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PRELIMINARY INVESTIGATION OF THE ORIGIN OF THE RILEY TRAVERTINE, SOCORRO COUNTY, NEW MEXICO

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INTRODUCTION

The origin of the late Cenozoic travertinelike limestone northeast and southeast of Riley has been variously ascribed to playa, lacustrine, pedogenic, or spring processes. The origin of such a large deposit of laminated, vuggy, or massive limestone of highly varied morphology is more likely to be complex than to be the single one proposed by most workers (Ruhe, 1967, p. 67).

The hypothesis presented here is that the limestone is the result of a nonpedogenic process producing proximal (surface and subsurface) and distal (subsurface) secondary carbonate deposits related primarily to lateral groundwater flow. The carbonate-charged water is interpreted to have been generated in Paleozoic limestones on the west flank of the Ladron Mountains and the southeast flank of Sierra Lucero in the late Cenozoic. These waters flowed over and through alluvial fans and other sediments into and down the axis of an elongate basin or valley draining southward. This drainage merged with an east-trending valley which drained eastward near the present latitude of San Lorenzo Canyon and emptied into the ancestral Rio Grande. Proximal spring, lacustrine, and reworked carbonate deposits were formed at the surface. They are contemporaneous with pervasive and expansive subsurface secondary calcite cementation of pre-existing host sediments. This depositional system is analogous in part to the groundwater calcrete (nonpedogenic) described in Western Australia by several authors (see for example Carlisle and others, 1978).

Use of the term Riley travertine will be retained in this report. The definition of travertine is broad and nongenetic enough to include the Riley deposit. Neither laminar nor vuggy structure, nor thermal spring origin is required for a travertine. Relatively rapid precipitation from carbonate-bearing surface or subsurface water is sufficient. Semantic problems abound concerning secondary calcite deposits and are discussed in detail by many authors, including Carlisle and others (1978), Reeves (1976), and Goudie (1972a, b).

The Riley travertine occurs in two main deposits 8 km northeast and 18 km southeast of Riley, hereafter called north mesa and south mesa, respectively (fig. 1). The once continuous body of Riley travertine has been bisected by incision of the Rio Salado. The Riley travertine of north mesa underlies about 46 km' in T2 and 3N, R3W, on the west flank of the Ladron Mountains. At south mesa, the travertine underlies about 21 km' in TIN and IS, R2 and 3W, and a small portion of the Sevilleta National Wildlife Refuge along the west edge of the Silver Creek drainage. It extends westward past La Jencia Creek.

The main work on the Riley travertine has been done by Denny (1940, 1941), Kottlowski (1962), Massingill (1977), and Chamberlin and others (1982). Regional mapping at various scales that included the Riley travertine has been done by Bachman (unpublished map for U.S. Geological Survey) and Machette (1978a). Chapin and others (1979) did not differentiate the Riley travertine from the surrounding upper Santa Fe Group. Condie (1976) mapped the Precambrian terrain of the Ladron Mountains and summarized earlier work.

Work with implications to the Riley travertine has been done by Hawley (1978), Machette (1978b), Bachman and Machette (1977), Sanford (1968), Kottlowski (1960), Armstrong (1958), and Bryan (1926). Groundwater aspects are covered by Clark and Summers (1971), Summers (1965), Hall (1963), and Spiegel (1955). Foster and others (1963) mentioned a caliche capping the mesa south of the Rio Salado. Regional structural aspects of the area are summarized in Callender and Zilinski (1976) and Kelley (1977). Siemers (1982) mentioned the Riley travertine as a high-calcium limestone resource.

REGIONAL GEOLOGY AND STRATIGRAPHY

The Riley travertine straddles the boundary between the Colorado Plateau and the Basin and Range provinces. It is at the western edge of the Rio Grande rift in central New Mexico and extends from the relatively stable Lucero uplift into the highly extended La Jencia basin south of the Ladron Mountains. The Riley travertine descends in elevation from north mesa to south mesa. It overlies progressively younger rocks to the southeast. The northern contact, which represents the basin margin, is on Paleozoic rocks of the Colorado Plateau. South of the Rio Salado, the Riley travertine rests on Cenozoic basin-center deposits.

The Riley travertine is not involved in major faulting and appears to be everywhere in depositional contact with underlying units. The Riley travertine at south mesa is tilted slightly (1-2°) to the west. At north mesa it is undeformed although it has a synclinal form which is a remnant of deposition on inclined substrates rather than of tectonism. Pre-Riley faulting is not considered relevant to this study except as it affects transmissivity of the carbonate source rocks or present erosion patterns.

The Popotosa Formation represents early basin-fill deposits related to incipient stages of Rio Grande rifting in the late Oligocene or early Miocene. The Popotosa consists of volcanic-rich fanglomerate and intertonguing playa deposits of the lower Santa Fe Group. The upper Santa Fe Group represents late basin-fill deposits, in part equivalent to the Sierra Ladrones Formation and comprised of fanglomerate derived from modern mountains and of fluvial sandstone deposited by the ancestral Rio Grande.

