, or else unbroken beds would not be so common in pipes of the southwestern part of the basin. In the absence of any evidence of large-scale dissolution of the limestone unit of the Todilto, the only soluble rock whose dissolution could plausibly be called on to explain the pipes is the evaporite unit that forms the upper part of the Todilto. An evaporite solution-collapse and associated evaporite-flowage origin for the pipes in the southeastern part of the basin was proposed and discussed briefly by Mirsky (1955), whereas a spring-vent origin for the same pipes was favored by Schlee (1963) and Moench and Schlee (1967). Water-escape and solution-collapse explanations have been favored for most other pipes on the Colorado Plateau. Water-escape interpretations have been proposed by Gabelman (1955), Phoenix (1958), and Hannum (1980), whereas solution-collapse interpretations have been proposed by Keys and White (1956), Weir and others (1961), Barrington and Kerr (1963), Hawley and others (1965), Gornitz and Kerr (1970), Bowles (1977), Wenrich (1985), Krewedl and Carisey (1986), and Wenrich and others (1988).

In the spring-vent interpretation proposed by Schlee (1963) and Moench and Schlee (1967), the downdropping that they recognized in the pipes was explained as the result of loss of strength in the column of sediment through which water was flowing upward. When the sediment lost its strength by dilation of the grain framework, sand could have sunk into underlying finer grained, less dense sediment. According to this interpretation, room for the downward displacement of sand was created by compaction of the underlying fine-grained sediment as its pore water escaped upward and by mixing of fine-grained sediment into the sand. Schlee (1963) and Moench and Schlee (1967) recognized that localized dissolution of the Todilto evaporite unit may have helped to create space for downdropping in some pipes, but they did not consider such dissolution to be essential for pipe formation. Other possible means of creating room for downward-displaced sand include the upward escape of fine-grained sediment around the edges of the descending mass of sand and the lateral pushing aside of fine-grained sediment.

A spring-vent interpretation seems implausible for the pipes in the southwestern part of the San Juan Basin, which commonly have unbroken or only slightly broken strata. We cannot conceive how stratification could have remained intact during upward water flow intense enough to dilate the grain framework and fluidize the sand. Moreover, we doubt that mechanisms other than solution-induced collapse could have created the space necessary for downdropping in the pipes. Compaction of fine-grained material underlying the sand would have restored strength to the sediment and halted the downdropping. Mixing of sand and underlying fine-grained sediment cannot be called on where the sand retains its original bedding. Fine-grained sediment could not have escaped upward where bedded sand within a pipe is in sharp contact with surrounding sand across the ring fault that bounds the pipe. Except at the bases of pipes, there is no evidence that material within the pipes was squeezed out laterally, and, as will be discussed later, the evidence of lateral spreading of pipe material at pipe bases can be explained by dissolution of an evaporite bed underlying the pipe.

Given the difficulties of a spring-vent interpretation, further consideration needs to be given to a solution-collapse origin of the pipes. Schlee (1963) and Moench and Schlee (1967) presented several kinds of evidence against collapse due to dissolution of the Todilto evaporite unit as the primary cause of the pipes in the southeastern part of the basin. One such piece of evidence is that pipes are found outside the area in which the evaporite unit is presently found. The probative value of this argument is controverted, however, by the possibility that the evaporite unit originally extended beyond its present limit and has been completely removed by dissolution in those areas. This possibility was admitted by Moench and Schlee (1967).

A stronger argument against the solution-collapse hypothesis is the claim of Schlee (1963) and Moench and Schlee (1967) that they observed the true bases of several pipes at stratigraphic levels within the Beclabito Member, at considerable distances above the top of the Todilto. We were unable to find downward terminations of pipes above the top of the Todilto, and we consider it very difficult to determine whether the apparent base of a pipe seen in outcrop is the true base. Even if a pipe is seen to terminate downward in a vertical exposure, that particular pipe could conceivably be one of the atypical pipes that are not essentially vertical, in which case the pipe might continue downward behind the outcrop surface or might have continued downward through now-eroded rock in front of the outcrop.

In our studies, we definitely identified the true bases of pipes only in a few outcrops 0–2 km west of Red Rock State Park. We are confident of those identifications because in that area the downward terminations of dozens of closely spaced pipes were observed in vertical outcrops. All the pipes terminated within a zone no more than 1 m thick at the top of the Todilto Limestone Member (figs. 8, 9). Nowhere else did we find comparable vertical exposures of the contact between the Beclabito and the Todilto, but many pipes extend to within short distances of the contact in other places (fig. 10). These observations are compatible with an origin of the pipes by dissolution of the evaporite unit at the top of the Todilto, although the precise mechanism of collapse remains to be demonstrated.

Gabelman (1957) presented additional evidence against a solution-collapse origin for clastic pipes on the Colorado Plateau, including the Jurassic pipes of the San Juan Basin. He claimed that the height-to-width ratios of the pipes are too great and the geometrical forms too nearly perfectly cylindrical for a collapse origin to be plausible. However, cylindrical collapse structures of large height-to-width ratio are known to form under a variety of conditions, as the following review demonstrates.

One type of collapse structure that is commonly cylindrical in form is volcanic ring complexes, including cauldron-subsidence structures and calderas (Billings, 1943; Macdonald, 1972; Williams and McBirney, 1979); however, a large height-to-width ratio can seldom be demonstrated for these structures. In structures interpreted to be of carbonate solution-collapse origin, cylindrical forms have been observed by many workers (for example, Dietrich, 1953; Keys and White, 1956; Barrington and Kerr, 1963; Hawley and others, 1965; Wenrich, 1985; Krewedl and Carisey, 1986; Wenrich and others, 1988), and at least some of these structures have large height-to-width ratios. Cylindrical structures interpreted to have formed by evaporite solution collapse also have been noted (for example,

Figure 9. Bases of pipes in the lower part of the Beclabito Member just west of Red Rock State Park (part of outcrop sketched in figure 8). Jacob's staff for scale is 1.5 m long. Bracketed interval comprises units 1–4 of figure 8; arrows point to thin red mudstone unit at top of unit 2 of figure 8. Note that the deformation associated with the pipes affects the red mudstone but does not affect the Todilto Limestone Member beneath the bracketed interval.

