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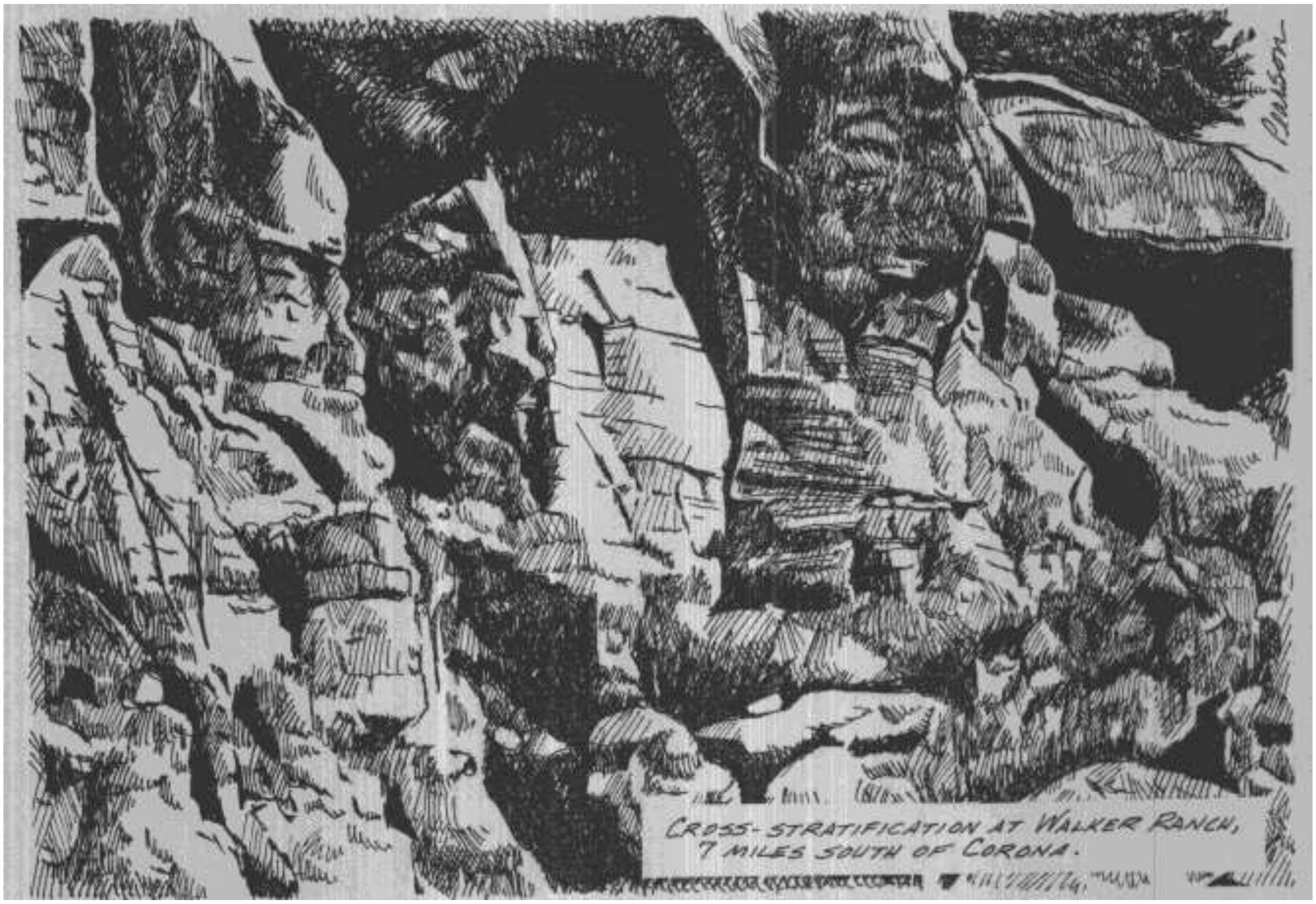

Genesis, provenance, and petrography of the Glorieta Sandstone of eastern New Mexico

by Sam Milner

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

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Preface

This report is primarily concerned with the genesis, provenance, and petrography of the Glorieta Sandstone Member of the San Andres Formation at its transition into an informal carbonate member in eastern Lincoln County, New Mexico. Hence, I placed the major emphasis of this study on the upper Yeso and lower San Andres Formations (both middle Permian) in Lincoln County. However, the Glorieta Sandstone and middle Permian stratigraphy were also examined outside of Lincoln County to acquire a regional framework within which to better understand the origin of the Glorieta.

ACKNOWLEDGMENTS—This report is based primarily on data collected for a master's thesis accepted by the University of Wisconsin at Madison. I extend my sincere appreciation to R. H. Dott, Jr., and L. C. Pray, who counseled me in all phases of my thesis work. Funds for summer field work were supplied by the American Association of Petroleum Geologists Grant-in-aid Program and the New Mexico Bureau of Mines and Mineral Resources; the Bureau also funded two later field checks. The considerable assistance of F. E. Kottlowski of the New Mexico Bureau of Mines and Mineral Resources is gratefully acknowledged.

Sam Milner
Senior Geologist
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Houston
April 27, 1978

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FIGURE 1—Location map of area studied in detail, Lincoln County. Circled numbers indicate locations of measured outcrop sections.

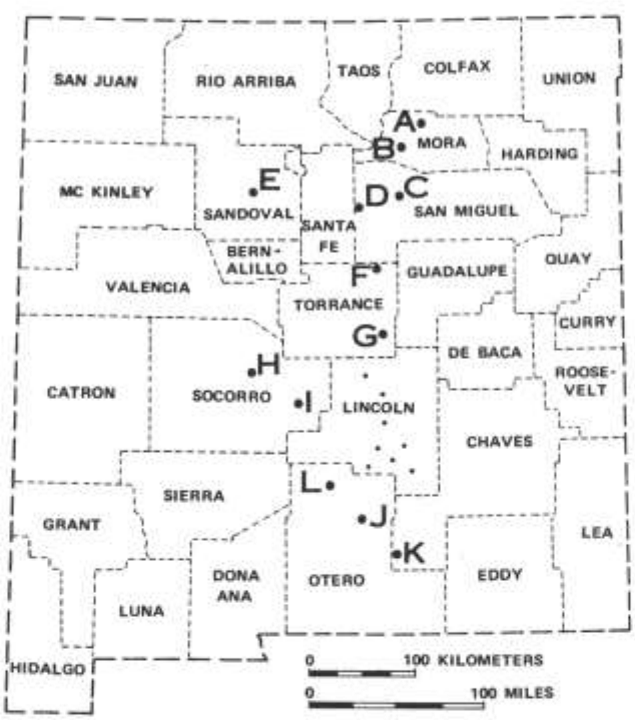


FIGURE 2—Location map of outcrops examined outside of Lincoln County. A, Ocate; B, Mora Gap; C, Romeroville; D, Rowe; E, Nacimiento Mountains; F, US-40; G, Duran Mesa; H, Joyita Hills; I, Chupadera Mesa; J, US-82; K, Stevenson Ranch; L, Rinconada Canyon (Harbour, 1970).

Abstract

The Glorieta Sandstone Member forms the lower 75 m of the San Andres Formation in northern Lincoln County, New Mexico. Three sandstone tongues, separated and capped by carbonate tongues, extend southward as the San Andres becomes predominantly carbonate in southern Lincoln County. The Glorieta Sandstone is a fine-grained, very well to moderately sorted, calcite-cemented quartz arenite that is medium to thick bedded. Internal cross-stratification, ripples, and parallel stratification are common in the Glorieta. The depositional model for the Glorieta Sandstone is based on the environmental interpretation of sandstones and associated carbonates and evaporites. Beach-uppershoreface, middle-shoreface, lagoonal, and tidal-channel deposits generally typical of Holocene barrier-island complexes are common. Most of the Glorieta Sandstone in eastern New Mexico was deposited along north-northeast to south-southwest-trending coastlines, which were dominated by eastward and southward prograding barrier-island complexes during relatively low sea levels. Relative low stands were followed by rises of sea level and the westward and northward transgression and reworking of regressive deposits. Carbonate deposition was predominant in eastern Lincoln County following rises of sea level. Glorieta prograding coastlines were probably localized at the transition between the positive Pedernal massif and the negative element east of it. The Ancestral Rocky Mountains and cratonic areas farther to the northeast are probable source areas for the Glorieta.

Middle Permian stratigraphy

The lower 100 m of the San Andres Formation in south-central New Mexico (figs. 1 and 2) is middle Permian (late Leonardian to early Guadalupian) in age (Dunbar and others, 1960). It consists of sandstones, carbonates, and evaporites (fig. 3), largely of marine origin.

The San Andres Formation is a shelf unit northwest of the Delaware Basin of southeastern New Mexico (fig. 4). The lower San Andres in south-central New Mexico is divided into three members for this report: the Glorieta Sandstone Member, the informal carbonate member, and the informal evaporitic member (fig. 5). The Glorieta Member is about 75 m thick in northern Lincoln County. It forms tongues southward as the lower San Andres passes into dominantly carbonate rocks in southern Lincoln County (fig. 3).

Although the primary purpose of this report is to describe middle Permian strata in eastern Lincoln County, this stratigraphy in central and northern New Mexico is also discussed.

Sangre de Cristo Formation

The Sangre de Cristo Formation (Permian- Pennsylvanian) of northeastern New Mexico consists of continental conglomerates, arkoses, shales, and sandstones (Bachman, 1953). The Sangre de Cristo Formation interfingers with the Yeso Formation and may interfinger with the Glorieta Sandstone. The contact between the Sangre de Cristo and the overlying Glorieta is gradational; the base of the Glorieta contains reworked pieces of the Sangre de Cristo (Bachman, 1953).

Yeso Formation

Only the upper 50-100 m of the Yeso Formation are important to this study. The Glorieta Sandstone and

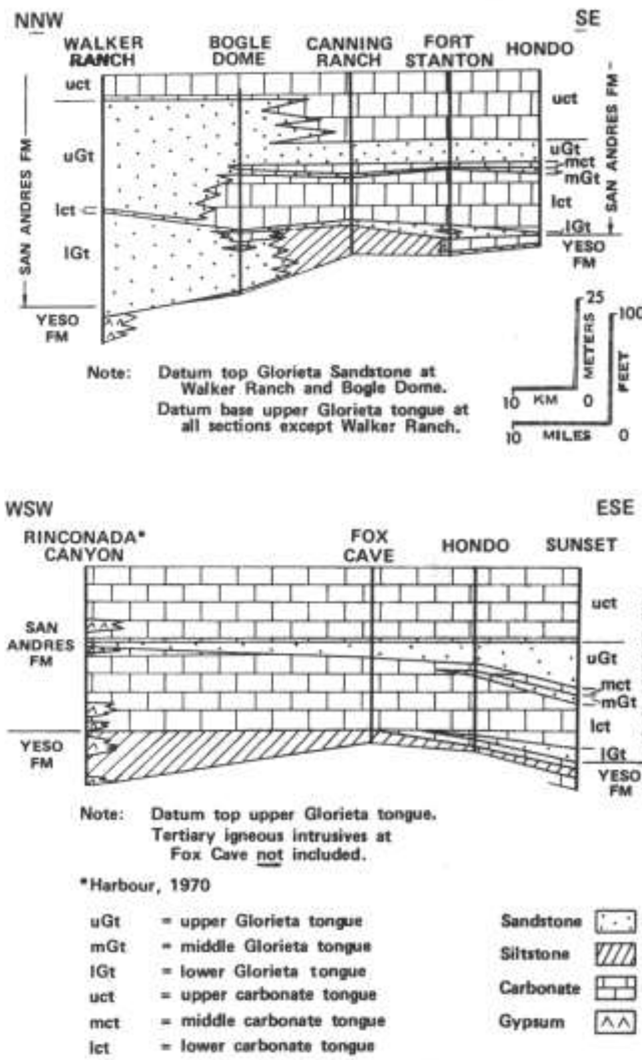


FIGURE 3—Gross lithology and stratigraphy of upper Yeso and lower San Andres Formations, Lincoln and Otero Counties.