The slightly diachronous Riley travertine is estimated to be between one and three million years old (Chamberlin and others, 1982). It is locally interbedded within the upper Santa Fe at south mesa (fig. 2). A nearly complete stratigraphic section is exposed from Silver Creek westward through locality 15. The Riley travertine reaches 15 m in thickness, but is typically 4-6 m thick.

Pre-travertine geology is complex within the study area. The Ladron Mountains are mainly Precambrian igneous and metamorphic rocks. A major fault juxtaposes Paleozoic rocks, primarily of the Madera Group, with Precambrian units along the northwestern slope of the Ladron Mountains (Kelley, 1977), although the contact is depositional to the south. The Paleozoic units are dominantly limestone and are composed of abundantly faulted Madera Group, and Abo, Yeso, Glorieta, and San

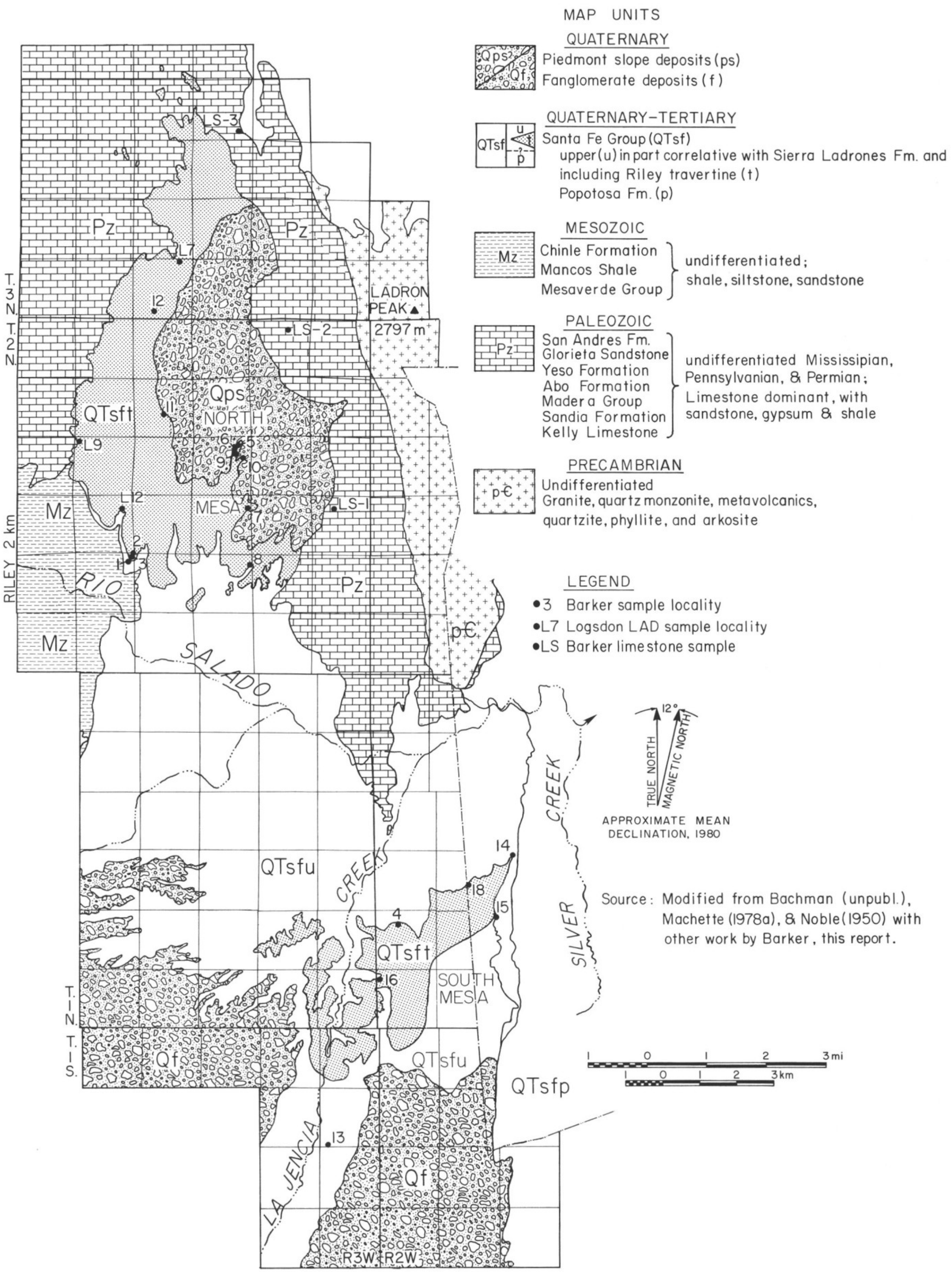

Figure 1. Generalized geologic map of the Riley travertine and adjacent area.

