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Sam Milner

LOWER SAN ANDRES FORMATION

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SEDIMENTOLOGY OF A SANDSTONE-CARBONATE TRANSITION, LOWER SAN ANDRES FORMATION (MIDDLE PERMIAN), LINCOLN COUNTY, NEW MEXICO

BY

SAM MILNER

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CONTENTS

	Page
Table of contents	i
Illustrations and tables	iv
Abstract	vi
Introduction	1
Purpose and scope of study	1
Location of study area	2
Field methods	2
Laboratory methods	4
Previous work	5
Acknowledgements	7
Storage of study materials	8
Regional Permian paleogeography	9
Penecontemporaneous tectonic elements	9
Permian climate	11
Middle Permian regional stratigraphy in central New Mexico	12
Introduction	12
Yeso Formation	12
San Andres Formation	15
Age of the San Andres Formation	17
Paleontology	19
Introduction	19
Trace fossils	19
Introduction	19
Carbonate member	21
Glorieta Sandstone Member	23
Body fossils	23
Carbonate member	23
Introduction	23
Normal marine assemblage	24
Restricted marine assemblage	25
Glorieta Sandstone Member	26
Carbonate member of the lower San Andres Formation	28
Introduction	28
Carbonate sedimentary structures	30
Introduction	30
Organo-sedimentary structures	30
Emergent desiccation features	32
Introduction	32
Fenestral fabric	33
Mud cracks	34
Brecciation	35
Conclusion	35
Petrography	37
Introduction	37
Skeletal grains	37

Peloids....37
Intraclasts....38
Oolites....38
Terrigenous grains....39
Porosity....39
Carbonate diagenesis....41
Introduction....41
Cementation....41
Dolomitization....42
Iron sulfides and iron oxides....44
Dedolomitization....45
Silicification....46
Stylolitization....46
Evidence of evaporites....48
Introduction....48
Anhydrite nodule molds....48
Evaporite crystal molds....51
Length-slow chalcedony....52
Carbonate depositional facies....53
Introduction....53
Tidal flat and lagoonal environments....53
Non-evaporitic tidal flat and lagoonal facies....56
Supratidal facies....56
Intertidal facies....56
Restricted subtidal facies....60
Evaporitic tidal flat and lagoonal facies....63
Introduction....63
Modern sabkha environments....64
Origin of evaporites in lower San Andres Formation.65
Evaporitic facies in lower San Andres Formation....68
Normal marine subtidal facies....71
Undaform-edge facies....74
Correlation by carbonate depositional facies....75
Glorieta Sandstone Member of the lower San Andres Formation.76
Field description....76
General petrology....76
Texture....76
Composition....79
Light minerals....79
Heavy minerals....81
Cements....82
Diagenetic features....82
Sedimentary structures....82
Wavy bedding....82
Cross-stratification....84
Even, planar stratification....87
Massive....87
Soft sediment deformation....87
Paleocurrent analysis....88
Provenance and dispersal of the sand....90
Depositional process facies....91
Environmental interpretation....93

Paleogeographic implications for early San Andres time in central New Mexico....98
"Transgressive-regressive" cycles....98
Introduction....98
Cycles in the upper Yeso and lower San Andres Formations....100
Significance of "transgressive-regressive" cycles....104
Pedernal positive element....105
Detailed paleogeography....107
Introduction....107
Nature and distribution of carbonate rocks and facies109
Eastern edge of the Pedernal positive element....112
Introduction....112
Thickness trends in the three Glorieta tongues....113
Paleocurrent analysis of the upper Glorieta tongue114
Depositional model for early San Andres time....115
Introduction....115
Carbonate depositional model....115
Introduction....115
Low sea level stands....117
High sea level stands....119
Intermediate sea level stands....120
Sandstone depositional model....121
Regional aspects of Glorieta Sandstone deposition....121
Marine Origin of the Glorieta Sandstone....124
Depositional model for Glorieta Sandstone north of Bogle Dome....125
Depositional model for Glorieta Sandstone south of Walker Ranch....128
Introduction....128
Lower Glorieta tongue....130
Middle Glorieta tongue....132
Upper Glorieta tongue....133
Conclusions....135
Appendix I: Location of measured sections....137
Appendix II: Interpretation of plates I to VIII....141
Introduction....141
Heading of plates I to VIII....143
References....146