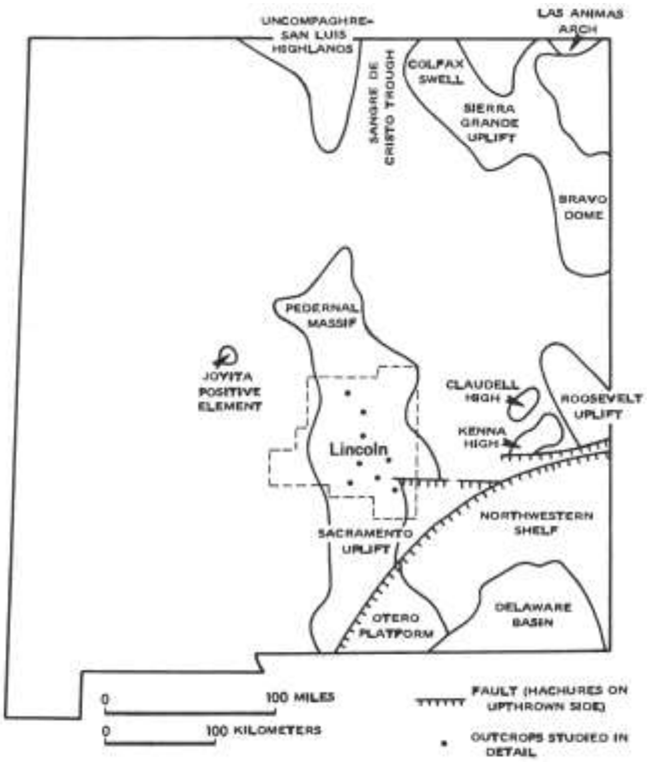


FIGURE 4—MAJOR PERMIAN TECTONIC ELEMENTS IN EASTERN NEW MEXICO (Hills, 1963; McKee, Oriel, and others, 1967).

Yeso are everywhere conformable and are lateral equivalents in northern Lincoln County. The contact between the Yeso Formation and the Glorieta Sandstone is most commonly gradational, but sharp contacts are locally present. The upper Yeso Formation in eastern Lincoln County consists almost entirely of siltstone and dolomite (Harbour, 1970; Milner, 1974).

San Andres Formation

Eastern Lincoln County

The lower 100 m of the San Andres Formation in eastern Lincoln County—the object of the detailed work of this study—was divided into two members: the Glorieta Sandstone Member and an informal carbonate member (fig. 5).

The Glorieta Sandstone forms the lower 75 m of the San Andres Formation at Walker Ranch in northern Lincoln County (fig. 1). Three sandstone tongues extend southward where the San Andres becomes predominantly carbonate in southern Lincoln County. These tongues are informally termed the lower, middle, and upper Glorieta tongues of the San Andres Formation.

The carbonate tongue between the lower and middle Glorieta Sandstone tongues is referred to as the lower carbonate tongue, the carbonate tongue between the middle and upper Glorieta tongues as the middle carbonate tongue, and the carbonates capping the upper Glorieta tongue as the upper carbonate tongue (fig. 3). The sandstone and carbonate tongues are conformable; their boundaries are gradational, although locally they may be quite sharp. The upper Glorieta tongue is the Hondo Sandstone of Lang (1937; Milner, 1974).

GLORIETA SANDSTONE MEMBER—The Glorieta Sandstone Member of the lower San Andres Formation is a fine-grained, very well to moderately sorted, calcite-cemented quartz arenite; it is very thick bedded (1.5 m or more) to medium bedded (15-50 cm) on an outcrop scale. However, the Glorieta contains internal cross-stratification, ripples, and even, parallel stratification. The Glorieta is yellow and light gray on fresh surfaces and weathers to shades of yellow, gray, brown, and orange. The lower part of the upper Glorieta tongue at Bogle Dome is oil stained and dark gray to black.

The Glorieta Sandstone Member separates the carbonates of the San Andres Formation from the Yeso Formation in most of east-central New Mexico. However, locally (for instance, Fox Cave, fig. 3), San Andres carbonates rest directly on characteristic Yeso lithologies. Characteristic Glorieta and Yeso lithologies are laterally equivalent in northern Lincoln County. Here upper Yeso and lower Glorieta rock units are depositional facies of each other (fig. 3).

The three Glorieta tongues in southern Lincoln County vary in thickness (fig. 3). The lower tongue ranges up to 5 m in thickness (but is sometimes locally absent), the middle tongue ranges from 20 cm to 3.5 m, and the upper tongue ranges from 5 to 17 m. The tongues at a single outcrop are all thicker or thinner than the norm; hence, an outcrop with a thin lower tongue tends to have a thin middle and a thin upper tongue.

CARBONATE MEMBER—The carbonate member of the lower San Andres Formation in eastern Lincoln County consists of the lower, middle, and upper carbonate tongues. About 75 percent of the rocks of the carbonate member are dolomite.

Mudstones and wackestones (after Dunham, 1962) constitute 94 percent of the carbonate member. Packstones and grainstones make up about five percent of the carbonate rocks present and are found in oolitic rock units at Canning Ranch and Bluewater; they are usually absent in the other sections. Boundstones constitute less than one percent of the carbonate member and consist of cryptalgal laminates, algal stromatolites, and bryozoan-ostracod bioherms.

South-central New Mexico

The lower San Andres Formation in south-central New Mexico is predominantly carbonate. However, several thin Glorieta-like quartz arenites have been reported in the Sacramento Mountains (Pray, 1961), San Andres Mountains (Kottlowski and others, 1956), Caballo Mountains (Kelley and Silver, 1952), and in southeastern New Mexico (Kelley, 1971). I have not attempted to correlate the lower, middle, and upper Glorieta tongues with Glorieta-like sandstones reported south of Lincoln County.

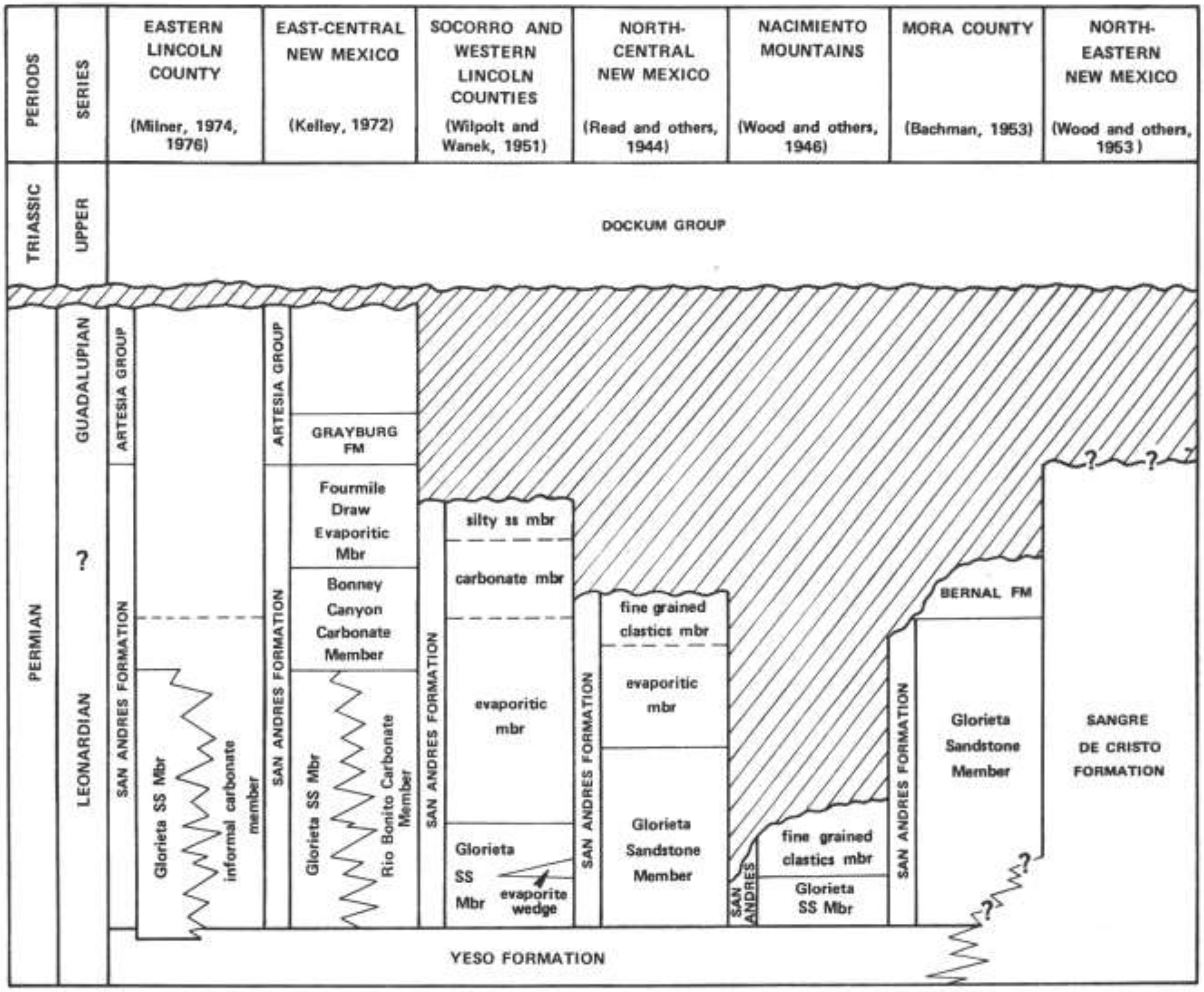


FIGURE 5—Middle Permian to Triassic stratigraphy in central and northern New Mexico.

West-central New Mexico

The San Andres Formation in west-central New Mexico consists of a basal Glorieta Sandstone Member, an evaporitic middle member with intercalated clastics, and an upper member (Kelley and Wood, 1946; Wilpolt and others, 1946; Wilpolt and Wanek, 1951). The evaporitic member is rich in gypsum near the Lucero uplift (northern Socorro and eastern Valencia Counties), where carbonate, sandstone, and siltstone are relatively minor constituents. In western Lincoln County and in eastern Socorro and Otero Counties, the San Andres contains abundant gypsum and carbonate and some interbedded sandstone in the middle member.

East-central New Mexico

The lower San Andres Formation in the subsurface of east-central New Mexico consists largely of carbonates with some intercalated Glorieta sandstones (Foster and others, 1972; Meissner, 1972).

Tectonic influence on lower San Andres deposition

Most of the major tectonic elements that influenced middle Permian sedimentation in eastern New Mexico were already fully formed or in decline at the beginning of Permian time. The major tectonic elements were the Uncompahgre-San Luis highlands, Sangre de Cristo trough, Colfax swell, Sierra Grande uplift, Bravo dome, Roosevelt uplift, Claudell high, Kenna high, Pedernal massif, and Joyita uplift (fig. 4; Hills, 1963; McKee, Oriel, and others, 1967).