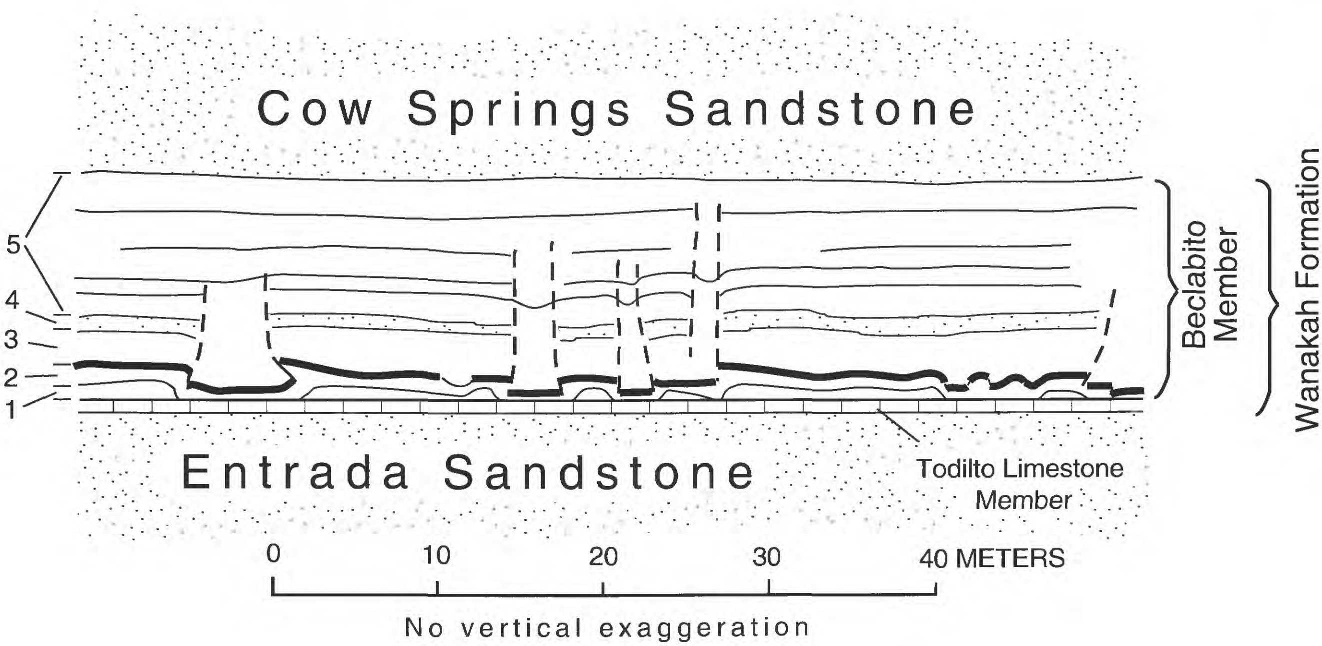

Figure 8. Cross section of several pipes in the Beclabito Member just west of Red Rock State Park (fig. 1), NE1/4 sec. 10, T. 15 N., R. 17 W., McKinley County, New Mexico. Sketched from a photograph. Resistant eolian sandstones represented by dotted pattern. Numbered units of the Beclabito Member are (1) salmon-colored sandstone, (2) siltstone with thin red mudstone bed at top (represented by heavy line), (3) structureless sandstone, (4) eolian cross-laminated sandstone, and (5) silty sandstone and siltstone. Note that the deformation associated with the pipes does not affect the Todilto Limestone Member. Also note the flared bases of several pipes, which indicate lateral spreading.

Figure 10. Deformed lower part of Beclabito Member overlying undeformed Todilto Limestone Member and Entrada Sandstone at Red Rock State Park (fig. 1). Bracketed interval is 5–6 m thick and comprises the lower part of the Beclabito (units 1–4 of fig. 8). The thin, resistant sandstone bed at the top of the bracketed interval (unit 4 of fig. 8) is penetrated by numerous small pipes and disturbed by small faults and folds that do not affect the Todilto. Note especially that the part of this bed adjacent to the pipe in the right part of this photograph is raised relative to parts of the bed farther from the pipe (arrows point to edges of raised area around pipe).

Landes, 1945; Christiansen, 1971; Anderson and others, 1978; Anderson and Kirkland, 1980), and some of these structures have large height-to-width ratios.

Some of the most instructive observations of collapse structures come from studies of inadvertent subsidence above underground mines (Dunrud, 1984) and artificially dissolved salt deposits (Walters, 1977; Ege, 1984) and from studies of planned collapse in the caving method of underground mining and the flow of granular material from outlets at the bottoms of storage bins (Yenge, 1980, 1981; Coates, 1981; Kvapil, 1982; Peters, 1984). These studies are particularly instructive because the structures are artificially induced and, therefore, unequivocally of collapse origin. Artificially induced collapse structures can reach heights more than twenty times their widths and, where they form above an equidimensional cavity or outlet and do not extend to the surface, are of highly prolate ellipsoidal (cigar-shaped) or elongate cylindrical form (Yenge, 1980, 1981; Coates, 1981; Kvapil, 1982; Peters, 1984). Where the collapse extends to the surface in unconsolidated material, a funnel-shaped top forms by the avalanching of material down the sides of the surface depression.

The foregoing comparison of hypotheses for the origin of the clastic pipes in the southern San Juan Basin suggests that an evaporite solution-collapse interpretation cannot be ruled out and is just as capable of accounting for the observed phenomena as a spring-vent interpretation, the previously most favored interpretation for the pipes. In the following section we discuss experimental evidence that adds further support to a solution-collapse interpretation.