Figure 2. Riley travertine capping mesa at western edge of Silver Creek drainage (localities 14 to 15) at south mesa (looking south).

Andres Formations. They underlie much of the Riley travertine at north mesa and form the northern and western basement upon which the Riley travertine is in depositional contact. To the southwest, the Riley travertine overlaps the Triassic Chinle Formation and the Santa Fe Group of Tertiary-Quaternary age (fig. 3). At the south edge of north mesa, where the main escarpment is prominent, the Riley overlaps the Upper Santa Fe Group with a sharp contact. Quaternary piedmont-slope deposits cover most of the eastern contact and thin remnants of post-Riley Upper Santa Fe Group and soils cover most of the Riley travertine elsewhere. The western and northern margins are less defined because of erosion and facies changes. The Riley travertine at north mesa thins from both the east and the west and from south to north.

The Riley travertine at south mesa was deposited on the upper Santa Fe Group. It is overlain by younger Santa Fe Group deposited on the strata which later became the host for the Riley travertine. The Riley travertine is well defined at the northern edge of the Silver Creek portion but it rapidly thins and changes facies to the south. The upper and lower contacts are generally sharp with a slight angular unconformity locally at the base. To the west, the travertine is indistinct and merges into the Santa Fe Group west of La Jencia Creek. It thins and becomes marly both westerly and southerly of locality 14 in the Sevilleta Wildlife Refuge. Poor- to well-developed calcic soils cover most of south mesa.

The Riley travertine caps the mesa on the western flank of the Ladron Mountains and the mesa west of the Silver Creek drainage on the northwestern flank of the Lemitar Mountains. The mesas grade into surrounding terrain except where well-developed escarpments facing the Rio Salado from the north and south locally dominate the skyline.

Figure 3. Riley travertine (2–3 m thick) capping well-indurated, ledge-forming fanglomerates of the Santa Fe Group at locality 7 on north mesa. Bear Mountains on skyline to southwest.

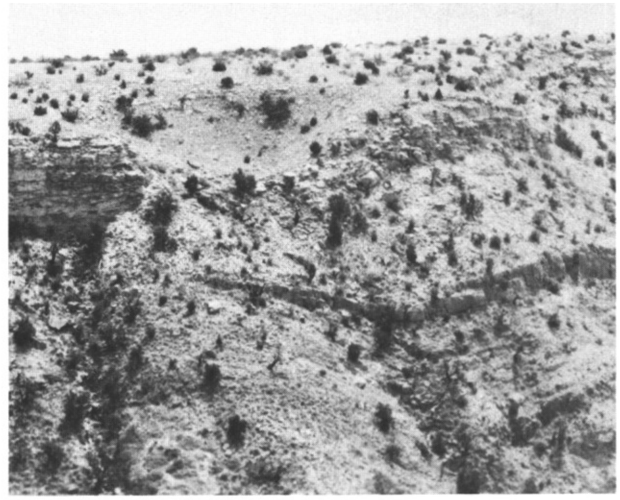

Figure 4. Collapse zone in Permian San Andres Limestone under the Riley travertine east of locality LAD 12 on north mesa (Source: M. J. Logsdon).

The Riley travertine forms very low-angle dipslopes which are most prominent in surface exposures near the edges of the mesas facing the Rio Salado. The Riley travertine generally descends in elevation to the south and southeast.

The east-west relief at north mesa is about 240 m and the north-south relief is about 95 m. Karst topography is present locally and developed mainly near the mesa rim. Some sinkholes or dolines exist near the west-central margin of the Riley travertine (fig. 4). Exposed surfaces typically exhibit carbonate-solution weathering features.

The Riley travertine at south mesa slopes less than 1° to the south and has relief of about 10 m. It slopes about 1-2° to the west with a relief of about 100 m. No karst topography was observed on south mesa although much of the exposed Riley travertine was differentially weathered.

The geochemical data summarized in Tables 1 and 2 suggest that carbonates of the Madera Group are the primary source of the Riley travertine and that south mesa was down the original flow path from north mesa. Insoluble residues were obtained from 18 samples of the Riley travertine by digestion in HC1. Five samples (— 230 mesh) analyzed by x-ray diffraction showed quartz was dominant followed in decreasing abundance by plagioclase, potassium feldspar, kaolinite, montmorillonite, illite, and hornblende. Hydrochloric acid dissolution of the limestone tends to eliminate clay minerals; other clay minerals may have been present prior to digestion. Microscopic analysis of the coarse (+ 230 mesh) fraction of 19 insoluble residues showed the predominate minerals in order of decreasing abundance were quartz, feldspar, hornblende, biotite, muscovite, and rock fragments.