The thickness of the Glorieta Sandstone in northeastern New Mexico (fig. 6) was mapped using subsurface data available at the New Mexico Bureau of Mines and Mineral Resources and reports of outcrop thicknesses in the published literature.

The Glorieta Sandstone is appreciably thinner over and west of the Pedernal massif than it is to the east (figs. 4 and 6). These differences indicate slower subsidence rates over and west of the massif than east of it because there is no evidence of major erosion within the lower San Andres Formation. Hence, the Pedernal massif seems to have acted as a positive feature during Glorieta time (Kelley, 1972; Hock, 1970). The transitional zone between this positive feature and the negative feature to the east is a reasonable place to expect the localization of coastal progradation. This depositional model is discussed in more detail in the section on paleogeography.

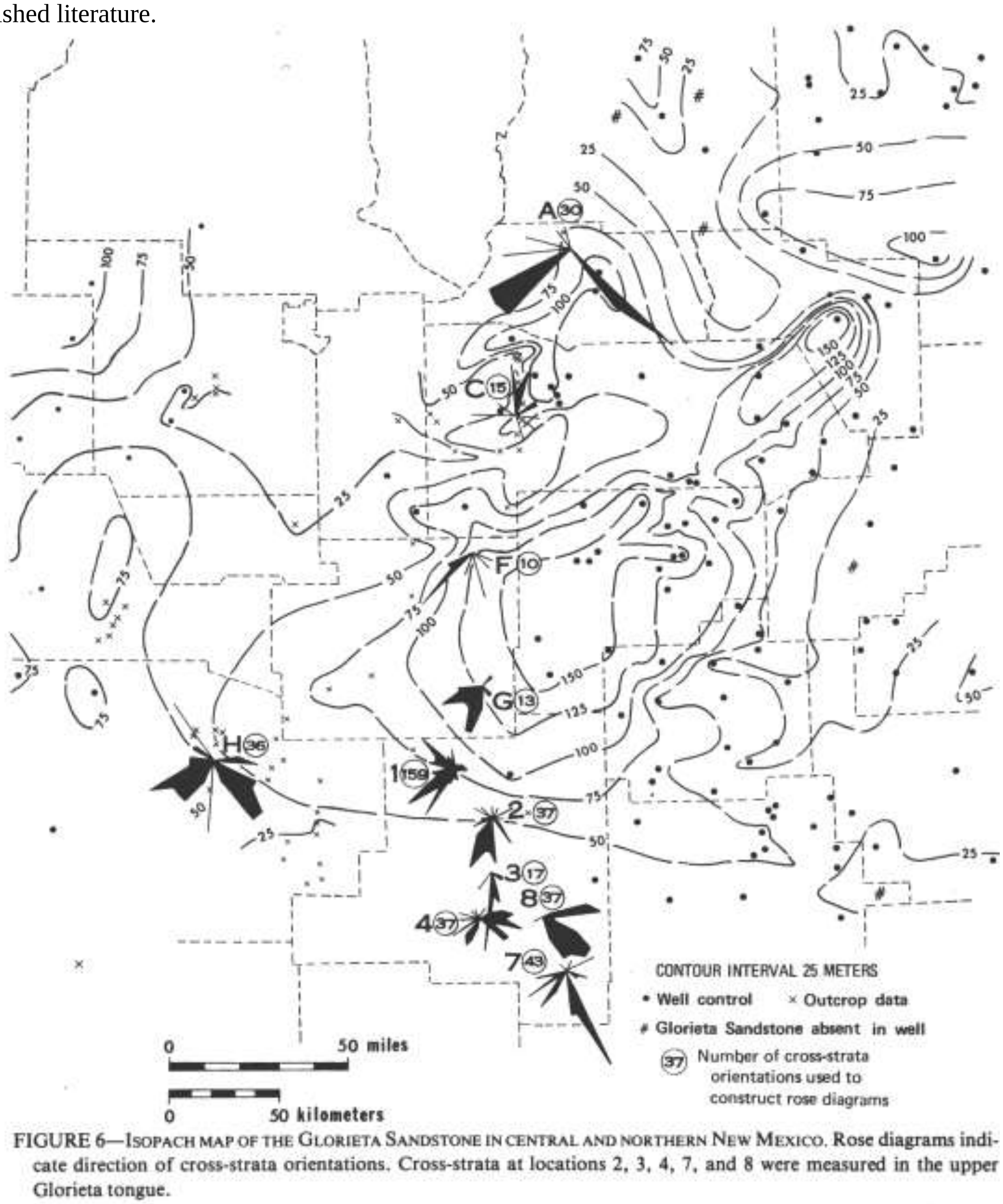


FIGURE 6—ISOPACH MAP OF THE GLORIETA SANDSTONE IN CENTRAL AND NORTHERN NEW MEXICO. Rose diagrams indicate direction of cross-strata orientations. Cross-strata at locations 2, 3, 4, 7, and 8 were measured in the upper Glorieta tongue.

Petrography of Glorieta Sandstone

Texture

Eleven samples from rippled, cross-stratified, and very well sorted to well-sorted massive units in eastern Lincoln County were disaggregated, treated with dilute hydrochloric acid, and sieved using 1/4 *q* sieve intervals down to and including 40. Statistical parameters were calculated (table 1) after the methods of Folk and Ward (1957).

Grain roundness is usually a function of grain size. The smaller grains are uniformly subangular to subrounded (Powers, 1953). Most larger grains are very well rounded to rounded and indicate a texturally mature source. However, a few large grains are subrounded and suggest a second, less mature source.

Composition

LIGHT MINERALS—Sixteen thin sections from rippled, cross-stratified, and very well sorted to well-sorted massive units were point counted (table 2); another 11 thin sections were examined qualitatively. The Glorieta Sandstone is almost entirely a quartz arenite, but a few units at Walker Ranch are feldspathic arenites (more than 10 percent feldspar). The feldspars (orthoclase, microcline, and sodic plagioclase) are restricted to the finer grain sizes. Compositional maturity generally increases upward in the measured sections, owing to increased maturity of the sediment source and/or greater abrasion of terrigenous grains during transport and deposition. Compositional maturity also generally increases southward along the inferred major paleocurrent direction probably because of additional sediment transport distance.

HEAVY MINERALS—Samples for heavy-mineral separation were taken from the lower and upper Glorieta tongues at Sunset and at Walker Ranch (table 3). All four samples contain the same heavy minerals in about the same proportions. Non-opaque heavy minerals never appear in more than trace amounts in unconcentrated samples. Some units have slightly more heavy minerals than others have. However, concentrations of heavy minerals in stringers or lenses were not noted.

CEMENTS—Calcite cement is abundant and is the most common cement type in the Glorieta Sandstone. Dolomite cement is volumetrically important locally (for example, in the middle Glorieta tongue at Sunset). Only one (upper Glorieta tongue at Bogle Dome) out of 37 thin sections examined had chalcedony cement. Optically, the chalcedony showed length slow; this show indicates that evaporitic brines possibly were present during cementation (Folk and Pittman, 1971). Clay frequently coats quartz grains in many rock units and may act as a cement.

DIAGENETIC FEATURES—Quartz overgrowths are common, particularly in the better sorted units. Orthoclase overgrowths and terrigenous grains with sutured pressure-solution contacts are very rare. Calcite-cemented spherules or concretions ranging from about 1 mm to 10 cm in diameter are abundant in many rock units. The spherules are more resistant than the host rock and weather out in relief to produce a distinctive knobby appearance on the outcrop surface.

TABLE 1—STATISTICAL MOMENTS OF 11 SIEVED SAMPLES FROM THE GLORIETA SANDSTONE (after Folk and Ward, 1957).

LOCATION	MEAN ø UNITS	MEDIAN ø UNITS	STANDARD DEVIATION	SKEWNESS	COARSEST 1 PERCENTILE ø UNITS	% GRAINS <4 ø	SEDIMENTARY STRUCTURES
WALKER RANCH lower tongue	2.60	2.50	±.87	+.30	.47	12.53	RIPPLED BEDDING
	2.34	2.13	±.67	+.45	.33	4.57	CROSS-STRATIFICATION
	1.58	1.65	±.37	+.54	.38	1.42	CROSS-STRATIFICATION
	1.82	1.76	±.30	+.31	.47	1.00	WELL SORTED MASSIVE
WALKER RANCH upper tongue	2.17	2.12	±.56	+.17	.38	2.68	RIPPLED BEDDING
	1.79	1.66	±.47	+.35	.54	.82	CROSS-STRATIFICATION
	1.93	1.90	±.44	+.30	.50	.42	WELL SORTED MASSIVE
SUNSET lower tongue	2.46	2.40	±.52	+.42	.29	7.36	RIPPLED BEDDING
	2.28	2.35	±.33	−.86	.33	2.54	CROSS-STRATIFICATION
SUNSET upper tongue	2.13	2.13	±.45	+.13	.41	2.78	CROSS-STRATIFICATION
	1.60	1.56	±.23	+.35	.38	<.01	CROSS-STRATIFICATION
	2.41	2.34	±.65	+.30	.38	7.52	AVERAGE OF THREE RIPPLED BEDS
	1.97	1.90	±.42	+.16	.40	2.02	AVERAGE OF SIX CROSS-STRATIFIED BEDS
	1.88	1.83	±.37	+.31	.49	.71	AVERAGE OF TWO MASSIVE BEDS

TABLE 2—Modal analysis of 16 samples from the Glorieta Sandstone. Abbreviations: n = number of points counted; * = trace amounts present; 1 = extinction positions greater than a few degrees; 2 = extinction positions less than a few degrees.

MINERAL CONSTITUENT \ SAMPLE LOCATION	WALKER RANCH lower tongue			WALKER RANCH upper tongue					SUNSET lower tongue			SUNSET upper tongue			FOX CAVE upper tongue	
	n = 450	n = 450	n = 400	n = 1065	n = 400	n = 400	n = 400	n = 400	n = 300	n = 300	n = 300	n = 300	n = 300	n = 300	n = 300	n = 300
MONOCRYSTALLINE QUARTZ	61.0	56.7	67.7	59.6	63.5	67.8	80.5	62.2	48.8	69.7	70.1	52.2	63.9	67.3	70.9	63.5
STRAINED[1]	13.5	6.2	5.5	5.2	2.0	2.3	4.8	3.3	1.3	3.0	5.9	3.4	5.0	6.0	9.4	6.3
UNSTRAINED[2]	47.5	50.5	62.2	54.4	61.5	65.5	75.7	58.9	47.5	66.7	64.2	48.8	58.9	61.3	61.5	57.2
POLYCRYSTALLINE QUARTZ	3.1	2.7	1.5	.5	1.0	3.3	2.5	2.3	2.3	1.3	1.6	2.7	3.3	3.0	4.4	4.0
QUARTZ OVERGROWTHS	9.4	5.7	14.3	4.6	10.3	3.3	.5	13.5	4.3	5.7	5.3	*	5.6	9.0	11.1	8.9
CHERT	.7	.6		*	.3	.5	.3	.5				*	.7	.3	.3	
ORTHOCLASE	5.7	7.8	.8	3.0	2.3	.5		.3	1.0	1.3	1.0					
MICROCLINE	.5	.9	.3	.1					*							
SODIC PLAGIOCLASE	.2	.2		.1												
FINE GRAINED MICA	17.9	16.0	1.7	4.0	6.4	4.3	12.8	3.2	.6	2.7	5.9			4.7	.7	
CLAY	1.4	1.0	*	.1	.3	.2	1.2	*	*	*	*			*	*	
MUSCOVITE	*	.5			*	.3	*	.5		*		*			*	
ZIRCON	*									*						
TOURMALINE	*	*		*						*						
RUTILE	*															
HEMATITE	*	1.3	.3	1.0	.3		2.0	.3		1.0						
CALCITE CEMENT		6.4		26.8	14.5	12.5			42.9	17.7	7.9	45.1	26.5	5.6	9.0	13.6
POROSITY			13.5		1.3	7.8	.3	17.3		.7	8.2		.7	10.0	3.7	9.9
% TOTAL	99.9	99.8	101.1	99.8	100.2	100.5	100.1	100.1	99.9	100.1	100.0	100.0	100.7	99.9	100.1	99.9

TABLE 3—Heavy minerals in the Glorieta Sandstone.

	heavy mineral	relative abundance	remarks
non-opaque	tourmaline	abundant	blue, green, yellow, pink, brown
	zircon	common	low and high birefringent varieties
	rutile	rare	
opaque	hematite	abundant	pseudomorphs after iron sulfide
	leucoxene	common	ilmenite alteration product

Sedimentary structures

This section includes observations of sedimentary structures within the Glorieta Sandstone from detailed studies in eastern Lincoln County and from brief examinations of outcrops in central and northern New Mexico.