ILLUSTRATIONS-SHORT LIST

page

Figure 1. Location map....................................3
2. Regional tectonic elements............................10
3. Middle Permian regional stratigraphy..................12
4. Rock units of upper Yeso and lower San Andres Formations..13
5. Lithology of upper Yeso and lower San Andres Formations..14
6. Occurrence of carbonate parameters....................20
7. Sequence of selective dolomitization..................43
8. Fence diagram...54
9. Polished slabs from supratidal facies.................57
10. Polished slabs from supratidal and intertidal facies...58
11. Polished slabs from restricted marine facies.........61
12. Polished slabs from restricted marine and normal marine facies...................................62
13. Polished slabs from evaporitic facies................69
14. Polished slabs from evaporitic facies................70
15. Polished slabs from normal marine facies.............72
16. Polished slabs from normal marine and undaform-edge facies..73
17. Wavy bedding and cross-stratification in Glorieta Sandstone..................................83
18. Cross-stratification in Glorieta Sandstone...........85
19. Rose diagrams for cross-stratified units in Glorieta Sandstone..................................89
20. Ideal bed forms and corresponding features in study area.......................................92
21. Polished slabs illustrating "shoaling upwards" sequence..103
22. Tectonic elements in New Mexico.....................106
23. Cross-bed orientations and approximate trend of undaform-edge...................................109
24. Isopach map of upper Glorieta tongue................113
25. Idealized and interpreted carbonate depositional models.......................................116
26. Regional aspects of Glorieta Sandstone deposition...122
27. Location of measured sections.......................138
28. Heading used in plates I to VIII....................141
29. Interpretation of relative abundance of sedimentary parameters in plates I to VIII.........142
30. Symbols used in graphic sections in plates I to VIII.......................................144
31. Interpretation of stratification in plates I to VIII.......................................144

Location
Plate I Walker Ranch section........................Pocket
II Bogle Dome section........................Pocket
III Canning Ranch section........................Pocket
IV Fort Stanton section........................Pocket
V Fox Cave section........................Pocket
VI Hondo section........................Pocket
VII Sunset section........................Pocket
VIII Bluewater section........................Pocket
IX Northwest-southeast cross-section..........Pocket
X Northeast-southwest cross-section..........Pocket
XI Heading used in plates I to VIII............Pocket

TABLES

page
Table 1. Statistical parameters of samples from Glorieta Sandstone........................77
2. Modal analysis of selected samples from Glorieta Sandstone........................80
3. Heavy minerals in the Glorieta Sandstone........81
4. Environmental interpretation of Glorieta Sandstone........................95

ABSTRACT

The lower San Andres Formation (Middle Permian) in Lincoln County, New Mexico consists of dolomite, limestone, and interbedded sandstone, which are largely of marine origin. The Glorieta Sandstone Member of the San Andres Formation is about 240 feet thick at the northern end of the study area and forms tongues southward as the lower San Andres passes into dominantly carbonate rocks. Lower, middle, and upper Glorieta Sandstone tongues alternate with lower, middle, and upper carbonate tongues. The carbonate tongues consist of the following depositional facies: 1) non-evaporitic tidal flat and deep lagoonal facies (consisting of supratidal, intertidal, and restricted subtidal facies), 2) evaporitic tidal flat facies, 3) subaqueous? evaporitic facies, 4) normal marine subtidal facies, and 5) undaform-edge sand facies. These facies are defined on the basis of body and trace fossils, sedimentary structures, and allochemical constituents. Subtidal depositional facies make up about 95% of the carbonate tongues, whereas supratidal and intertidal facies only about 5%. The carbonate depositional facies permit detailed correlation throughout the study area and some of them are probably useful for correlation outside it.