ORIGIN OF THE RILEY TRAVERTINE

The most general conclusion has been an origin ascribed to spring activity. One's perception of the origin can be biased because of the variation from a true laminated travertine (fig. 5) to marl or limy sandstone and siltstone.

The genesis of large-scale, tabular, secondary calcium-carbonate bodies is controlled by the primary movement of carbonate-charged solutions. Vertical flow is dominant in pedogenesis which is a subsurface process related to either descending fluids (gravitational water) or ascending fluids (capillary water). Lateral flow is dominant in nonpedogenic carbonate systems which can have either surface movement or subsurface movement.

Table 1. Chemical and isotopic analyses of selected samples of Riley travertine and other carbonate rocks.

Sample	Description & location[1]		HCl insoluble percent	HCl soluble percent	$CaCO_3$ calc. percent	Calcium titr. percent	Magnesium AA percent	Strontium AA ppm	Strontium XRF ppm	Manganese AA ppm	O^{18}/O^{16} SMOW	C^{13}/C^{12} PDB
RTB 1	basal, laminated	NM	2.20	97.80	92.15	36.9	0.26	1300	1483	34	+24.2	+6.8
2	upper massive	NM	0.47	99.53	97.89	39.2	0.23	639	775	81	+23.7	+6.2
3	middle, mass. to lam.	NM	14.47	85.53	87.66	35.1	0.27	583	807	53	+23.7	+7.0
4	massive	SM	16.27	83.73	79.16	31.7	0.39	278	490	35	+23.2	+0.6
5	laminated	NM	1.14	98.86					1087			
5a	laminated	NM	0.96	99.04					1099			
6	laminated	NM	2.03	97.97					933			
7	massive	NM	5.74	94.26	92.40	37.0	0.23	528	710	117		
8	massive	NM	4.11	95.89	95.65	38.3	0.22	635	857	23		
9	crudely laminated	NM	6.32	93.68					1083			
10	travertine facies	NM	8.26	91.74	91.64	39.1	0.30	757	1099	150		
11	massive, some recrystall.	NM	10.01	89.99	96.89	38.8	0.33	462	608	78		
12	massive, some recrystall.	NM	2.43	97.57	99.64	39.9	0.22	416	555	1123		
13	calcrete, not Riley trav.[2]		21.07	78.93					569			
14	massive	SM	27.34	72.66	64.93	26.0	0.38	396	488	114		
15	massive, recryst.	SM	29.04	70.96	83.66	33.6	0.38	318	331	84		
16	massive	SM	4.58	95.42	93.40	37.4	0.34	<300	373	56		
18	massive	SM	12.39	87.61					233			
LAD 7	Chamberlin et al.1982	NM				>20	0.15	500				
9	Chamberlin et al.1982	NM				>20	0.3	1000				
12c	Chamberlin et al.1982	NM				20	0.2	700				
12d	Chamberlin et al.1982	NM				>20	0.5	1500				
MATB	travertine, Lucero Quarry		0.91	99.09	98.39	39.4	0.27	471	617	37		
LS 1	Madera Group Ls., Ladron Mtns.				99.46	39.83	0.42	831	759	81		
2	Madera Group Ls., Ladron Mtns.				96.07	38.47	0.29	1458	1339	404		
3	Madera Group Ls., Ladron Mtns.				99.49	39.84	0.36	868	759	369		
Kottlowski, 1962 Riley trav.				99.46	40.04	0.13						

1) NM = north mesa; SM = south mesa
2) Sample RTB 13 is from a calcrete younger than the Riley travertine; 1/3 kilometer east of Hudgins Ranch.
NOTE: AA = atomic absorption; XRF = x-ray fluorescence; SMOW = standard mean ocean water; PDB = Chicago standard (Pedee belemnite); titr. = E.D.T.A. titration.

Carbonate supersaturation is induced by loss of CO, from solution, by evaporation, or by both. This is true for vertical and for lateral processes. The dominant mode of Riley travertine formation was lateral movement of carbonate-charged water which produced nonpedogenic secondary carbonate deposits.

The terms caliche and calcrete were introduced simultaneously but calcrete did not become prominent in the United States until the uranium discoveries of the 1970's in Western Australia. These were deposited by lateral groundwater processes in sediments along axes of fluvial valleys. They are nonpedogenic valley calcretes, a subcategory of groundwater calcrete (Carlisle, 1980; Carlisle and others, 1978).

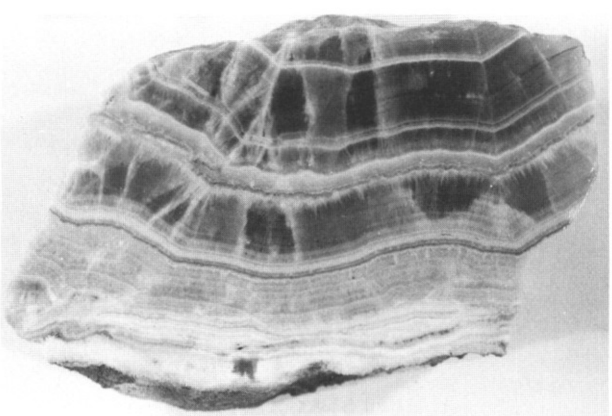

Figure 5. Polished slab of spring-deposit facies of Riley travertine from locality 10 on north mesa.