RIPPLES—Ripples are very common in the Glorieta Sandstone (fig. 7). They were recognized by their external geometry; internal micro-crosslamination was never observed. Ripple amplitudes range from approximately 1 to 5 cm; hence, rippled rock units are very thin bedded. Rippled beds are moderately to well sorted. Comparatively, they are the most poorly sorted units in the Glorieta because they have the largest percentage of grains finer than 40 (table 1).

CROSS-STRATIFICATION—Tabular and trough cross-stratification are both common in the Glorieta Sandstone. Tabular cross-stratification was most often noted in long, low-angle (less than 10 degrees) medium-scale cross-sets suggestive of beach to upper-shoreface deposition (fig. 8; Conybeare and Crook, 1968). High- to medium-angle, medium-scale tabular cross-sets are rare. Medium-scale trough cross-stratification (fig. 9) was commonly noted in central New Mexico but is rare in Lincoln County.

PARALLEL STRATIFICATION—Parallel, even stratification is comparatively rare in the Glorieta Sandstone, particularly outside of Lincoln County. A 15-m-thick section is present in the lower Glorieta tongue at Bogle Dome (fig. 10); thinner sections are present at Walker Ranch, Sunset, Hondo, and Fort Stanton. At least some parallel stratification may actually be low-angle cross-stratification seen in strike section on the outcrop.

MASSIVE BEDS—Massive beds, characterized by the apparent lack of sedimentary structures, are common in some outcrops in eastern Lincoln county. Sedimentary structures are probably present, although invisible (Hamblin, 1962). Two types of massive units are recognized: 1) moderately sorted to well-sorted silty units with the comparatively poorer sorting associated with rippled units and 2) very well sorted to well-sorted sandstones with the better sorting associated with cross-stratified and even, parallel stratified units. The better sorted units lack any evidence of burrowing, whereas the comparatively poorer sorted units are locally mottled, but without distinct burrows.

SOFT-SEDIMENT DEFORMATION—Evidence of soft-sediment deformation (Potter and Pettijohn, 1963) is uncommon in the Glorieta Sandstone and has been noted only in the lower Glorieta tongue at Sunset. Soft-sediment deformation is suggested by the confinement of deformation to a single bed between undeformed beds.

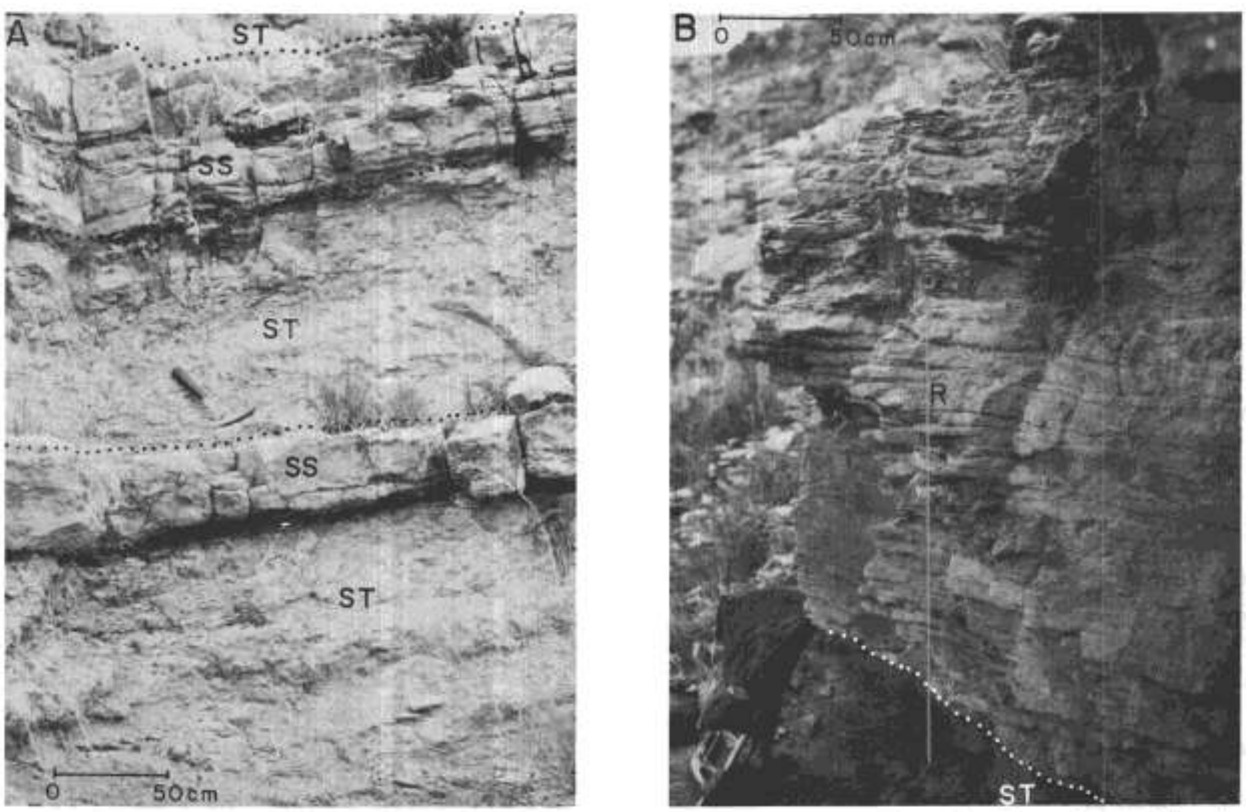


FIGURE 7—VIEWS OF MIDDLE-SHOREFACE DEPOSITIONAL FACIES. **A)** Walker Ranch outcrop: alternating silty sandstones (SS) and sandy siltstones (ST) in lower Glorieta tongue; **B)** Bogle Dome outcrop: rippled sandstone (R) in lower Glorieta tongue overlain by uniform, parallel stratification and underlain by sandy siltstone (ST).

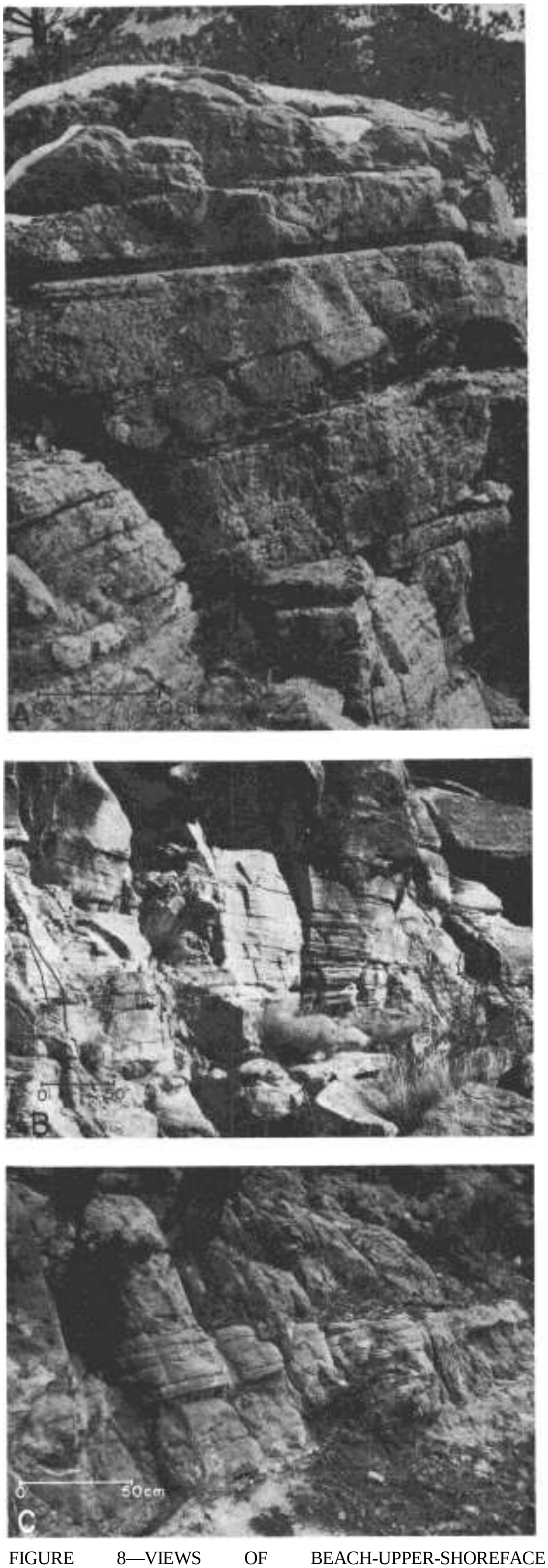


FIGURE 8—VIEWS OF BEACH-UPPER-SHOREFACE DEPOSITIONAL FACIES. Long, low-angle tabular cross-stratification in **A)** Ocate outcrop, **B)** Walker Ranch outcrop (lower Glorieta tongue), and C) Bluewater outcrop (upper Glorieta tongue).

FIGURE 9—VIEW OF BEACH-UPPER-SHOREFACE DEPOSITIONAL FACIES. Even, parallel stratification in lower Glorieta tongue at Bogle Dome (LGT, lower Glorieta tongue; MCT, middle carbonate tongue; YF, Yeso Formation).

FIGURE 10—VIEW OF TIDAL-CHANNEL DEPOSITIONAL FACIES. Note bimodality of cross-stratification orientations in middle Glorieta tongue at Sunset outcrop.

Paleocurrent analysis

Cross-stratification was the only sedimentary structure used to infer paleocurrent directions. The orientation of cross-strata was measured wherever possible.

The rose diagrams of figs. 6, 11, and 12 show that the predominant Glorieta paleocurrent direction was to the south-southwest. In the upper Glorieta tongue of southern Lincoln County, the inferred paleocurrents are chiefly to the south-southeast. Fig. 12 summarizes the predominant paleocurrent directions measured in the Glorieta Sandstone and their likely origin.

The inferred southerly paleocurrent directions are probably the result of sediment movement by longshore drift along a coastline oriented approximately north-northeast to south-southwest. Northwesterly cross-strata orientations are inferred to have formed in backshore, coastal-dune, and tidal-channel (ebb-stage) environments. These orientations may also have been formed during wave attack against a coastline (Tanner, 1963). Southeasterly cross-strata orientations are inferred to have formed in foreshore to upper-shoreface, coastal-dune, and tidal-channel (flood-stage) environments.