Experiments on Collapse Structures

Previous experiments on the collapse of granular material above an actual or potential cavity all resulted in highly elongate, vertically oriented structures (Yenge, 1980, 1981; Coates, 1981; Kvapil, 1982; Peters, 1984), but some questions remained unresolved. In particular, it was not obvious how the external form and internal structure of the collapse structure would vary under different conditions of cohesive strength. Some theoretical and experimental work suggests that a collapse structure will expand in width upward from its base (for example, Yenge, 1981; Kvapil, 1982). On the other hand, the theoretical analyses and experiments of Anderson (1937), Sanford (1959), and others suggest that faults on opposite sides of a collapse structure will tend to arch over and meet upward, leading to upward narrowing and termination of the collapse structure. To address these uncertainties we designed a series of simple experiments in which the cohesive strength of the material was varied by changing its degree of water saturation.

The experimental apparatus consisted of a 5-gallon paint bucket (30 cm diameter) and a small can (7.5 cm or 2.5 cm in diameter). The bucket was cut open on one side and covered with a removable wall to allow a window for viewing the structure at the end of the experiment (fig. 11*A*). In the bottom of the bucket a hole was cut just large enough to allow the can to slide through. The experiment was begun by raising the can approximately 5.5 cm (4 cm for the smaller of the two cans) through the hole in the bottom of the empty bucket. The bucket was filled loosely with alternating thick layers of a light-colored, medium-grained sand, similar to that found in pipes in the study area, and thin layers of a dark, fine-grained sand to delineate the pattern of deformation produced during the experiment (fig. 11*A*). The can was then slowly (over a period of several minutes) lowered flush to the bottom of the bucket so as to cause gradual collapse of the overlying sand. Finally, the bucket was turned on its side while a partial lid was put on the top of the bucket to keep sand from spilling out, the upward-facing removable wall was taken out, and sand was scraped away by a long spatula or machete to allow a view of the resulting deformation in a cross section through the sand.

Six experiments were performed in which either the water content of the sand was varied or the diameter of the can was changed. Table 1 gives the values of these parameters for the six experiments and a brief description of

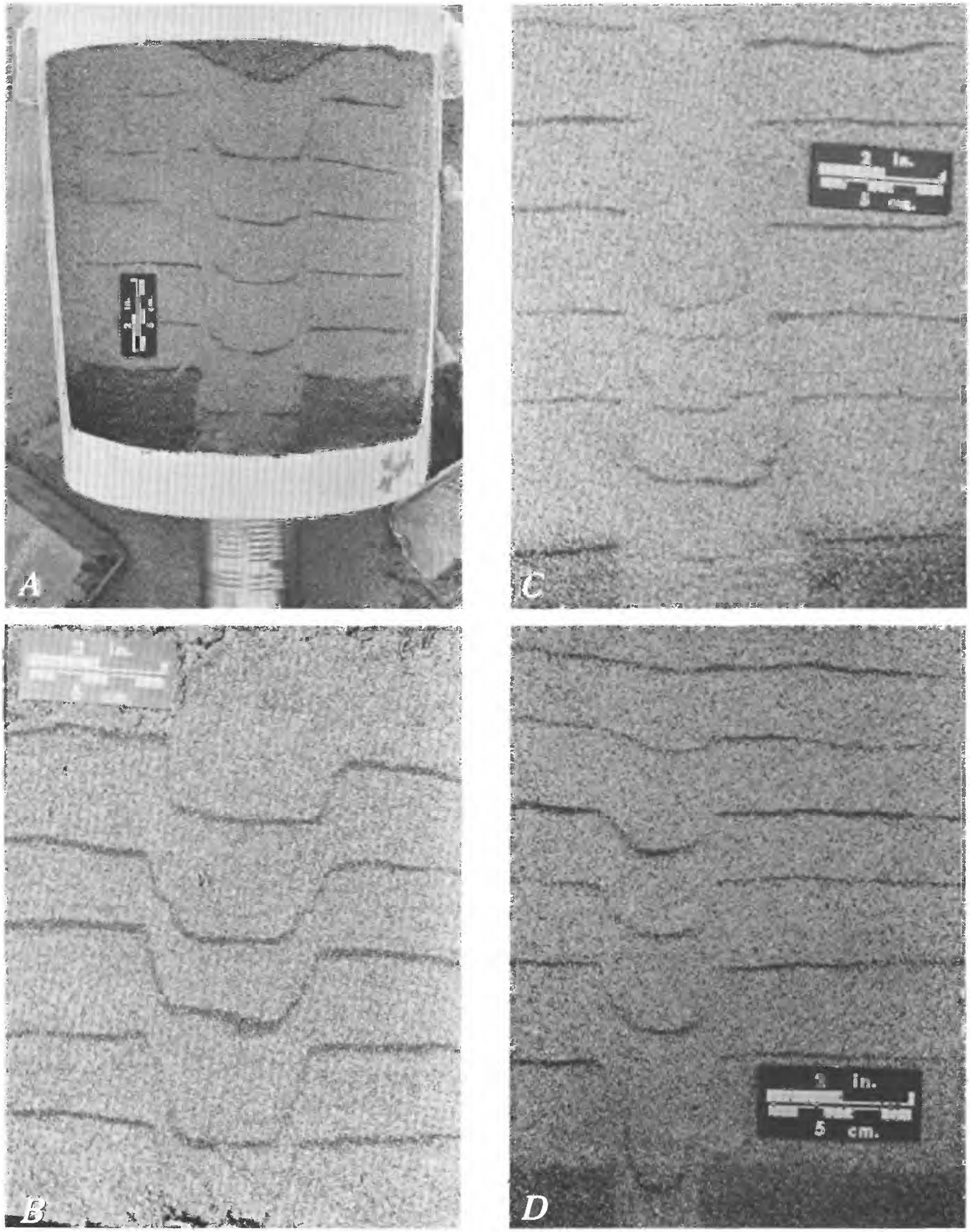

Figure 11. Collapse-induced pipes produced in experiments. *A*, Experiment 2; sand completely dry except for damp, relatively dark sand that was placed in bottom of bucket up to initial level of top of can. *B*, Experiment 6; sand completely water saturated. *C*, Experiment 3; sand damp. *D*, Experiment 1; sand dry, can diameter 2.5 cm instead of 7.5 cm as in the other experiments.