Dolomitization, cementation, iron sulfides and iron oxides, dedolomitization, silicification, and stylolitization are the main carbonate diagenetic features present. The patterns of dolomitization are almost entirely consistent with an emergent tidal flat dolomitization model. Dolomitization and silicific-

ation appear to be early diagenetic processes.

No preserved evaporite minerals were noted. However, anhydrite nodule molds, evaporite crystal molds, and length-slow chalcedony suggest the former presence of evaporites in the carbonate tongues. The very limited evidence of evaporites in the study area suggests an open physical setting, since the climate during the Middle Permian appears to have been arid. Little or no evidence of an emergent tidal flat or sabkha origin for these former evaporites was observed, even though the study area was on a positive element that appears to have been active during the Permian.

The Glorieta Sandstone Member of the San Andres Formation is generally a fine-grained, very well to moderately sorted, calcite-cemented quartz arenite. Cross-bed dip orientations in the upper Glorieta tongue are generally toward the south-to-southeastward, whereas they are generally southwestward in the Glorieta Sandstone in the northern part of the study area. Compositional maturity generally increases upward in the measured sections and southward along the inferred paleocurrent direction. Most of the terrigenous sand in the Glorieta most likely came from Paleozoic sandstones in cratonic areas to the north.

Bed forms and comparative sorting were used to classify the Glorieta Sandstone into depositional process facies, which represent deposition in lower-lower, upper-lower, and lower-upper flow regimes. Sandstone sedimentary structures, grain size analyses, and detailed quartz grain surface textures provided conflicting and ambiguous environmental information. Shallow-marine burrow types and interbedded shallow-marine carbonates suggest that at least much of the Glorieta is of shallow marine origin. Long, low-angle cross-stratification in several Glorieta rock units is suggestive of beach fore-slope deposition. Wavy bedded rock units are interpreted to have been deposited in low-energy shallow lagoonal environments.

Seventeen "transgressive-regressive" cycles were noted in the study area on the basis of transgressive "kicks," such as are described by Irwin (1965). However, only three of these cycles demonstrably suggest absolute sea level fluctuations. The regressive deposits of these cycles are relatively much thicker than the transgressive deposits. The cycles permit detailed correlation throughout the study area independent of the continuity of individual carbonate depositional facies. Most of these cycles should be present in the lower San Andres outside the study area. Apparent cycles in the Glorieta Sandstone in the northern part of the study area have been correlated into the cycles in the lower, middle, and upper carbonate tongues to the south.

Sedimentation of the lower San Andres Formation in the study area appears to have been controlled by the Pedernal positive element, which acted as a buried, yet relatively positive feature. Several independent lines of evidence suggest the hypothesis that most of the lower San Andres in the study area was deposited on an undaform behind an undaform-edge that was present east of the study area in eastern Lincoln and western

Chaves Counties during low sea level stands. The undaform-edge carbonate sand facies in the study area is inferred to have been deposited as a result of the migration of the undaform-edge environment westward in response to a rise in sea level.

The Glorieta Sandstone does not have any convincing aeolian or deltaic characteristics within the study area. Its genesis must be inferred largely from the associated carbonate depositional facies. At least much of the Glorieta in the study area was probably deposited in relatively shallow marine environments. The terrigenous sands of the lower, middle, and upper Glorieta tongues appear to have been transported southward across the study area along the inside of pre-existing oolitic barriers of the undaform-edge environment during low sea level stands. The terrigenous sands in northern Lincoln County may also have been transported along the inside of pre-existing oolitic barriers. However, no independent evidence is available to support this hypothesis.

INTRODUCTION

PURPOSE AND SCOPE OF STUDY

The lower San Andres Formation of central New Mexico is Middle Permian (Late Leonardian to Early Guadalupian) in age (figure 3). It consists of dolomite, limestone, and interbedded sandstone (figure 5), which are largely of marine origin. The San Andres is a shelf unit northwest of the major basin edge (figure 2).