At least some of the measured southwesterly and southeasterly cross-strata orientations probably represent dispersion around a southerly mean paleocurrent direction. Such deviations are the expected result of measuring trough cross-stratification in section view. Bedding plane exposures of cross-stratification were only rarely noted.

Northeastward cross-strata orientations were most commonly observed in the Romeroville outcrop. The exposed Glorieta Sandstone is here characterized by fluvial (-deltaic?) channels. Aerial photographs of Holocene fluvial-meander systems clearly demonstrate that portions of individual channels may meander at any angle to the overall flow direction of the system. The cross-strata orientations at Romeroville may have resulted from deposition in northeastward-flowing meander-channel segments. Some of the northeasterly cross-strata orientations may also result from improper correction of post-depositional structural tilt.

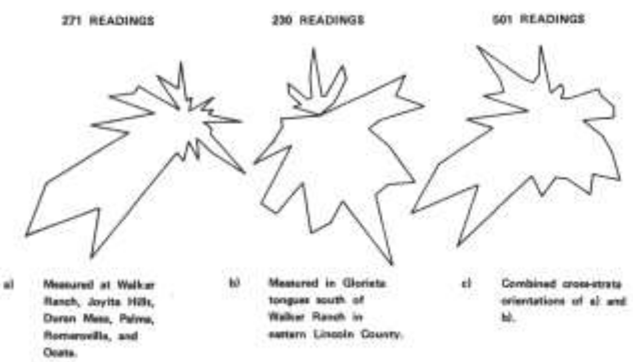


FIGURE 11—Rose diagrams indicating cross-strata orientations determined in Glorieta Sandstone in central and northern New Mexico, in the Glorieta tongues in eastern Lincoln County, and in all outcrops examined during this study.

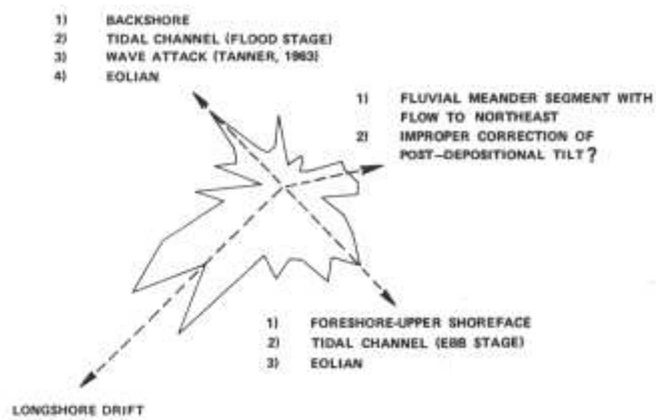


FIGURE 12—Rose diagram indicating cross-strata orientations (and their probable origin) determined for all outcrops studied.

Sand provenance and dispersal

Inferred Glorieta paleocurrent directions and isopach mapping (figs. 6 and 11-14) clearly suggest that sand was supplied from the north and northeast. The Ancestral Rockies of Colorado and cratonic areas farther to the north-northeast are probable source areas. The extreme textural and compositional maturity of the Glorieta Sandstone suggests a preexisting sandstone source (Pettijohn and others, 1973). The Ancestral Rockies were stripped to crystalline Precambrian basement long before Glorieta depositional time (McKee, Oriel, and others, 1967). Todd (1964) has calculated that the Ancestral Rockies were not extensive enough to have supplied all of the sand present in the late Paleozoic blanket sandstones of which the Glorieta forms a southern feather edge. These considerations suggest that the Ancestral Rockies did not supply more than a small fraction of the Glorieta sands. The larger subrounded quartz grains present in most Glorieta Sandstone samples in eastern Lincoln County may have come from the Ancestral Rockies. The primary source of terrigenous sand was probably lower Paleozoic sandstones in cratonic areas to the north-northeast of New Mexico. The absence of middle Permian terrigenous mud deposits in the Permian Basin suggests a source area poor in clay-sized particles, such as the lower Paleozoic of the central craton (Dott and Batten, 1971).

Angular fragments of quartzite and gneiss from the higher parts of the ancestral Pedernal Mountains, which were probably above sea level, occur locally in the Glorieta Sandstone north of Lincoln County (Kelley, 1972). However, none were found in the vicinity of a Precambrian knob about 8 km north of Corona (fig. 1). The knob is a granitic gneiss with abundant microcline and some orthoclase and sodic feldspar. Such emergent knobs probably contributed feldspars to the Glorieta, but remarkably little detritus seems to have been supplied by the Corona knob.

Glorieta Sandstone paleogeography

Previous work on the paleogeography of the Glorieta Sandstone generally consists of published regional papers and unpublished academic theses of more limited geographic scope. Most authors of regional reports suggest littoral to offshore marine environments of deposition for the Glorieta Sandstone (Baars, 1961; Tanner, 1963; Kelley, 1972; Foster and others, 1972; Baars, 1972). Kelley (1972) and Tanner (1963) suggest that a transgressing sea was responsible for the localization of these environments. Baars (1961) and Kelley (1972) suggest an eolian input into the Glorieta.

The Glorieta Sandstone has been interpreted locally in differing ways by the authors of academic theses: Huntington (1949), central New Mexico—stable marine shelf; Chisholm (1950), Chupadera Mesa—stable shelf by transgressing sea; Huber (1961), Joyita Hills—river channel or delta, beach bar, shallow neritic; Hock (1970), Torrance County—lower Glorieta eolian and upper Glorieta marine; Koehn (1972), San Miguel County—deposition and reworking of barrier beaches during transgression; Milner (1974), eastern Lincoln County—foreshore to shallow marine.

Depositional environments

The depositional model for the Glorieta Sandstone described in the next section is based primarily on the environmental interpretation of sandstones, carbonates, and evaporites in central and northeastern New Mexico.

Glorieta Sandstone Member

GRAIN SIZE—The Glorieta Sandstone consists predominantly of fine sand. This uniformity of grain size makes environmental interpretation difficult. The general absence of fine-grained clastics during lower San Andres depositional time in the Permian Basin suggests that clay-sized particles were missing from the grain-size distribution available for modification by Glorieta environments of deposition. Consequently, the lateral transition between the sandstones and carbonates of the lower San Andres Formation in eastern Lincoln County is relatively sharp and narrow. Whether grain size fines or coarsens upward within siliciclastic rock units is often difficult to determine.

SORTING—Rock units in the Glorieta Sandstone range from very well sorted to moderately sorted. There is an excellent correlation between sedimentary structures in individual rock units and the degree of relative sorting. Cross-stratified and parallel-stratified rock units are wellsorted to very well sorted, whereas rippled rock units are moderately sorted to well sorted. Consequently, sorting alone was used to infer the depositional flow regime in massive (structureless) and poorly exposed rock units. The large percentage of moderately sorted rock units in the Glorieta Sandstone in central New Mexico limits the amount of eolian deposition that may be inferred from other criteria.

SAND BODY GEOMETRY—Isopach mapping of the Glorieta Sandstone in the northern two-thirds of New

Mexico and of the lower and upper Glorieta tongues in southern Lincoln County is presented in figs. 6, 13, and 14. These isopach maps define the geometry of the Glorieta Sandstone and thereby permit environmental inferences about it.

The Glorieta Sandstone in the northern two-thirds of New Mexico has an overall blanket geometry (fig. 6). However, the nature of Holocene coastal sedimentation and the repetition of sequences of sedimentary structures suggest that the Glorieta is a composite sand body consisting of units deposited in a succession of environments. Consequently, the isopach map of the total thickness of the Glorieta is not characteristic of any particular depositional environment, but the mapping does suggest the general direction of depositional strike of the Glorieta. In east-central New Mexico, the depositional strike is generally from northeast to south. This direction is generally consistent with the predominant inferred paleocurrent direction (figs. 6 and 14).

The lower, middle, and upper Glorieta tongues of southern Lincoln County usually do not contain repetitions of sedimentary structures or sorting. Hence, each is inferred to have been deposited in a single depositional cycle. Isopach mapping of the lower and upper Glorieta tongues (figs. 13 and 14) illustrates a pattern characteristic of barrier-island deposits such as the reservoir of the Bell Creek oil field (fig. 15).

SEDIMENTARY SEQUENCES—The continuous, parallel stratification of the Glorieta Sandstone at the outcrop scale in central New Mexico consists internally of alternating *lower* and *higher* flow-regime deposits (Harms and Fahnestock, 1965; I am using these terms in a relative sense rather than in the specific sense of the authors). The *lower* flow-regime units consist of moderately sorted to well-sorted rippled or massive silty sandstone. The *higher* flow-regime units consist of very well sorted to well-sorted, cross-stratified, parallel-stratified, or massive sandstone (Harms and Fahnestock, 1965). This alternating sequence was noted in all well-exposed Glorieta outcrops exclusive of the Glorieta tongues in southern Lincoln County. The Glorieta tongues are thin and commonly do not contain repetitions of sedimentary structures; single phases rather than repeated cycles of deposition probably occurred here (figs. 16 and 17).

The Glorieta Sandstone in central and northern New Mexico consists chiefly of coarsening-upwards sequences representing increasing depositional flow regime or energy. Whether the alternating flow-regime units are fining or coarsening upwards is frequently dif-

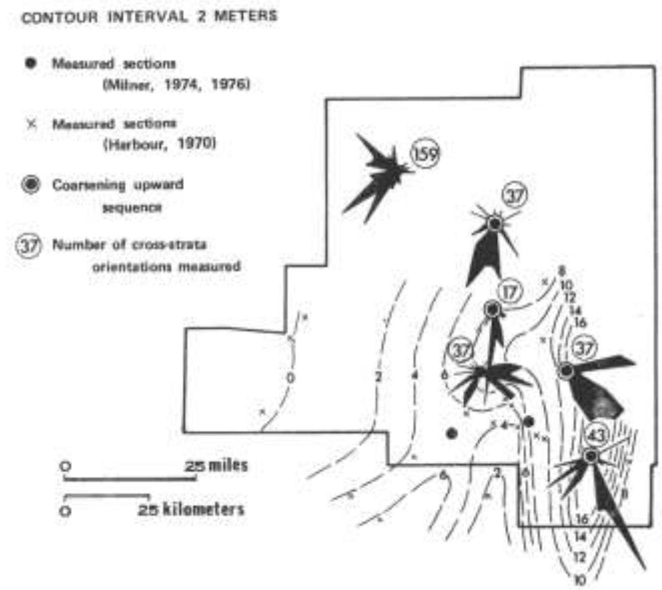


FIGURE 14—ISOPACH MAP AND CROSS-STRATA ORIENTATIONS IN THE UPPER GLORIETA TONGUE IN LINCOLN COUNTY.

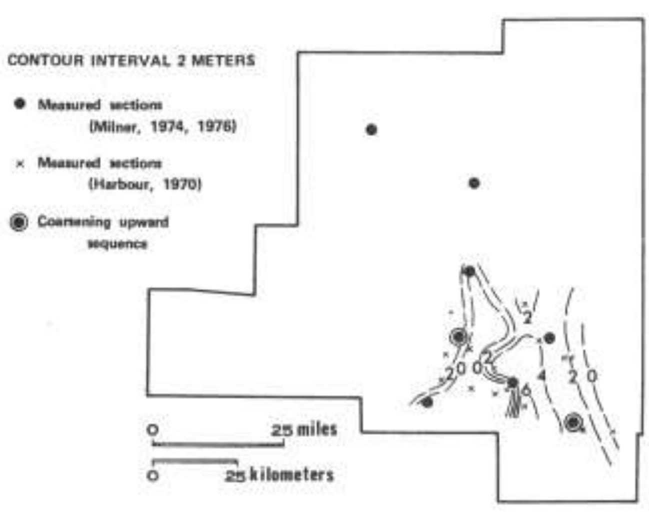


FIGURE 13—ISOPACH MAP OF THE LOWER GLORIETA TONGUE IN SOUTHEASTERN LINCOLN COUNTY.