Table 1. Data on collapse experiments

Experiment	Water content (percent)	Cavity diameter (centimeters)	Results
1	0	2.5	Collapse did not extend to surface (fig. 11*D*)
2	0	7.5	Collapse extended to surface, walls vertical (fig. 11*A*)
3	3	7.5	Collapse extended to surface, narrowed toward top (fig. 11*C*)
4	4	7.5	No collapse, cavity remained open
5	64	7.5	No collapse, cavity remained open
6	100	7.5	Collapse extended to surface, walls vertical (fig. 11*B*)

the results. The degree of water saturation was determined from the weight percent of water for each run, scaled by run 6, which was carried out underwater with the sand completely saturated.

In experiments 4 and 5, which involved damp, cohesive sand, the strength of the sand was not exceeded; therefore no deformation occurred above the cavity formed by the lowered can. In experiments 2 (dry sand) and 6 (completely saturated sand), the sand was essentially non-cohesive, and the results were almost identical. In both of these experiments the walls of the collapsed material were almost vertical, extending from the top of the can to the top of the bucket, where a small avalanche funnel formed (figs. 11*A*, *B*). The center of the collapsed material was always downdropped the most, giving a broad U-shaped appearance to the stratification. Upon close examination it was observed that the walls of the collapse structure were zones of finite thickness (approximately 0.75 cm) and that the sand within the wall zone was strongly sheared, as indicated by drag of the originally horizontal layers within the wall zone.

In experiment 3, in which the sand was slightly cohesive because of its low water content, the collapse extended to the surface but narrowed toward the top (fig. 11*C*). The downward widening of the collapse structure caused the material near the top of the structure to drop a greater distance than the can was lowered. In experiment 1, in which the sand was dry and the smaller can was used, the collapse did not extend all the way to the surface. The walls of the collapse were almost vertical for approximately 15 cm from the base; above that level the collapse narrowed and disappeared at a point 22 cm from the base (fig. 11*D*). In this experiment, the amount of downdrop was greatest at the base of the bucket and decreased upward.

Our experiments were of such small scale that a relatively small cohesive strength prevented collapse; however, scaling principles suggest that a relatively small cohesive strength in our experiments would correspond to a greater cohesive strength in a structure of larger scale. Within the limitation of the small range of cohesive strengths investigated, it can be stated that, in both noncohesive and cohesive sand, the collapse structures were pipes that had large height-to-width ratios and almost vertical walls. Layers within the collapse structures were deformed by drag but were not broken.

Altogether, the experimental collapse structures closely simulated the pipes of the southwestern part of the San Juan Basin. Although this similarity does not prove a collapse origin for the natural pipes, the experimental evidence adds support to a collapse interpretation.

The Problem of Excessive Downdrop

The hypothesis that the pipes originated by collapse resulting from local dissolution of a relatively thin evaporite bed presents problems not yet discussed. One such problem is finding an explanation for amounts of downdropping in the pipes that are excessive in the sense of being greater than the original thickness of evaporites that were later dissolved. The amount of downdroping in pipes in the southwestern part of the basin is as much as 15 m, and evaporites at the top of the Todilto Limestone Member were probably no more than 1 or 2 m thick in that part of the basin.

Keys and White (1956) and Hawley and others (1965) noted an amount of downdropping greater than the thickness of underlying dissolved rock within pipes in Utah interpreted to be of solution-collapse origin. They speculated that the excessive amount of downdropping might be due to lateral spreading of downdropped material at the base of a pipe as the underlying bed of soluble rock was progressively dissolved outward from a central point beneath the pipe. Similar lateral spreading of collapsed material into underground mine workings was called on by Dunrud (1984) to explain mine subsidence pits deeper than the thickness of the underlying material removed by mining. Excessive amounts of downdrop can be caused by gradual downward widening of a pipe, such as occurred in our experiment 3 (fig. 11*C*), as well as by widening due to lateral spread at the very base.

Another possible cause of downdropping greater than the thickness of underlying dissolved rock is dissolution of part of the material in the pipe itself. For example, Keys and

White (1956) and Hawley and others (1965) mentioned dissolution of carbonate cement, carbonate-rock beds, and siliciclastic grains within the pipes as possible contributing causes of the excessive downdropping that they observed; however, significant amounts of carbonate are not available for dissolution in the pipe-bearing parts of the stratigraphic section in the southern San Juan Basin. In addition, although mineralogical comparisons of pipe rock and surrounding rock suggest that some feldspar grains in the pipes were altered to clay minerals (Megrue and Kerr, 1965), we doubt that the alteration caused significant volume changes. Certainly no changes in thickness of preserved beds within the pipes can be demonstrated by comparison with the same beds outside the pipes.

Yet another possible cause of excessive downdropping is the flushing of material from pipe bottoms by underground streams that flowed through caverns in the underlying soluble rock. There is no evidence, however, of caverns or underground stream deposits in or at the top of the Todilto Limestone Member in the southern San Juan Basin.

We have not observed systematic downward widening of pipes, although the vertical extent of pipe outcrops may not be great enough to rule out such widening. On the other hand, we have observed evidence of lateral spreading at the bases of pipes. In the small pipes whose bases we observed west of Red Rock State Park, a small amount of lateral spreading is indicated by basal flaring of the pipes (fig. 8). Additional lateral spreading is suggested by the fact that a distinctive salmon-colored sandstone bed (unit 1, fig. 8) that generally rests on the Todilto Limestone Member is absent beneath the pipes; deformed bedding in the salmon-colored sandstone adjacent to the pipes suggests that sand in this bed was squeezed to the sides as the pipe material descended. Other abrupt lateral variations in bed thickness in the lower few meters of section above the Todilto (units 1, 2, and 3, fig. 8) suggest significant lateral redistributions of material in this part of the section; however, we cannot demonstrate that these variations are the result of lateral spreading from the bases of pipes.