The San Andres Formation has been much studied in west Texas and southeastern New Mexico, where it is a reservoir for billions of barrels of oil and gas (e.g. Chuber and Pusey, 1972; Galley, 1958). Detailed work on the sedimentology of the San Andres Formation and its Glorieta Sandstone Member in central New Mexico has never been published. This study is limited to an examination of the lower 200 to 300 feet of the San Andres in the eastern 2/3 of Lincoln County. The lower San Andres in the northern part of the study area is dominantly sandstone. The sandstone tongues southward as the lower San Andres becomes chiefly carbonate (figure 5) in the southern part of the study area.

The purposes of this study are to describe in detail the sandstone to carbonate transition in the lower San Andres Formation, establish correlations between outcrops, interpret the environments of deposition of the rock units, and seek a depositional model to explain sedimentation patterns in the study area.

The study is based almost exclusively on surface outcrops and no serious attempt was made to obtain subsurface information. Almost continuous exposures of the lower San Andres Formation are present south of the Canning Ranch section (figure 1). Outcrops for detailed study were selected on the basis of exposure, accessibility, and location within the study area. Exposures of the lower San Andres are relatively rare north of the Fort Stanton section and the best available outcrops were measured. The San Andres Formation does not outcrop east of the study area. A few scattered lower San Andres outcrops are present in westernmost Lincoln County (Harbour, 1970), but are not included in this study.