Groundwater calcretes are nonpedogenic accumulations of calcium carbonate deposited under both surface and subsurface conditions, primarily by lateral flow of cool, carbonate-charged groundwater. They are deposits of the water table rather than of soil water. Nonpedogenic calcrete may be locally indistinguishable from pedogenic caliche and calcrete and from lacustrine, playa, marine, spring-apron, or other limestones. Travertine was excluded from groundwater calcrete by Carlisle and others (1978) but "cienega calcrete" related to surface seeps was included. Cienega calcrete formed from a seep and travertine from a spring are very similar, so the spring-deposit facies of the Riley travertine is a part of groundwater calcrete. Portions of the Riley travertine have been formed by deposition of nonpedogenic calcium carbonate by lateral groundwater flow as recognized by Bachman and Machette (1977), Chamberlin and others (1982), and J. W. Hawley (1983, oral commun.).

Several relationships must be explained by the Riley travertine depositional process: (1) the large area (67 km') underlain now by the Riley travertine and the high probability of a significantly larger areal extent in the past; (2) the highly variable texture and lithology, plus the paucity of spring deposits and pedogenic structures; and (3) the regional paleodrainage system, terrigenous clast provenance, and carbonate source rocks.

Table 2. Calculated mean compositions and ranges in composition of Riley travertine.

	Insoluble residue percent		HCl soluble percent		$CaCO_3$ percent		Calcium percent		Magnesium percent		Strontium ppm	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
North Mesa	4.85 (12)	0.47–16.27	95.15 (12)	85.53–99.53	94.38 (9)	79.16–99.64	38.26 (9)	31.7–39.9	0.26 (13)	0.15–0.33	856 (16)	500–1500
South Mesa	17.92 (5)	4.58–29.04	82.08 (5)	70.96–95.42	82.79 (4)	64.93–93.40	32.18 (4)	26.0–37.4	0.37 (4)	0.34–0.39	383 (5)	233–490
All Samples	8.69 (17)	0.47–29.04	91.31 (17)	70.96–99.53	90.81 (13)	64.93–99.64	36.39 (13)	26.0–39.9	0.28 (17)	0.15–0.39	659 (21)	1500

	Manganese percent		O^{18}/O^{16} SMOW		C^{13}/C^{12} PDB		$\frac{Ca}{Mg}$		Sr/Ca $x10^{-2}$	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
North Mesa	207 (8)	34–1123	+23.9 (3)	+23.7 to +24.2	+6.7 (3)	+6.2 to +7.0	150 (8)	118–181	0.23 (8)	0.14–0.40
South Mesa	72 (4)	35–114	23.2 (1)	—	+0.6 (1)	—	87 (4)	68–110	0.14 (4)	0.10–0.18
All Samples	162 (12)	34–1123	23.7 (4)	+23.2 to +24.2	+5.15 (4)	+0.6 to +7.0	129 (12)	68–181	0.20 (12)	0.10–0.40

Note: Parenthetical integers = number of samples; SMOW = standard mean ocean water; PDB = Chicago standard (Pedee belemnite).

Areal Extent

The Riley travertine now underlies about 67 km' with possibly twice that area implied as the original extent prior to erosion. Travertine of localized spring origin rarely covers such large areas. Supersaturated waters emerging from an orifice will typically equilibrate within a few hundred meters, especially on a caliche substrate and in the presence of biota.

A large area could have been sequentially or simultaneously covered by coalescing spring deposits. Evidence for multiple springs is lacking at south mesa. Chamberlin and others (1982) report possible spring mounds and vents at several localities on north mesa, so a spring-apron origin is reasonable for some portions.

The inferred maximum extent of the limestone has an elongate shape. The width (W) is about 8 km and the length (L) about 32 km for a 0.25 W/L ratio. Very elongate limestone bodies are known, such as the nonpedogenic calcrete of Western Australia (W/L about 0.01). Genesis of large volumes of travertine requires many small springs or a few springs with very high flow rates to inundate a large area before carbonate equilibration with surface conditions can occur. Field evidence for many simultaneously active springs is lacking. A series of springs related to a fault is most likely but no evidence for such a fault exists.

Most active springs are on the east side of the fault blocks in the Ladron-Lemitar Mountains area rather than the west-facing slopes occupied by the Riley travertine (Kottlowski, 1962). This implies that the Ladron Mountains may not be the primary groundwater source. The areas to the north or northwest toward the Lucero uplift, and ultimately the San Juan basin, may be the dominant source (Goff and others, 1983; Trainer and Lyford, 1979).