Material that spread laterally would support the overlying sediment after complete dissolution of the evaporite bed from areas around the pipes; therefore, it might be expected that the elevation of individual beds in the host rock would be highest adjacent to the pipes, where the beds would be supported by the greatest thickness of injected pipe material (fig. 12). Although sagging or downfaulting of beds toward the pipe axis was observed adjacent to many pipes, in several pipes the beds adjacent to the pipes are higher than those farther away (fig. 10). Beds adjacent to some pipes have a relative vertical displacement on opposite sides of pipes that amounts to tens of centimeters (fig. 8). This displacement suggests that material from the pipes spread differentially in opposite directions.

The evidence of lateral spreading helps to explain the large amounts of downdrop observed in some of the pipes. We cannot claim, however, to have demonstrated that the amount of lateral spreading is sufficient to account for amounts of downdrop that almost certainly exceed the original thickness of evaporites later dissolved. Although the solution-collapse hypothesis thus cannot be regarded as completely satisfactory at present, we regard it as being better able to account for downdropping than the alternative spring-vent hypothesis.

The Problem of Complete Dissolution

In addition to the problem of excessive downdropping, a serious problem facing the hypothesis of pipe origin by solution collapse is what will be called the problem of complete dissolution. Complete dissolution of the evaporite bed following the localized dissolution that gave rise to the pipes would cause the beds adjacent to the pipes to settle to the same level as the beds filling the pipes, thereby eliminating the relative downdrop of the pipe fill (fig. 12).

The problem of spatially discrete collapse structures in an area where an evaporite bed has been completely dissolved pertains primarily to the southwestern part of the San Juan Basin. In the southeastern part of the basin, the gypsum-anhydrite unit has been thinned or removed by dissolution only locally, and many pipes are concentrated in areas of appreciable gypsum-anhydrite dissolution (Schlee, 1963; Moench and Schlee, 1967), as would be expected if they were evaporite solution-collapse structures. Even in that part of the basin, however, discrete pipes are present in large areas where the gypsum-anhydrite unit is now absent. Why did recognizable collapse structures not form between the pipes in areas where the solution-collapse hypothesis requires that the evaporite unit be completely dissolved?

We can offer several partial answers to the question. First, lateral spreading of pipe material into potential cavities around the bases of the pipes, such as we observed west of Red Rock State Park (fig. 8), reduces the amount of downdrop required in areas between the pipes. Second, if small-diameter pipes that extend only short distances upward from the Todilto are taken into account, the areal density of pipes is much greater than is suggested by the relatively small numbers of pipes at higher stratigraphic levels. Third, the later stages of evaporite dissolution may have occurred when the sediments were more lithified and rigid than they were when the pipes formed, and the downdropping accompanying this later dissolution may have taken a form other than pipes.

An example of later downdropping in a form other than pipes is faulting, which might not be easily recognized as being caused by solution collapse. Many faults having small offsets (less than 0.4 m) are present in the Beclabito Member and Cow Springs Sandstone in and near Red Rock