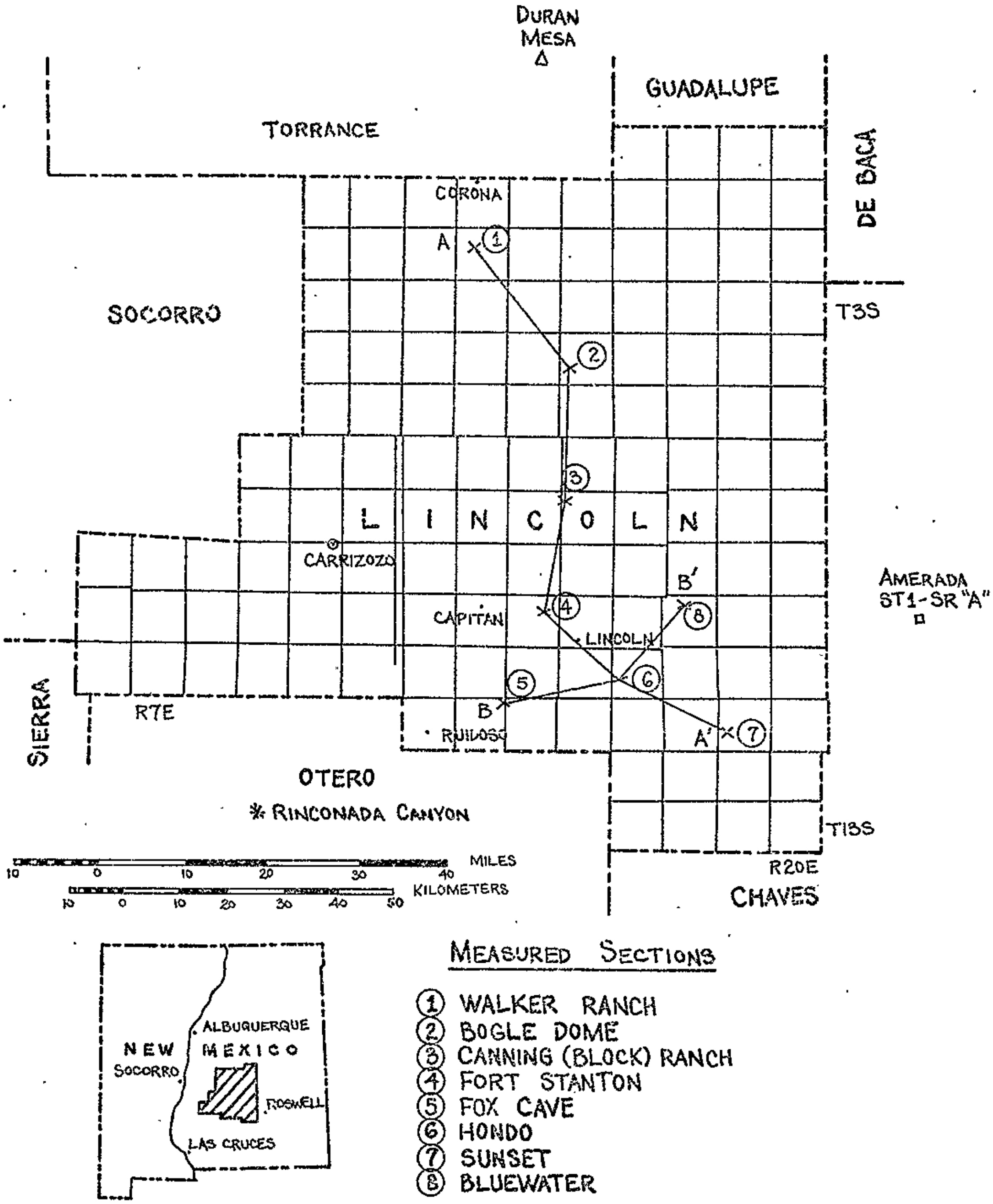
LOCATION OF STUDY AREA

The study area is located in the eastern 2/3 of Lincoln County, New Mexico (figure 1). The exact location of measured sections is given in Appendix I.

FIELD METHODS

The author spent thirteen weeks in the field between May and August, 1973. A two week field check was made during the last two weeks of December, 1973.

Eight detailed stratigraphic sections were measured (Plates I to VIII) using a brunton compass as a hand level. Megascopic features were studied, photographed, and sampled in the field. About 425 samples were collected for laboratory examination. Stratification was described using the following scale:



* RINCONADA CANYON
NE $\frac{1}{4}$, SE $\frac{1}{4}$, SEC. 8, T.13S., R.10S.
FROM HARBOUR, 1970

△ DURAN MESA
SEC. 22, T.3N., R.14E.
FROM KELLEY, 1972

□ AMERADA, ST1-SR "A"
SEC. 14, T.9S., R.22E.
FROM MEISSNER, 1972

FIGURE 1 LOCATION MAP OF STUDY AREA, LINCOLN COUNTY, NEW MEXICO (SEE APPENDIX I FOR EXACT LOCATIONS OF MEASURED SECTIONS)

< 1/10	Inches	Thinly Laminated
1/10 - 1/2	Inches	Thickly Laminated
1/2 - 2	Inches	Very Thinly Bedded
2 - 6	Inches	Thinly Bedded
1/2 - 1 1/2	Feet	Medium Bedded
1 1/2 - 5	Feet	Thickly Bedded
> 5	Feet	Very Thickly Bedded

Cross-stratification was described using the following scales for set thickness and angle of inclination of cross-strata:

<3 Inches	Small Scale
3 Inches - 3 Feet	Medium Scale
>3 Feet	Large Scale

$<10^\circ$	Low Angle
$10^\circ - 25^\circ$	Medium Angle
$>25^\circ$	High Angle

These scales for stratification and cross-stratification were used because they were familiar to the author and because no universally recognized scales exist. Grain size was described using the Wentworth (1922) size scale. A rock color chart (Goddard et al, 1970) was used to determine the value (lightness) of rock units.

LABORATORY METHODS

Three hundred and fifty carbonate samples were slabbed, polished, stained for calcite using alizarin-red S (Friedman, 1959), and studied under a binocular microscope. One hundred thin sections were made of representative slabs and studied under a petrographic microscope.

A boundary between mud and grains of 0.06mm was used to classify limestones. Dolomite crystals of uniform diameter apparently acting as matrix were inferred to have been $CaCO_3$ mud originally. Such crystals were treated as mud in determining the Dunham (1962) rock classification for dolomite rocks. Dolomite crystals have been described using the following scale: <0.01mm, 0.01 - 0.03mm, and>0.03mm. Field and laboratory data are presented graphically in Plates I to VIII. Polished slabs were photographed in the spacial orientation in which they outcropped in the field.