Apart from water source and abundance problems, a high flow rate from a few springs implies deposition of the Riley travertine primarily by surface waters in either lacustrine, cienega, or fluvial environments. Evidence for general lacustrine conditions is lacking, although local ponding in cienegas seems likely. Fluvial channels were not observed within the Riley travertine.

Variable Texture and Lithology

The texture and lithology of the Riley travertine is highly variable. It ranges from massive to laminar with vuggy, oncolite- or algal-like, and fragmented portions (fig. 6). Locally, travertine (including reworked) and calcite-cemented breccia, conglomerate, and finer clastic sediments are abundant (figs. 7 and 8). This suggests deposition under locally different conditions on and in different substrates and related to a larger more unified process. The multiple textures of the Riley travertine can be encompassed under a valley axial-flow model. The variability of the Riley travertine is related to connected but localized conditions in which lateral groundwater flow occurs in several forms and in strata of differing lithology and age. The flow was primarily subsurface but had significant surface flow, ponding, and spring activity closer to the recharge areas. The flow was entirely subsurface at south mesa. This combination of local spring, cienega, lacustrine or playa, and groundwater activity yields the variability associated with the Riley travertine.

Lack of Pedogenic Morphology

The Riley travertine has often been described as a pedogenic caliche. Vertical transport involving meteoric or capillary water is overwhelm-

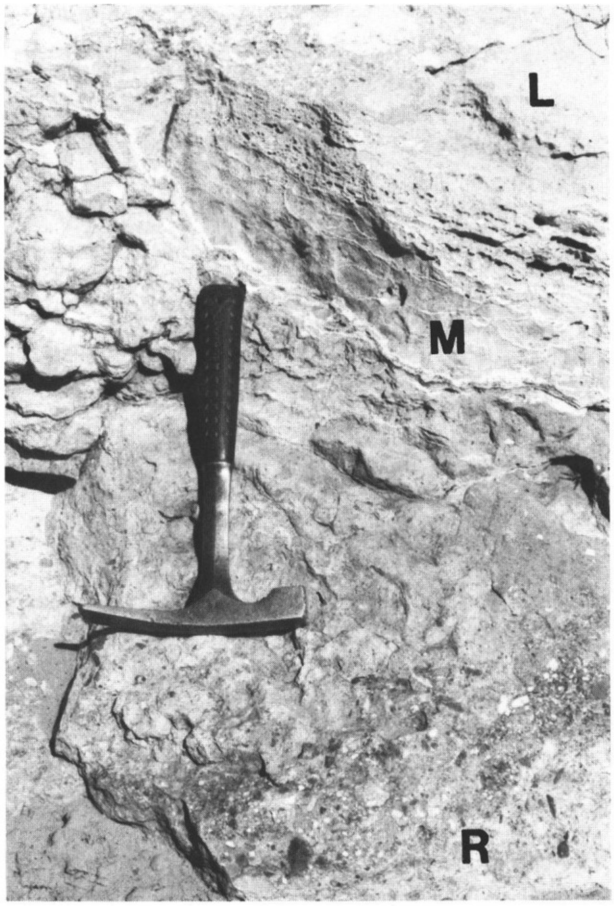

Figure 6. Lamellar (L), massive (M), and reworked (R) facies of Riley travertine at locality 5 on north mesa.

ingly dominant in pedogenesis. In most cases, percolation downward is the primary process. Lateral transport is not specifically excluded but usually is limited to localized movement. Pedogenesis generally produces very complex micro-morphology with massive and laminar structure only part of the sum of the morphological elements (for example, see Arakel, 1982). While massive caliche exists, laminar carbonate is not restricted in any way to pedogenesis. Of the two predominant textures of the Riley travertine—laminated and vuggy-massive—neither is diagnostic of pedogenesis. The Riley travertine lacks the complex vertical sequence of morphologic elements typical of pedogenic calcite horizons.

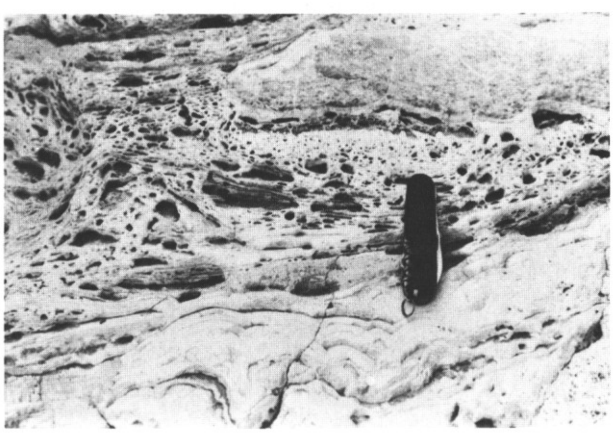

Figure 7. Laminar and vuggy Riley travertine at locality LAD 7 on north mesa (Source: M. J. Logsdon).