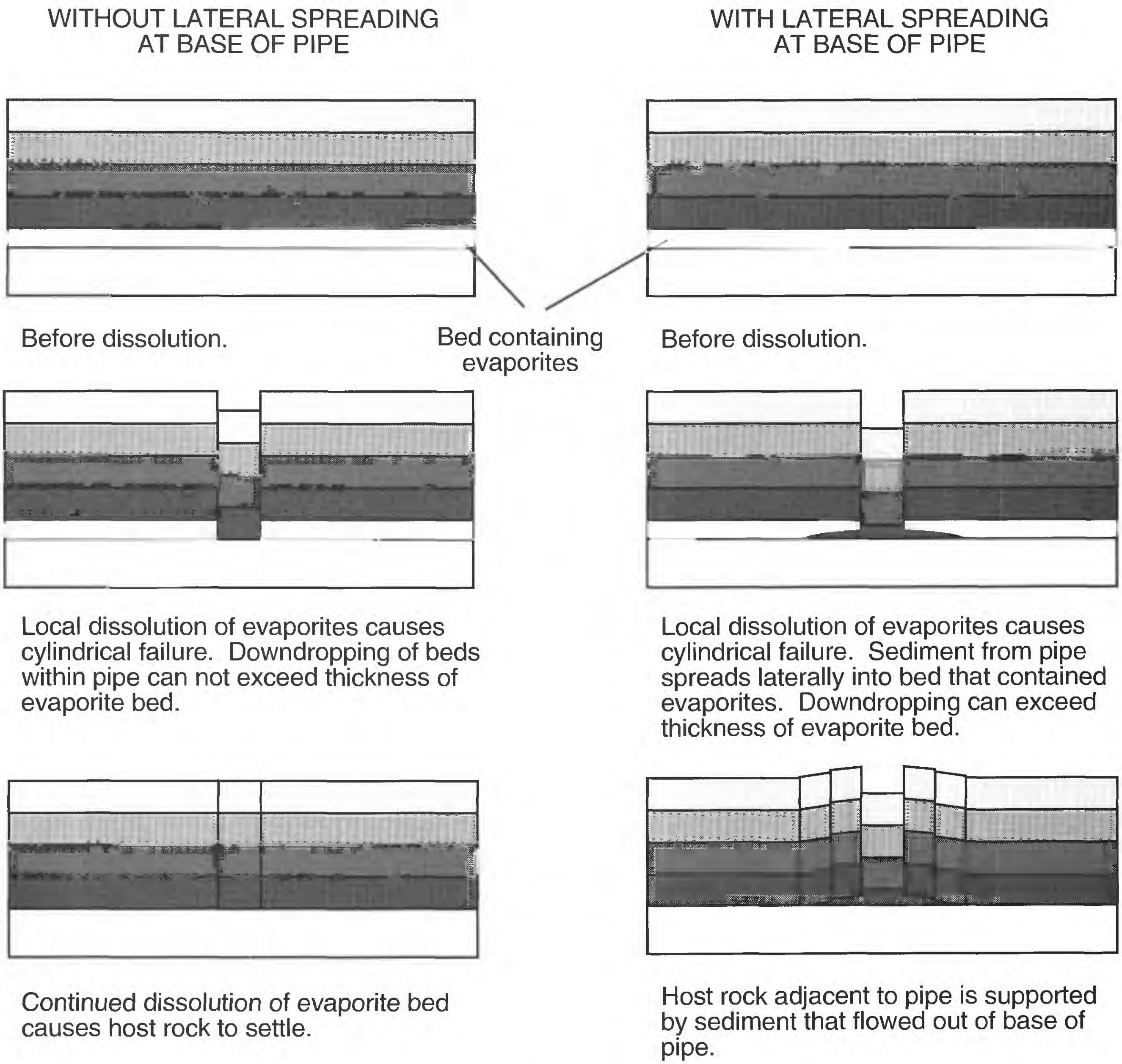

Figure 12. Schematic drawings showing postulated role of lateral spreading at pipe base in producing observed characteristics of pipes. Without lateral spreading or other methods of reducing bulk volume of material within pipe (left), initial downdrop within pipes cannot exceed thickness of evaporite bed; downdrop is eventually eliminated as the evaporite bed continues to dissolve and rock surrounding the pipe drops. Lateral spreading from bottom of pipe (right) enables initial downdrop within pipe to exceed thickness of evaporite bed. Rock adjacent to pipe is supported by sediment that spreads laterally from base of pipe, thereby preserving the relative downdrop after remainder of evaporite bed dissolves and rock farther away from pipe settles.

State Park. These faults do not extend downward into the Todilto Limestone Member, and at least many of the faults terminate upward in the Cow Springs Sandstone, though not in a manner that suggests faulting contemporaneous with deposition of the Cow Springs. The faults are vertical to high-angle reverse and are spaced 5–20 m apart within a given set of faults. All faults in a given set have similar orientation and displacement. The faults in one set curve in plan view as much as 50° in a distance of 300 m; such a degree of curvature suggests that the faults are not of tectonic origin. Possibly these faults are the result of solution collapse, predominantly at a stage following pipe formation.

The evidence presented in this section helps to explain the fact that the pipes preserve a record of localized downdropping even though the hypothesized evaporite bed has been dissolved not only under the pipes but also in areas between the pipes. As in the problem of excessive downdrop, however, we cannot claim to have demonstrated conclusively that the processes called on here are sufficient to account for the observed features.

Original Extent of Dissolved Evaporite Unit

According to the solution-collapse interpretation of pipes in the southwestern part of the San Juan Basin, the gypsum-anhydrite unit that forms the upper part of the Todilto Limestone Member originally extended far beyond its present limits. In this section we attempt to reconstruct its former distribution along the southern margin of the San Juan Basin and its precise stratigraphic position in this area.

The gypsum-anhydrite unit that forms the upper part of the Todilto crops out only in the southeastern part of the San Juan Basin. In the subsurface just a few kilometers north of the outcrop belt, however, the unit extends as far west as Prewitt (Hilpert, 1969). Local dissolution near the present edges of the evaporite unit is indicated by great variations in evaporite thickness over short distances (Moench and Schlee, 1967; Stapor, 1972; Tanner, 1972). Another feature that has been attributed to the dissolution of evaporites from a sequence of interbedded limestone and evaporites in the Todilto is brecciation and recrystallization in the upper part of the limestone unit of the Todilto Limestone Member beyond the present edges of the gypsum-anhydrite unit (Rawson, 1980; Ridgley, 1986). Evidence (other than the presence of pipes) that evaporite minerals were present as far west as the western pinchout of the Todilto Limestone Member, a few kilometers west of Red Rock State Park, includes (1) recrystallization of the upper 0.1–0.2 m of the limestone as far west as its pinchout and (2) the presence of abundant vugs, which are probably molds of gypsum nodules and crystals, in the salmon-colored calcareous sandstone (unit 1, fig. 8) that immediately overlies the limestone from the Coolidge area to the western pinchout of the limestone. The inference that the vugs were originally filled by gypsum is based on the rhombic shapes of some of the vugs (fig. 13).

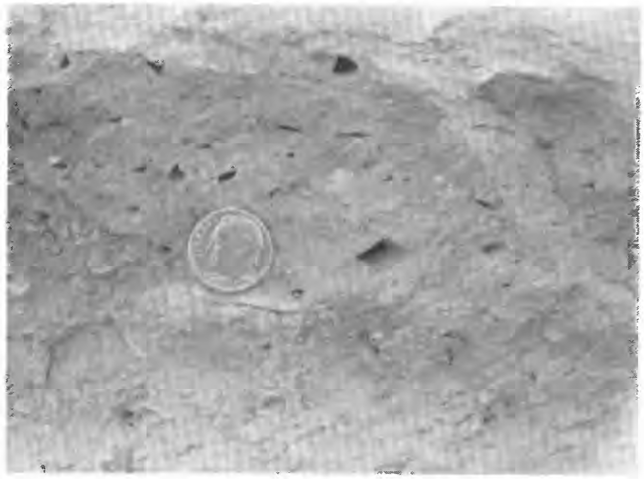

Figure 13. Vugs in salmon-colored sandstone bed (unit 1 of fig. 8) immediately above the Todilto Limestone Member in Red Rock State Park (fig. 1). Coin for scale is 18 mm in diameter. Rhombic shape of vug to right of coin suggests origin by dissolution of a gypsum crystal; rounded vugs probably originated by dissolution of gypsum nodules.

The stratigraphic position of the hypothesized former evaporite in the southwestern part of the basin can be inferred within narrow limits. In and near Red Rock State Park, the Todilto Limestone Member is overlain sequentially by (1) 0.5–1.0 m of fine- to medium-grained, moderately to very calcareous, vuggy, salmon-colored (typically 10R6/4 in the Munsell notation) sandstone, commonly with swirled bedding; (2) 0.8–2.0 m of thin-bedded to structureless, dark-grayish-red mudstone and reddish-brown siltstone; (3) 1.5–2.3 m of fine- to medium-grained, reddish-orange to brown, structureless sandstone; (4) 1.0–1.2 m of fine-grained, light-grayish-pink, cross-laminated, resistant eolian sandstone; and (5) a thick sequence of very fine to fine grained, thick-bedded, indistinctly bedded, reddish-brown silty sandstone and siltstone typical of the Beclabito Member (fig. 14). A lower limit for the stratigraphic position of the former evaporite is the base of the recrystallized upper 0.1–0.2 m of the Todilto Limestone Member, as indicated by the absence of deformation in the underlying thin-bedded limestone. An upper limit for the stratigraphic position of the evaporite is the base of the red mudstone in unit (2) of the Beclabito Member, as indicated by the fact that the red mudstone is the lowermost bed in pipes with preserved, downdropped bedding just west of Red Rock State Park (figs. 8, 9). Units (1) and (2) pinch out westward at about the same point that the Todilto Limestone Member pinches out, and the western limit of pipes that are easily visible in the resistant unit (4) coincides with these pinchouts (fig. 14). We infer that the western limit of the former evaporite unit coincided with the western limit of the limestone unit of the Todilto Limestone Member.