PREVIOUS WORK

The literature of the San Andres Formation commonly deals with areas in west Texas and southeastern New Mexico. It is not within the scope of this study to review this literature. Most studies in central New Mexico that include the San Andres have mainly been concerned with the regional stratigraphy of the Permian section. A few master's theses contain environmental interpretations of selected localities (Huber, 1961; Chisholm, 1950; Huntington, 1949). These studies predate most of the major recent work on modern carbonate and sandstone depositional environments.

The San Andres and Yeso rock units were first named by Lee (1909). The type section of the San Andres is in the San Andres Mountains of southern New Mexico. The name Glorieta was first applied by Keyes (1915) to the Dakota, a Cretaceous sandstone at the south end of the Rocky Mountains. The name Glorieta has since been applied to the prominent Permian sandstone on Glorieta mesa, the type locality, in north-central New

Mexico.

Fiedler and Nye (1933) studied the Roswell Artesian Basin, which includes southeastern Lincoln County. They renamed the San Andres Limestone the Picacho Limestone. The upper and lower Glorieta tongues of this study were also called Glorieta Sandstone. However, Fiedler and Nye thought that the Glorieta might have been lenticular rather than a continuous stratigraphic unit. Lang (1937) rejected the nomenclature introduced by Fiedler and Nye (1933) and returned to the use of the name San Andres. Lang introduced the term Hondo Sandstone for the sandstone separating the San Andres from the Yeso. The thickness of the Hondo of Lang corresponds to the thickness of the upper Glorieta tongue of this study (see REGIONAL STRATIGRAPHY). Hence, Lang's contact between the Yeso and San Andres is higher than the contact accepted by most later stratigraphers (e.g. Harbour, 1970; Kelley, 1971). Needham and Bates (1943) redescribed the type sections of the San Andres and Glorieta without changing names or type localities. They considered the Glorieta to be identical to the Hondo of Lang (1937).

The reservoir properties and general stratigraphy of the San Andres Formation were the subjects of a symposium held in 1969 (Summers and Kottlowski).

Most of the detailed work on the stratigraphy of the San Andres Formation in central New Mexico has been by Harbour (1970) and Kelley (1971, 1972). Harbour (1970) measured twenty-four stratigraphic sections, most of which were in southern Lincoln County. He concluded that the Hondo Sandstone was not demonstrably a Glorieta Sandstone tongue. Kelley (1971) mapped the geology of the Pecos Country (southeastern New Mexico) and included the eastern half of Lincoln County. He divided the San Andres Formation into a sandstone, two carbonate, and an evaporitic member. In 1972, Kelley mapped the geology of the Fort Sumner Sheet, which includes the northern quarter of Lincoln County, as a continuation of his 1971 study.

Foster et al (1972) presented an isopach map and a brief description of the San Andres Formation (including the Glorieta Sandstone) in the subsurface northeast of the study area.

ACKNOWLEDGEMENTS

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STORAGE OF STUDY MATERIALS

Specimens important to this study and all materials illustrated are in the thesis collection of the Department of Geology, University of Wisconsin, Madison, Wisconsin 53706, under U.W. #1589.

REGIONAL PERMIAN PALEOGEOGRAPHY

PENECONTEMPORANEOUS TECTONIC ELEMENTS

A period of major crustal instability preceded the end of Pennsylvanian time. The most important elements were the Pedernal positive element, the Sierra Grande arch, the Palo Duro basin, the ancestral Front Range, and the Uncompaghre-San Luis highlands (figure 2; Dixon, 1967). By Early Permian time, the tectonic elements that influenced Late Paleozoic sedimentation in central New Mexico were fully formed or in decline.

The Pedernal positive element and the Sierra Grande arch were the only positive elements in New Mexico that may have been active during Leonardian time. These elements acted as broad blocks. They were probably very low and may have been buried by uppermost Leonardian strata. After the destruction and burial of all positive areas and the rapid filling of all basins by the end of Leonardian time, the surface of the south to south-eastward sloping shelf was very regular on a regional scale, however, local irregularities were present. In Colorado, the shelves and landmasses were stable during Leonardian time. These landmasses were much reduced in height from Early Permian time (Dixon, 1967).