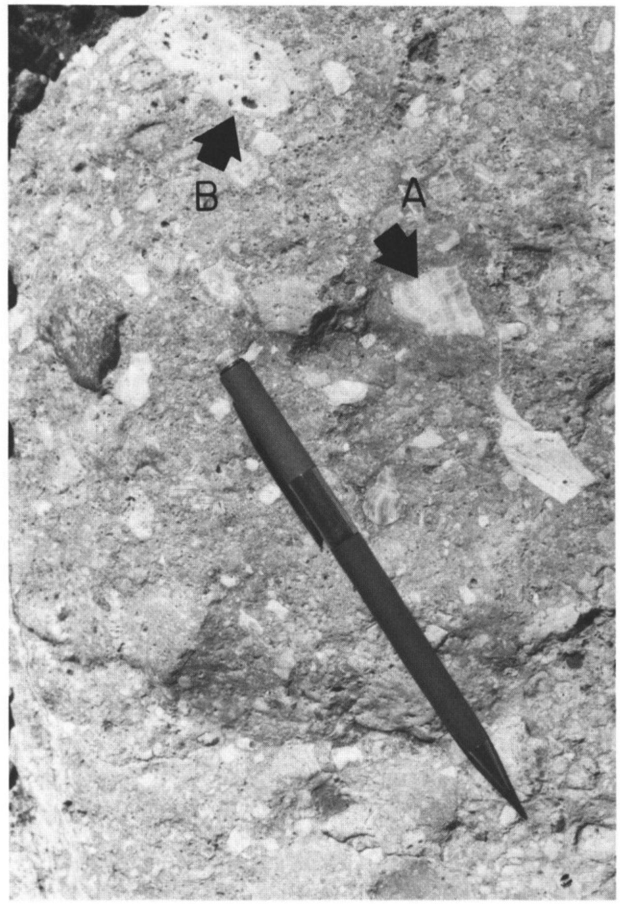

Figure 8. Reworked facies of Riley travertine showing clasts (arrows) of spring-deposit facies (A) and vuggy massive facies (B) at locality 5 on north mesa.

Calcic soils typically are less indurated downward (Gardner, 1972). The Riley travertine is entirely well-indurated. Mature pedogenic calcrete is typically nodular or nodular laminar, with abundant brecciation and bioturbation, unlike the generally laminated or massive Riley travertine. The terrigenous clasts in the Riley travertine do not have caliche-like rinds and lack the thicker basal rinds related to pedogenesis (Gile and others, 1965). Pedogenic calcite shows evidence of cyclic or episodic deposition in contrast to the more pervasive and continual precipitation of nonpedogenic calcite. Subaerial or near-surface features such as cracking, bioturbation, or rootlet horizons are generally lacking in the Riley travertine.

Similarities between pedogenic and nonpedogenic secondary calcite do exist as shown by the relatively recent distinction made between them. Both show evidence of secondary calcite precipitation. Displacive calcite is strongly suggested in many instances by the floating grains and carbonate cement in excess of that allowed by a simple void filling model (Goudie, 1972b; Gile and others, 1981; Lattman, 1973; Watts, 1978; Klappa and Watts, 1979; and Gardner, 1972). The Riley travertine is locally case hardened on external surfaces and in some voids and vugs.

Regional Paleodrainage

The modern drainage system did not exist at the time the Riley travertine was deposited. Rather than the modern west-to-east flow, the paleodrainage was north to southeast. A paleodrainage flowing west to east merged with this flow near south mesa. This interpretation is supported by the clast provenance (Denny, 1940), paleocurrent indicators in the Santa Fe Group (R. M. Chamberlin, 1983, oral commun.), and by geochemical data (this study). The paleodrainage most likely passed north of what is now San Lorenzo Canyon because the Lemitar Mountains were a major topographic high in upper Santa Fe time (R. M. Chamberlin, 1983, oral commun.).

The —1 permil depletion of ISO between north and south mesa (table 2, basal samples) reflects the northerly to southerly flow of groundwater proposed above. Friedman (1970) has shown that equilibrium fractionation between water and the CO, and CaCO, lost from it depletes the remaining water in '₈0. The net result is that downflow, the water is depleted in '₈0 and CaCO, precipitated from it is similarly depleted.

Calcite is not deposited until a supersaturation of about 10 is achieved, typically by loss of CO, from the system. The CO, lost is enriched in ^{12}C making the solution isotopically heavy with "C. After a supersaturation of 10 is achieved, the system simultaneously loses light CO, gas and heavy CaCO, precipitate. These combine to yield less "C in solution than for degassing alone (Usdowski and others, 1979). The calcite precipitated will be heavier than the dissolved carbonate, theoretically by + 2.3 to + 2.9 permil (Dandurand and others, 1982). Downflow calcite will be relatively depleted in '₃C compared to upflow calcite. A large relative '₃C depletion of — 6.2 permil exists between north mesa (+ 6.8 permil) and south mesa (+ 0.6 permil; table 2) indicating groundwater flow from north to south.