Model of Pipe Origin

The evidence for an evaporite solution-collapse origin of the pipes in Jurassic rocks of the southwestern part of the San Juan Basin is strong, although not conclusive, and no other mode of origin seems plausible. Moreover, we consider the evidence from the southeastern part of the basin to be compatible with a solution-collapse origin for the pipes in that area as well, and we see no reason to favor different origins for pipes in the two parts of the basin. We now propose a scenario for the development of pipes throughout the southern San Juan Basin.

Pipe formation by evaporite solution collapse requires that dissolution begins in small areas beneath the future pipes. The cause of such localization of dissolution is unknown, but upward water flow through spring vents, as

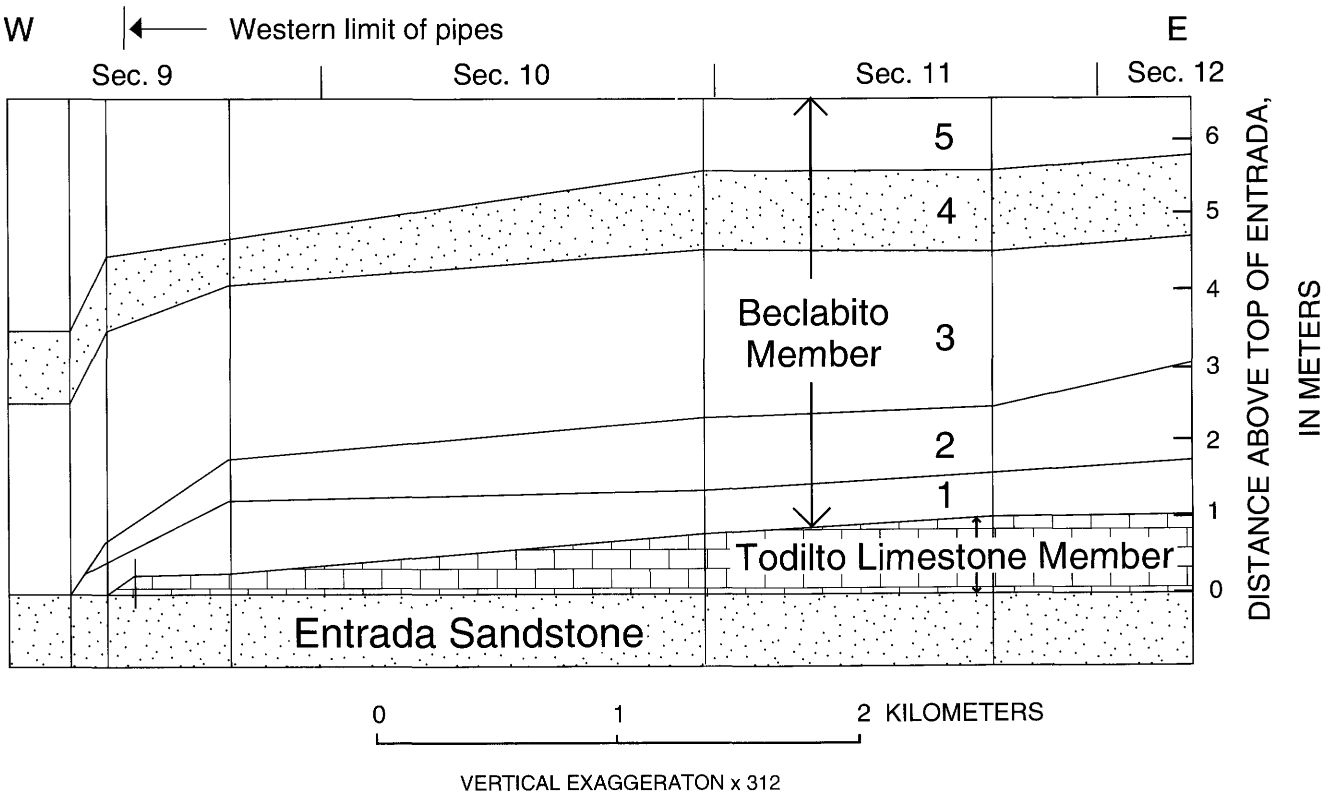

Figure 14. Stratigraphic cross section of the Todilto Limestone Member and lower part of Beclabito Member in and near Red Rock State Park (fig. 1). The line of section is near the north edge of sections 9, 10, 11, and 12, T. 15 N., R. 17 W., McKinley County, New Mexico. Vertical lines represent measured sections. Numbered units correspond to those in figure 8.

hypothesized by Schlee (1963), may have played a role in the localization, although we doubt its direct role in pipe formation. A solutional role for upward water flow was suggested by Barrington and Kerr (1963) for other solution-collapse pipes on the Colorado Plateau. On the other hand, Anderson and Kirkland (1980) proposed a model for localized evaporite dissolution by brine density flow through permeable rock beneath an evaporite bed; this process eliminates the need for upward water flow through sediment overlying the evaporite bed. Whether or not localized upward water flow was involved in the initiation of the evaporite dissolution that led to pipe formation, the pipes probably served as conduits for water movement after they formed, and such water movement was undoubtedly important in pipe mineralization both in the San Juan Basin and elsewhere (Keys and White, 1956; Barrington and Kerr, 1963; Hawley and others, 1965; Megrue and Kerr, 1965; Gornitz and Kerr, 1970; Bowles, 1977; Wenrich, 1985).