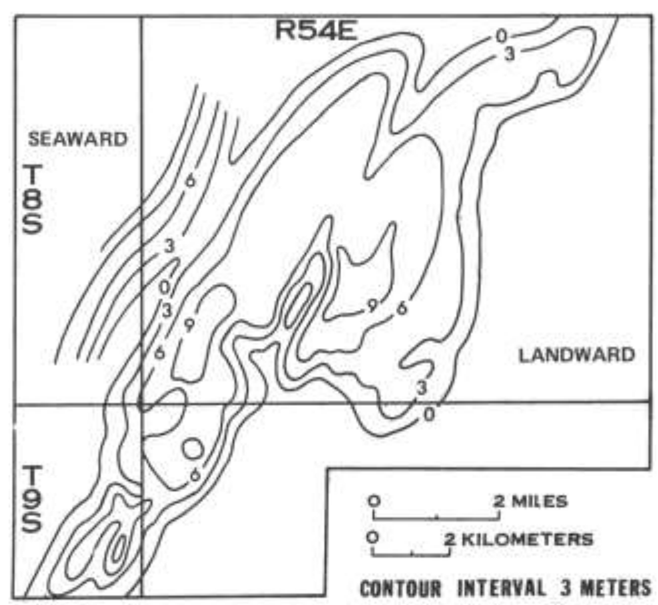
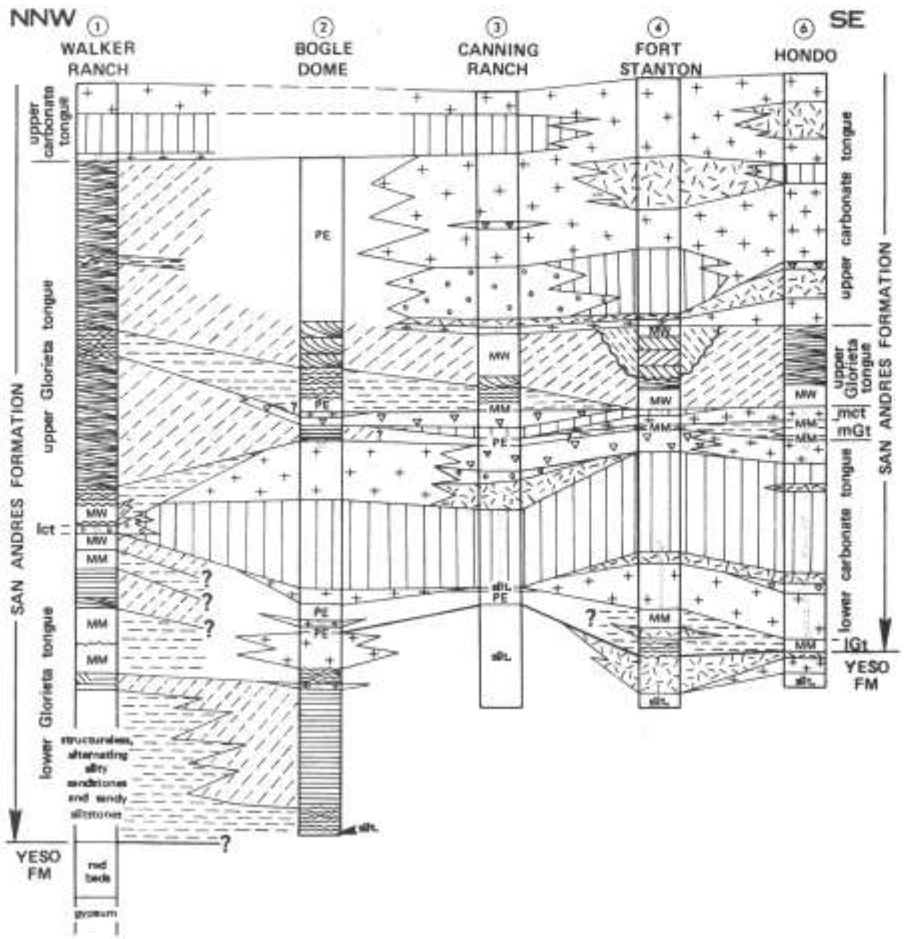
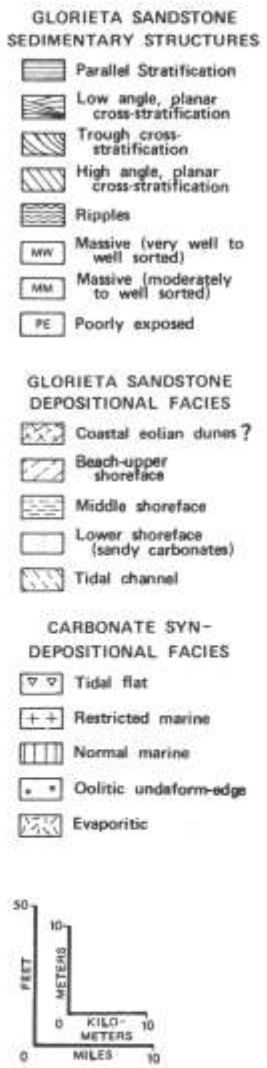


FIGURE 15—ISOPACH MAP OF A CRETACEOUS BARRIER-ISLAND COMPLEX, BELL CREEK OIL FIELD, MUDDY SANDSTONE, MONTANA. Contours based on approximately 200 wells (Davies and others, 1971; McGregor and Biggs, 1968).

FIGURE 16—NORTHWEST–SOUTHEAST CROSS SECTION ILLUSTRATING GLORIETA SANDSTONE SEDIMENTARY STRUCTURES AND DEPOSITIONAL FACIES AND CARBONATE SYNDEPOSITIONAL FACIES IN UPPER YESO AND LOWER SAN ANDRES FORMATIONS, LINCOLN COUNTY. Datum top Glorieta Sandstone at Walker Ranch and Bogle Dome. Datum base upper Glorieta tongue at all sections except Walker Ranch.





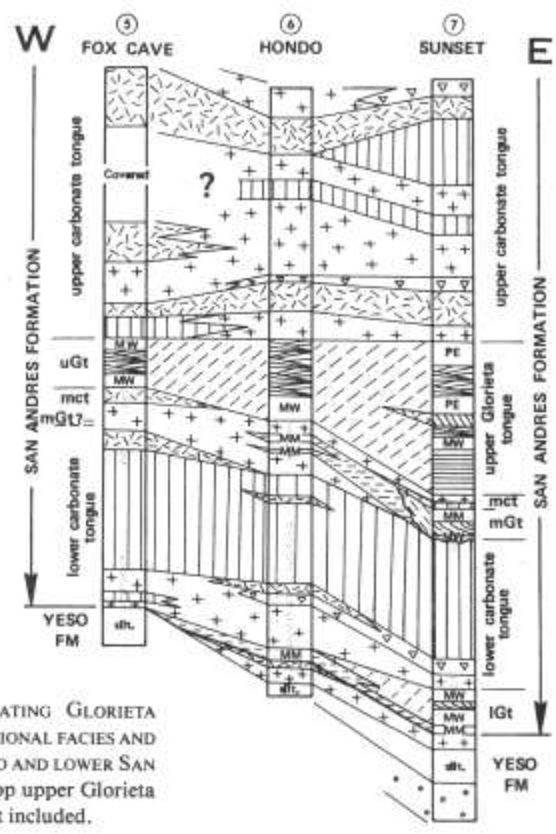


FIGURE 17—EAST-WEST CROSS SECTION ILLUSTRATING GLORIETA SANDSTONE SEDIMENTARY STRUCTURES AND DEPOSITIONAL FACIES AND CARBONATE SYNDEPOSITIONAL FACIES IN UPPER YESO AND LOWER SAN ANDRES FORMATIONS, LINCOLN COUNTY. Datum top upper Glorieta tongue. Tertiary igneous intrusives at Fox Cave not included.

ficult to determine because the grain size of the Glorieta is almost uniform. This paleogeographic distinction is fundamental because fining upwards suggests transgression or channel fill whereas coarsening upwards indicates regression or progradation. The upper and lower Glorieta tongues of southern Lincoln County commonly pass upwards from *lower* flow-regime to *higher* flow-regime rock units; this passing upwards indicates coarsening-upwards sequences. Unambiguous fining-upwards sequences are rare in the Glorieta tongues. By analogy, therefore, the thicker Glorieta Sandstone to the north and northwest consists predominantly of coarsening-upwards sequences.

The thin carbonate rock unit in the middle of the Glorieta Sandstone at Walker Ranch is overlain by *lower* flow-regime silty sands, overlain in turn by *upper* flow-regime cross-stratified sandstones (fig. 16). A similar coarsening-upwards sequence is present in the uppermost Yeso Formation at Walker Ranch. The sequence consists of gypsum overlain by siltstone, which is in turn overlain by a reddish Yeso sandstone (fig. 16). The continuous, parallel stratification of the Glorieta in central New Mexico indicates that fining-upwards sequences related to channel deposition are rare or absent. Koehn (1972) reported coarsening-upwards sequences in the Glorieta Sandstone near Rowe (fig. 2). Hence, the Glorieta Sandstone in central New Mexico was probably deposited in environments associated with repeated episodes of progradation or regression.

CHANNELING—The Glorieta Sandstone in northeastern New Mexico commonly contains channeling, ranging from less than a meter to several meters in relief. Evidence of major channeling was noted at the Ocate, Mora Gap, and Romeroville outcrops (figs. 2 and 18). These outcrops generally lack the continuous, parallel stratification of the Glorieta in central New Mexico, where channeling is rare and ranges from 10 to 50 cm in relief (fig. 2; Palma, Joyita Hills, Chupadera Mesa, Nacimiento Mountains). Long, low-angle cross-stratification suggestive of foreshore to upper-shoreface deposition (Harms and others, 1975) was noted above and below major channels at Ocate and Romeroville.

On the basis of the sequence of sedimentary structures and the upward decrease of grain size within depositional cycles, the major channels are interpreted to be of fluvial or fluvio-deltaic origin. Medium-scale cross-strata commonly pass upward into ripples; this sequence indicates the waning energy commonly associated with fluvial deposition. The Romeroville outcrop area contains nestled channels, several separated by shaly siltstone (fig. 18). A thin gravel to pebble conglomerate that fines upward to well-sorted sandstone was also noted. The conglomerate has an irregular lower contact that truncates an underlying rippled sandstone (fig. 18).

BURROWING—Distinct burrowing is very rare in the Glorieta Sandstone. It was noted only in the upper Glorieta tongue at Bluewater (fig. 19) and the lower Glorieta tongue at Fort Stanton. The burrows at Bluewater are shallow-marine burrows of the *"Cruziana"* facies (Heckel, 1972). Mottling is locally common in the Glorieta but is not demonstrably due to burrowing organisms.