Strontium should be preferentially retained in the early, near-source, rapidly deposited calcite and manganese should be concentrated in later calcite (Lorens, 1981). Travertine on north mesa, with higher average strontium, was deposited before (or upflow of) travertine with lower average strontium at south mesa. The higher manganese concentration at north mesa, in contrast to the expected lower value, may represent a secondary overprinting of manganese associated with a small deposit of manganese vein mineralization on the southwest side of north mesa.

ECONOMIC GEOLOGY

The Riley travertine has long been recognized as a source of high-calcium limestone (Kottlowski, 1962). The most likely use is in manufacture of cement (Chapin and others, 1979) although lime production is also possible (Chamberlin and others, 1982). The main obstacles to development are the remoteness of the area (Siemers, 1982) and the possibility of wilderness withdrawal of much of the area over the deposit. High-calcium limestone is defined as greater than 95 percent $CaCO_3$. Based on the calcite contents obtained for this study (table 2), the deposit averaged only about 92 percent $CaCO_3$. One-third of the deposit may exceed 95 percent $CaCO_3$, primarily at north mesa, thus dropping the high-calcium limestone resource from 225 million metric tons (Logsdon, *in* Chamberlin and others, 1982) to perhaps 75 million metric tons.

The less-pure limestone may make excellent feed for cement manufacture since impurities are added to limestone in the manufacturing process. Local supplies of water, shale, and coal indicate that cement manufacture may be possible (Chapin and others, 1979). The Riley travertine is everywhere at or near the surface making open-pit mining at low stripping ratios feasible. A railroad spur or paved highway (about 50 km each) must be built as basic infrastructure to initiate any development.

SUMMARY

The Riley travertine is a secondary carbonate of complex origin deposited in the upper Santa Fe Group, probably between one and three million years ago. It is the result of lateral groundwater flow from Paleozoic carbonate aquifers and associated bajadas. This flow was both surface and subsurface and produced carbonate deposits of complex morphology with spring, lacustrine, reworked and pervasively or displacively cemented facies. The unit is composed of nonpedogenic secondary carbonate deposited on and within existing sediments and pre-Santa Fe rocks; consequently, it is somewhat diachronous. It corresponds to a nonpedogenic groundwater calcrete with valley calcrete predominating and cienega or other calcrete locally abundant.

The groundwater was initially charged with carbonate in peripheral Paleozoic limestone strata or bajadas derived from them. The dominant recharge area was either the west slope of the Ladron Mountains, where uplift provided increased precipitation and greater hydraulic head, or northern and northwestern source areas on the Lucero uplift and possibly the San Juan basin. Groundwater flowed toward the site of north mesa from the west, north, and east then turned south along the valley paleodrainage axis and flowed southeast through the area now occupied by south mesa. The flow merged with a west-to-east drainage which then passed north of San Lorenzo Canyon and probably entered the ancestral Rio Grande.

The carbonate-charged waters flowed on and in pre-Tertiary basement rocks and then across Santa Fe sediments at the foot of the slopes and on or under the valley floor. Some water was debouched from springs with extensive subsurface flow below them or was present as episodic surface flows, although the bulk of the carbonate-charged water stayed below the surface in the Santa Fe sediments.

The carbonate-charged waters pervasively cemented the host Santa Fe sediments and spread outward and downstream from the source areas. As transmissive zones in the Santa Fe plugged with carbonate cement, a stronger lateral flow developed above these newly formed aquicludes and produced localized laminar deposition related to transmissivity and prior calcite deposition patterns. Contemporaneous surface ponding and spring activity yielded localized lacustrine or algal limestone and travertine. The various types of carbonate accumulation on alluvial fans (Lattman, 1973) were developed locally as shown by the calcite-cemented breccias and conglomerates, some with reworked Riley travertine clasts in them.

The massive portions with localized crude laminations, which increasingly dominate the Riley travertine downflow, were precipitated from laterally flowing subsurface groundwaters. The groundwater moved pervasively into some sections and less so into others, where flow pulses over localized plugged zones yielded discontinuous laminations. The bed was thickened by displacive calcite, a process which may yield lamination and floating grains. Matrix material is diagenetically altered and commonly removed during calcite diagenesis, thus increasing the calcite content of the deposit.

The processes that formed the Riley travertine seem to be fundamental ones. The Riley travertine, while anomalously large, must represent a type of deposit present elsewhere in the arid southwestern United States and other arid regions of the world. Many secondary calcite deposits formerly thought to be pedogenic are probably nonpedogenic, although differentiating them is often very difficult without detailed study. Further investigation of the interrelations among secondary calcite depositional processes is needed for a clearer understanding of the relationship between pedogenic and nonpedogenic deposits.

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