It is not certain if the Pedernal positive element and the Sierra Grande arch were tectonically active during Guadalupian time, but remnants of these elements were probably low landmasses that shed some detritus. Stable shelf conditions continued in Colorado during the remainder of Permian time.

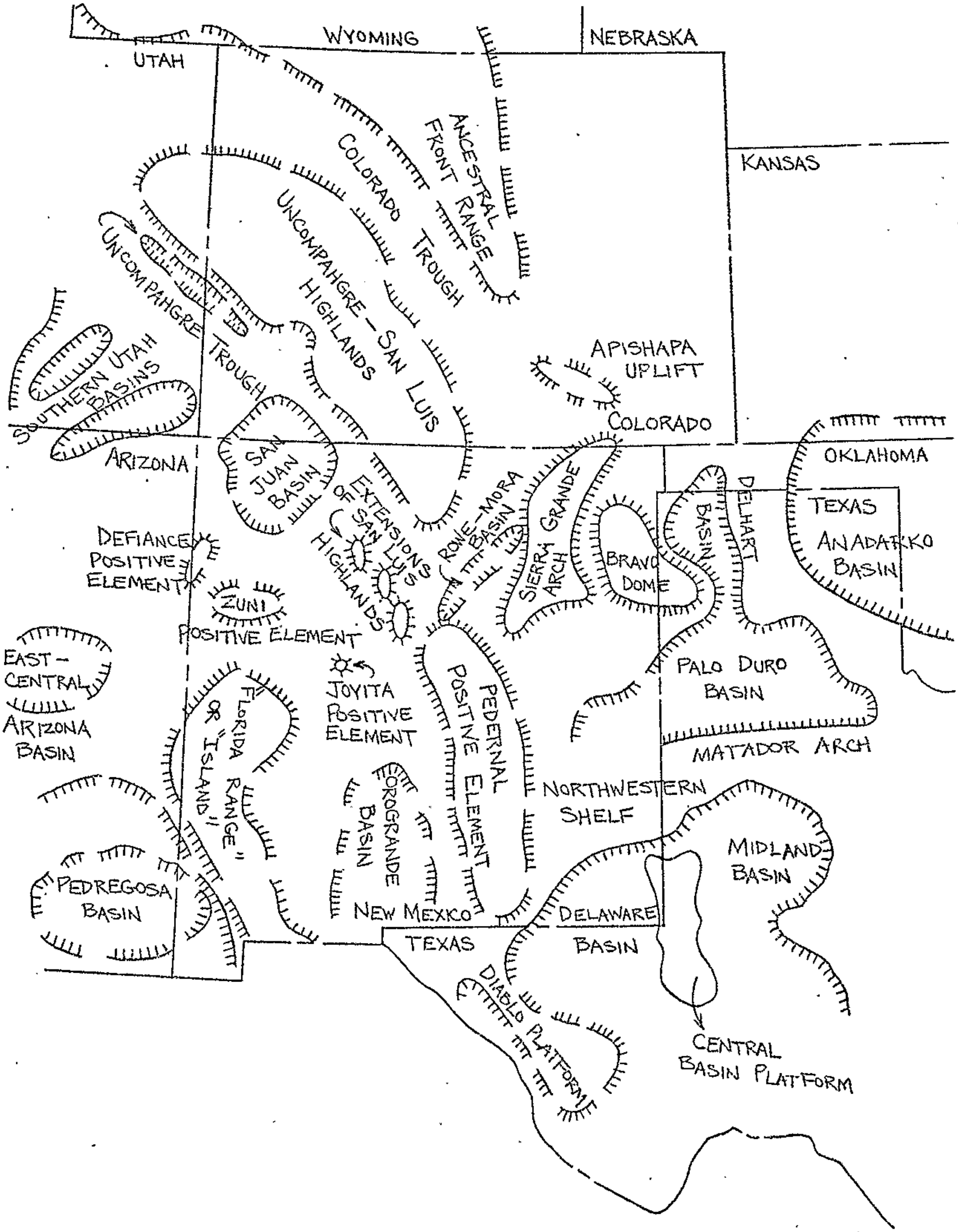


FIGURE 2 TECTONIC ELEMENTS OF NEW MEXICO AND ADJACENT REGIONS IN LATE PENNSYLVANIAN AND EARLY PERMIAN TIME (AFTER McKEE ET AL, 1967)