Carbonate member

The carbonate member of the lower San Andres Formation in eastern Lincoln County consists of dolomite

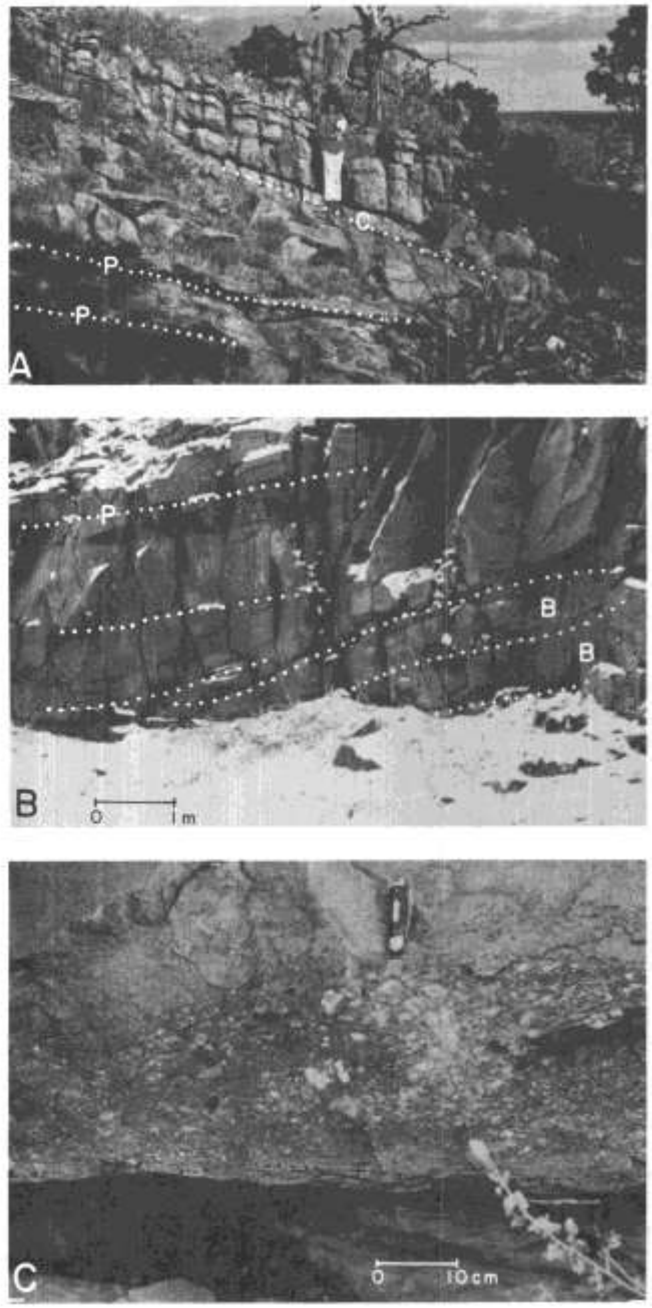


FIGURE 18—VIEWS OF FLUVIAL (-DELTAIC?) DEPOSITIONAL FACIES. **A)** Ocate outcrop: channel base (C) overlain by cross-stratified sandstone, which is overlain by rippled sandstone. This sequence indicates an upward waning of depositional energy or "flow regime." Note even, parallel stratification (P) below channel. **B)** Romeroville outcrop: channel migration indicated by probable lateral accretion of point-bar deposits (B). Note even, parallel stratification (P) above channeling. **C)** Romeroville outcrop: thin conglomerate with sharp erosional lower contact (E) truncates underlying rippled sandstone. Grain size fines upward overall within depositional unit.

FIGURE 19—VIEW OF "CRUZIANA"-TYPE BURROWS IN FLOAT FROM UPPER GLORIETA TONGUE, BLUEWATER OUTCROP. Burrows are oriented parallel to bedding.

and limestone tongues intercalated with the Glorieta Sandstone (fig. 3). The carbonate tongues are stratigraphic markers within the sandstone and so allow it to be subdivided into the lower, middle, and upper Glorieta tongues of this study. Furthermore, the carbonates are more environmentally diagnostic than the intercalated sandstones and thereby provide boundary conditions on environmental interpretations of the Glorieta. Milner (1974, 1976) treats the carbonate member in greater detail.

SYNDEPOSITIONAL FACIES—The carbonate tongues consist of the following major syndepositional facies: 1) tidal flat, 2) restricted marine, 3) normal marine, 4) undaform-edge carbonate sand (Rich, 1951), and 5) evaporitic. These facies are defined on the basis of petrography, paleontology, and sedimentary structures. Subtidal syndepositional facies make up about 95 percent of the carbonate tongues, whereas supratidal and intertidal facies make up only about 5 percent. Figs. 16 and 17 illustrate the lateral and vertical distribution of syndepositional facies in the carbonate member.

No preserved evaporite minerals were noted in eastern Lincoln County. However, anhydrite-nodule molds, evaporite-crystal molds, and length-slow chalcedony suggest the former presence of diagenetic evaporites in the carbonate tongues. The very limited evidence of evaporites suggests an open physical setting during deposition (Kinsman, 1969) owing to the arid middle Permian climate (Milner, 1974).

Mud-supported carbonate fabrics indicative of low-energy deposition characterize about 95 percent of the carbonate member. Of the remaining 5 percent, oolitic grain-supported fabrics indicative of high-energy deposition are found only in the easternmost measured sections in Lincoln County. The distribution of low and high-energy environments suggests that most of the carbonate member was deposited in low-energy environments behind and protected by oolitic sand bodies formed in a high-energy undaform-edge environment.

Evaporitic member

The upper Yeso and lower San Andres units are strongly evaporitic in western Lincoln and eastern Socorro Counties (figs. 1 and 3; Harbour, 1970; Kottlowski, 1963). One outcrop of the evaporitic member was examined during this study. At Chupadera Mesa (fig. 2), interstratified dolomite and gypsum rock units overlie the Glorieta Sandstone, and a thin gypsum unit may be present in its upper part. The carbonates in the first 25 m above the Glorieta were deposited in a restricted marine environment (Milner, 1976). The absence of supratidal and intertidal features characteristic of modern sabkhas (Lucia, 1972) in the associated carbonates suggests that the gypsum was deposited subaqueously in a restricted lagoonal environment.

Modern and ancient analogues

Holocene barrier-island complexes consist of barrier-island (beach-upper-shoreface, middle-shoreface, lower-shoreface), coastal-eolian-dune, tidal-channel, and lagoonal deposits (LeBlanc, 1972; Davies and others, 1971). Fig. 20 compares a composite sequence of characteristic features noted in the Glorieta Sandstone in Lincoln County with features of the Holocene Galveston Island complex as well as with an interpreted ancient complex (Davies and others, 1971) and with an ancient prograding sandy shoreline (Harms and others, 1975). The Glorieta composite section more closely resembles the modern and ancient barrier-island complex than it does the ancient prograding sandy shoreline in sedimentary structures and thickness. However, several significant differences between the Glorieta composite section and the Galveston Island and Muddy Sandstone barrier-island complexes are apparent.

The interpreted Glorieta lower shoreface consists of sandy carbonate rather than of fine terrigenous clastics because fine material was absent in the sediment load entering Glorieta seas. The middle shorefacies of the Glorieta and Muddy Sandstone are about the same thickness, although appreciably thinner than the Galveston Island middle shoreface.

The trough cross-strata occasionally found at the base of the upper-shoreface unit in the Glorieta are not reported from Galveston Island or the Muddy Sandstone, but are very common in the prograding sandy shoreline of the Gallup Sandstone. The cross-strata may have been formed by longshore traction currents on longshore bars (Harms and others, 1975) or by storm-wave attack on the coast (Tanner, 1963). Much of the trough cross-strata noted in this study probably formed on shoreface bars and in tidal channels (figs. 16 and 17).

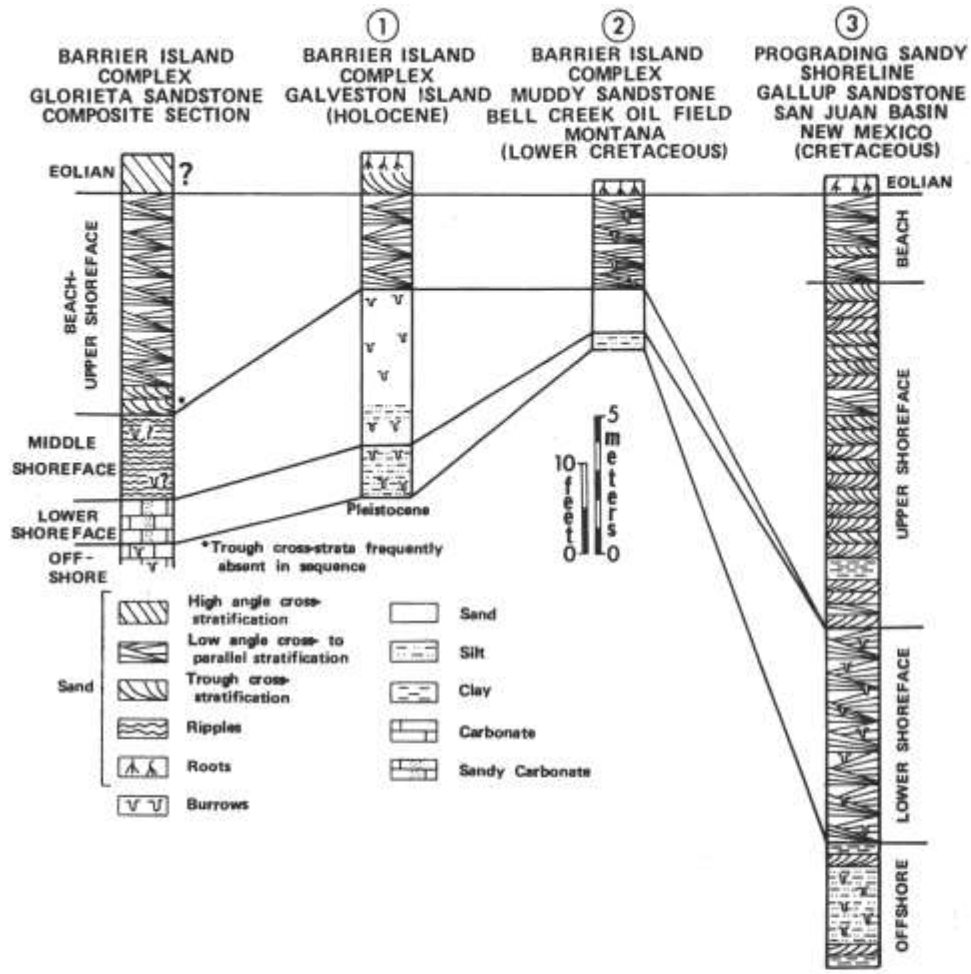


FIGURE 20—STRATIGRAPHIC COLUMNS COMPARING INFERRED GLORIETA SANDSTONE BARRIER-ISLAND DEPOSITS WITH DEPOSITS OF MODERN AND ANCIENT ANALOGUES. (Columns 1 and 2 from Davies and others, 1971; column 3 from Harms and others, 1975).

The Glorieta beach-upper-shoreface unit is considerably thicker than the corresponding unit at Galveston Island or in the Muddy Sandstone. The greater thickness suggests that the upper-shoreface unit may have been deposited in more than a single depositional cycle. The depositional model for the Glorieta Sandstone postulates several cycles of coastal progradation during relatively low sea-level stands followed by relative sea-level rises and transgressions. The reworking of coastal dunes and possible inland eolian deposits (Silver and Todd, 1969) along a transgressive beach-upper shoreface would result in an exceptional thickness of transgressive and regressive beach-upper-shoreface deposits. This explanation also accounts for the seeming absence of eolian deposits in the Glorieta Sandstone and their presence at Galveston Island and in the Muddy Sandstone; they were probably deposited, but not preserved. High-angle cross-strata are rarely noted in the Glorieta. They may represent the remnants of eolian deposits (McBride and Hayes, 1962).