As the evaporite gradually dissolved locally, the overlying unconsolidated or poorly consolidated sediment probably subsided equally gradually because the sediment was too weak to allow open cavities to form or to prevent upward propagation of the subsidence. The gradual nature of the subsidence probably inhibited fracturing of the downdropped sediment and thus helped to preserve stratification of the sediment. Gradual subsidence of unconsolidated sediment simultaneous with dissolution has been called on to explain other solution-collapse structures that have bedding preserved (Dietrich, 1953).

The degree to which bedding in the downdropped sediment was disrupted must have depended in part on the distance of downdropping. A larger amount of downdropping in the southeastern part of the basin, where the thickness of dissolved evaporite was much greater than it was farther west, is probably a major factor accounting for the greater rarity of preserved bedding in pipes in the southeastern part of the basin. Disturbance of the grain framework during downdropping would have caused the sediment within the pipe to become more loosely packed, and this increase in bulk volume could have compensated for the volume lost by evaporite dissolution and led to the end of growth of some pipes before they reached the surface, as in our experiment 1 (fig. 11*D*).

As the area of evaporite dissolution expanded outward from a point directly beneath a pipe, the downdropped material at the base of the pipe tended to spread laterally into the potential cavity, producing an amount of downdrop greater than the original thickness of the evaporite bed. In the southeastern part of the basin, where the evaporite unit was thick, dissolution and pipe formation generally ceased before the evaporite unit was completely removed, but not before a few pipes extended into beds as high as the upper part of the Morrison Formation. In the southwestern part of the basin, where the evaporite unit is interpreted to have been thin and is now absent, the processes at work during the final stages of evaporite dissolution are not clear. Lateral spreading at the bases of pipes probably played some part in preserving the downdrop within the pipes relative to the surrounding beds. In addition, the final stages of evaporite dissolution probably occurred when the overlying beds were sufficiently lithified and rigid for their collapse to take the form of faults that were less tightly curved and of much greater lateral extent than the faults that bound the pipes.

BROADER IMPLICATIONS

We suspect that some other large pipes previously interpreted as water-escape or slurry-injection structures may be of solution-collapse origin. In particular, a solution-collapse origin should be considered for pipes in southern Utah studied by Hannum (1980). These pipes have a stratigraphic range from the Carmel Formation into the overlying Entrada Sandstone and possibly higher. Two kinds of evidence that suggest a solution-collapse origin for these pipes are (1) the probable occurrence of downdropped material within the pipes, as noted by Hannum (1980), and (2) the occurrence of gypsum within the Carmel Formation in the area of pipe occurrence.

Jurassic rocks of the San Juan Basin contain deformational features other than pipes that may be the result of subsidence due to dissolution of the gypsum-anhydrite unit that forms the upper part of the Todilto Limestone Member. Among such features are (1) broad sags between remnants of gypsum in the eastern part of the San Juan Basin described by Stapor (1972) and Tanner (1972) and (2) folds and associated faults of Jurassic age in the southeastern part of the basin described by Moench and Schlee (1967) and Hilpert (1969). The folds are in rocks as young as the Morrison Formation and are truncated by the unconformity at the top of the Morrison. The folds are mapped as extending only short distances into the Entrada Sandstone and have not been recognized in older formations; they probably do not extend down to basement. Many of the folds are closely associated with belts of pipes and with variations in thickness of the gypsum-anhydrite unit.

The Jurassic folding and faulting affected sedimentation in parts of the stratigraphic section from the limestone unit of the Todilto Limestone Member to the Morrison Formation (Moench and Schlee, 1967). We suspect that much of the folding and associated phenomena was caused by evaporite dissolution. Such dissolution cannot account, however, for folds at the Todilto-Entrada contact or for variations in thickness of the Todilto limestone unit associated with the folds, because these features are beneath the evaporite unit. Rather than being due to folding, these features may be expressions or effects of depositional topography at the top of the Entrada Sandstone, similar to the preserved dune topography mapped at the top of the Entrada in the subsurface by Vincelette and Chittum (1981). Other intraformational folding in the limestone unit of the Todilto may be the result of differential loading by overlying sediments (Green, 1982).

CONCLUSIONS

New observations on clastic pipes in Jurassic rocks of the southern San Juan Basin indicate that the pipes are present as far west as the pinchout of the Todilto Limestone Member of the Wanakah Formation in the vicinity of Gallup, New Mexico. The pipes in the southwestern part of the basin commonly contain downdropped, almost unbroken strata identical to strata surrounding the pipes, whereas previously studied pipes in the southeastern part of the basin typically contain brecciated or homogeneous rock. This difference in character probably reflects a difference in the amount of downdrop of the pipe-filling material—less in the southwestern part of the basin and more in the southeastern part—rather than a difference in pipe origin. The less advanced state of pipe development in the southwestern part of the basin more readily permits interpretation of pipe origin than does the relatively advanced stage of pipe development in the southeastern part.

The presence of downdropped but otherwise little disturbed strata within many pipes in the southwestern part of the basin is not easily explained by a spring-vent interpretation, the explanation proposed in the most detailed study of pipes in the southeastern part of the basin (Schlee, 1963). We interpret the clastic pipes in the southwestern part of the basin to be solution-collapse structures resulting from the dissolution of evaporites originally present at the top of the Todilto Limestone Member. Some aspects of the pipes—amounts of downdrop greater than the probable original thickness of dissolved evaporites and the restriction of easily recognizable downdropping to discrete pipes in areas where any original evaporite bed has been entirely dissolved—remain difficult to explain by a solution-collapse mechanism. Nevertheless, we regard the overall body of evidence as favoring a solution-collapse origin for the pipes in the southwestern part of the basin. Moreover, we favor the solution-collapse interpretation for the pipes in the southeastern part of the basin, and we regard subsidence that accompanied dissolution of evaporites as a probable cause of folding and faulting of Jurassic rocks in the southern San Juan Basin.

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