Tidal-channel deposits were noted in the middle Glorieta tongue at Sunset and in the upper Glorieta tongue at Fort Stanton (figs. 16 and 17). They were identified by the presence of bimodally distributed cross-strata orientations approximately normal to the inferred north-northeast to south-southwest trend of the Glorieta coastline in central New Mexico (figs. 21, 22, and 23). A distinct scour is present at the base of tidal-channel deposits in the middle Glorieta tongue at Sunset.

Lagoonal deposits are inferred to be chiefly restricted marine carbonates in eastern Lincoln County and restricted marine carbonates and evaporites in western Lincoln, eastern Socorro, and northern Otero Counties (fig. 2). The general absence of interstratified carbonates and evaporites within the Glorieta Sandstone north of Bogle Dome suggests that lagoonal deposits were mainly terrigenous clastics. Large quantities of sand might have been introduced into the lagoons by eolian processes. Transgressive seas may have commonly reworked these lagoonal deposits. Some of the comparatively poorly sorted, rippled rock units postulated as having formed in middle-shoreface environments of deposition may have been deposited instead in lagoons behind barrier-island complexes. Figs. 16 and 17 illustrate the sedimentary structures and depositional facies in the Glorieta Sandstone and the interstratified carbonate syndepositional facies.

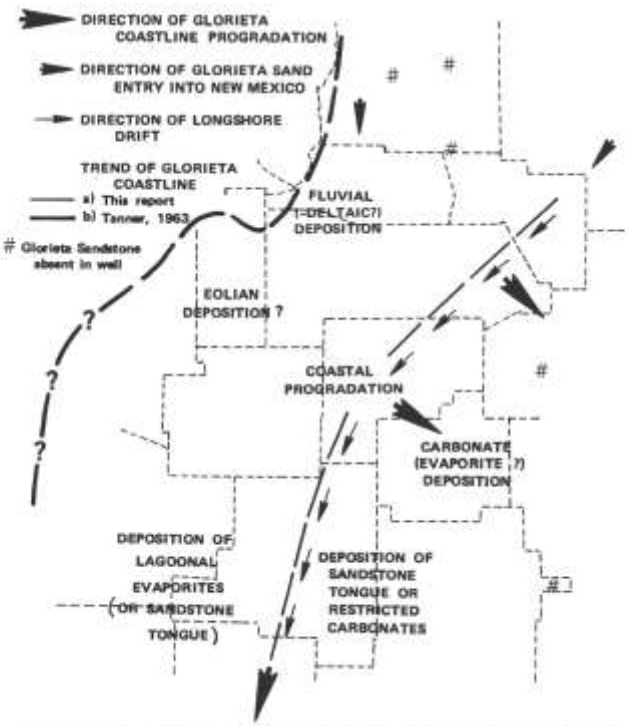


FIGURE 21—Depositional model for the lower San Andres Formation during low relative sea-level stands.

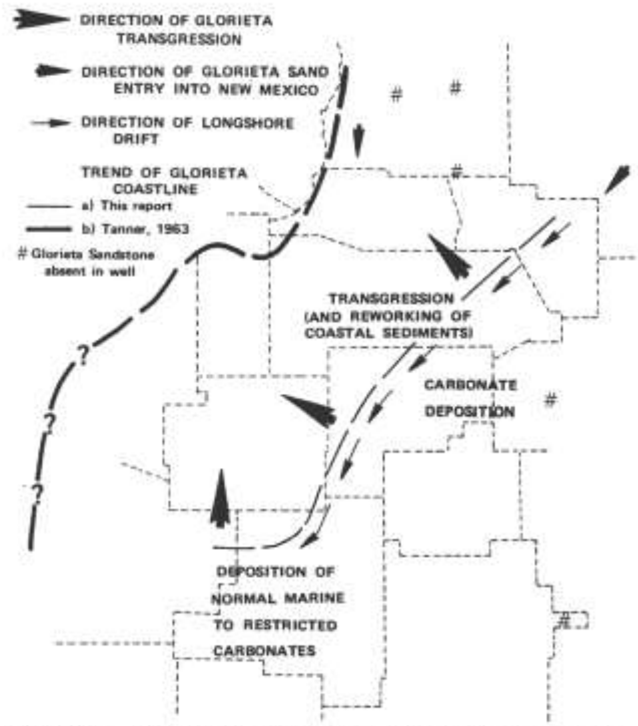


FIGURE 22—Depositional model for the lower San Andres Formation during high relative sea-level stands.

Depositional model

Most of the Glorieta Sandstone in east-central New Mexico probably was deposited along north-northeast- to south-southwest-trending coastlines dominated by prograding barrier-island complexes during relatively low sea-level stands (fig. 21). The low stands were followed by relative rises in sea level and transgression. The Glorieta Sandstone is generally thickest between the relatively positive Pedernal massif and the relatively negative element east of it (fig. 6). Glorieta prograding coastlines were probably repeatedly localized at this transition. Figs. 21, 22, and 23 illustrate the depositional model during relative low and high sea-level stands.

Low sea-level stands

The Glorieta coastline in east-central New Mexico prograded to the east-southeast and the south during low relative sea-level stands (fig. 21). Marine carbonates were probably deposited seaward of the Glorieta littoral zone (Foster and others, 1972). Eolian environments may have been dominant landward of the coastline to the west-northwest (Silver and Todd, 1969). Fluvial (-deltaic?) environments were present in the Permian highlands of northeastern New Mexico. They were probably marginal to the continental environments within which the Sangre de Cristo Formation was deposited (Bachman, 1953).

Southward longshore drift probably transported sand into east-central Lincoln County (fig. 21). Continued

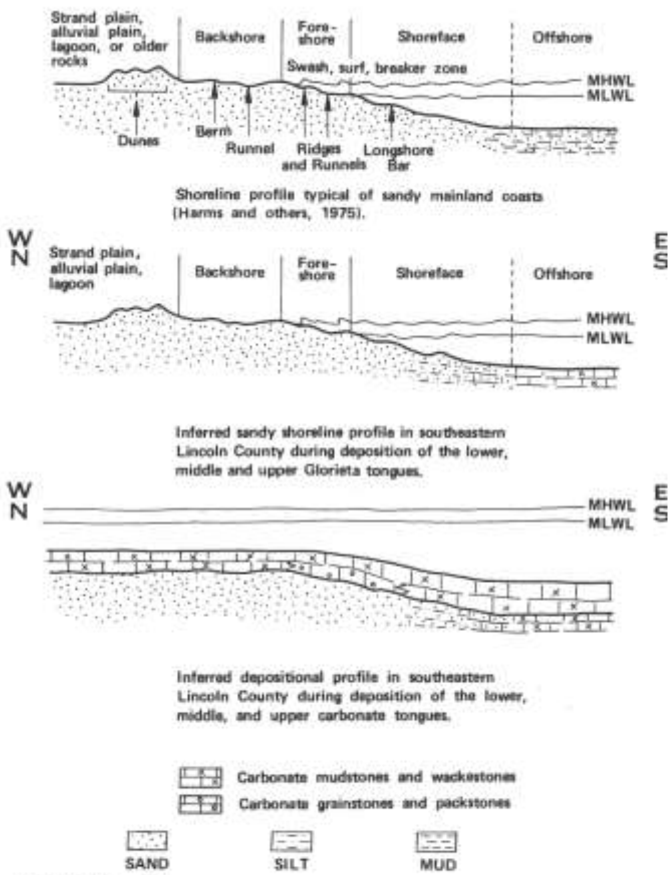


FIGURE 23—East-west and north-south profiles illustrating the depositional model for the lower San Andres Formation during deposition of the Glorieta Sandstone and carbonate tongues.

sand transport resulted in progradation of the coastline to the south and deposition of one of the three Glorieta tongues. In western Lincoln and eastern Socorro Counties, the restricted circulation accompanying relative sea-level fall and the progradation of the Glorieta Sandstone into eastern Lincoln County may have resulted in the formation of lagoonal evaporites and/or restricted marine carbonates.

High sea-level stands

A relative rise of sea level probably resulted in the transgression of the coastline to the north and west and the reworking of the coastal and eolian sands deposited during low sea-level stands (fig. 22). The predominance of parallel bedding in Glorieta outcrops in central New Mexico suggests that eolian sands were either very effectively reworked by transgression or that they were never very significant in volume. In northeastern New Mexico, higher relative sea-level stands resulted in the deposition of coastal sands and the end of fluvial (-deltaic?) deposition.

The rise of relative sea level resulted in the end of sand deposition in eastern Lincoln County south of Walker Ranch and in the introduction of carbonate sedimentation. In western Lincoln and eastern Socorro Counties, higher relative sea levels probably resulted in increased circulation, which caused the end of lagoonal evaporite deposition and the beginning of carbonate sedimentation. In east-central New Mexico, carbonate deposition was predominant (Foster and others, 1972; Meissner, 1972).

Economic considerations

The primary economic value of this study of the Glorieta Sandstone probably lies in the deductions made about the origin of the interfingering and overlying carbonates of the lower half of the San Andres Formation (fig. 3). The Glorieta Sandstone in New Mexico does not produce oil and gas although it has been penetrated by many exploration wells. The absence of production from the Glorieta is probably due to its widespread surface exposure and shallow burial coupled with its commonly excellent reservoir properties (for example, Havenor, 1968). However, the presence of abundant dead oil in the upper Glorieta tongue at the Bogle Dome outcrop section (fig. 1) suggests that similar accumulations may be preserved in the subsurface to the east. The lower half of the carbonates of the San Andres Formation (Slaughter zone) produces oil and gas in northern Lea, Roosevelt, Chaves, and Eddy Counties of New Mexico (Havenor, 1968) and so has more prospects than the Glorieta Sandstone.

The paleogeographic framework of Glorieta-lower San Andres deposition proposed in this report (figs. 21, 22, and 23) suggests that the lower San Andres carbonate facies that crop out in Lincoln County (Milner, 1974, 1976) should be analogous to producing and potentially producing carbonate facies in the subsurface of east-central New Mexico (Havenor, 1968). The proposed regional framework should help subsurface explorationists to predict gross lithofacies trends prior to drilling as well as to organize the detailed correlation and interpretation of well logs.

Conclusions

The following conclusions are based on a detailed study of the sandstones and carbonates of the lower San Andres Formation in eastern Lincoln County as well as on regional considerations. The regional perspective is based on visits to outcrops of the lower San Andres throughout New Mexico and on examination of lithologic well logs.

1) Compositional maturity of the Glorieta Sandstone generally increases upward in measured sections and south-southwestward along the inferred paleocurrent direction in eastern Lincoln County.

2) Sand was transported into New Mexico from the north and northeast. The Ancestral Rockies and cratonic areas farther to the northeast are probable source areas.

3) Most of the Glorieta Sandstone in east-central New Mexico was deposited along north-northeast- to south-southwest-trending coastlines. The coastlines were dominated by eastward and southward prograding barrier-island complexes during relatively low sea-level stands. Fluvial (-deltaic?) deposition near the Permian highlands of northeastern New Mexico was probably related to relatively low sea-level stands.

4) Relatively low sea-level stands were followed by relative rises in sea level and the westward and northward transgression and reworking of regressive deposits. Carbonate deposition was predominant in eastern Lincoln County following relative rises of sea level.

5) Glorieta prograding coastlines were probably repeatedly localized at the transition between the relatively positive Pedernal massif and the relatively negative element east of it.

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