PERMIAN CLIMATE

New Mexico was apparently positioned very near to and north of the equator during Permian time on the basis of paleomagnetic data (Runcorn and Opdyke, 1960). The presence of evaporitic rock units throughout the Permian geologic section in the southwest (McKee et al. 1967) suggests an arid regional climate. The presence of abundant bedded evaporites in the upper Yeso Formation, in the upper San Andres in the study area, and in the lower San Andres west of the study area is compatible with an arid climate during San Andres time, as is the absence of almost all evidence of tidal flat channel deposits in the study area (Roehl, 1967).

The regional paleowind direction during the Permian was apparently towards the southwest. This direction is based on the position of the equator with respect to the position of Lincoln County and on the idealized wind patterns to be expected on an earth free of major landmasses (figure 26).

MIDDLE PERMIAN REGIONAL STRATIGRAPHY IN CENTRAL NEW MEXICO

INTRODUCTION

The Middle Permian Yeso and San Andres Formations, and the Artesia Group outcrop in central New Mexico (figure 3).

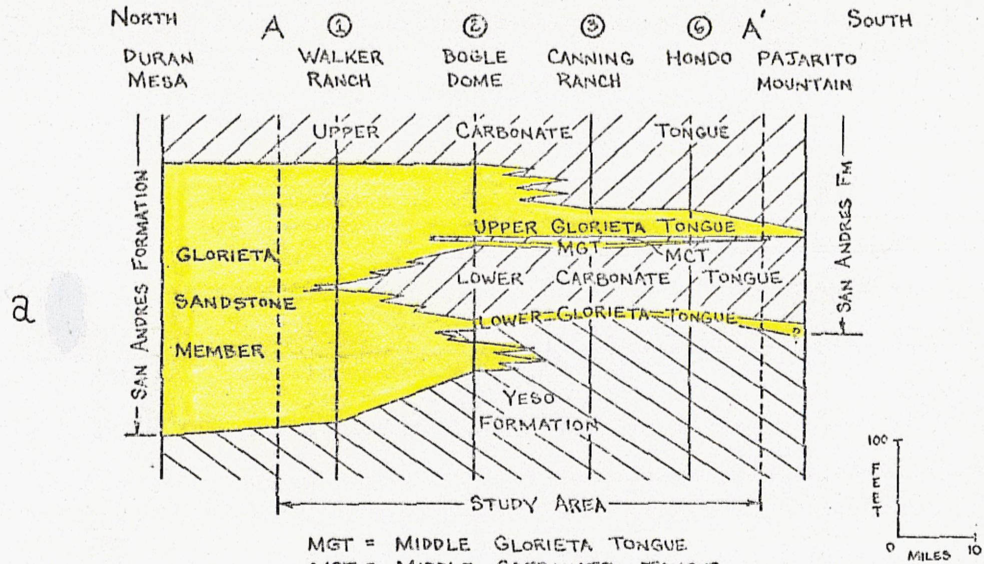
Time Units		Rock Units		Lithology
Middle Permian	Guadalupian Series	Artesia Group	Grayburg Fm	Dolomite, Sandstone, Gypsum, Mudstone
			San Andres Formation	Dolomite, Limestone, Gypsum, Sandstone
	Leonardian Series		Yeso Fm	Sandstone, Siltstone, Dolomite, Gypsum

FIGURE 3 MIDDLE PERMIAN REGIONAL STRATIGRAPHY OF CENTRAL NEW MEXICO (AFTER KELLEY, 1972)

This study is confined to about the upper 5 to 20 feet of the Yeso and the lower 200 to 300 feet of the San Andres Formation in eastern Lincoln County. Figure 4 illustrates the stratigraphic nomenclature used in this study, whereas figure 5 illustrates the gross lithology of the rock units studied.

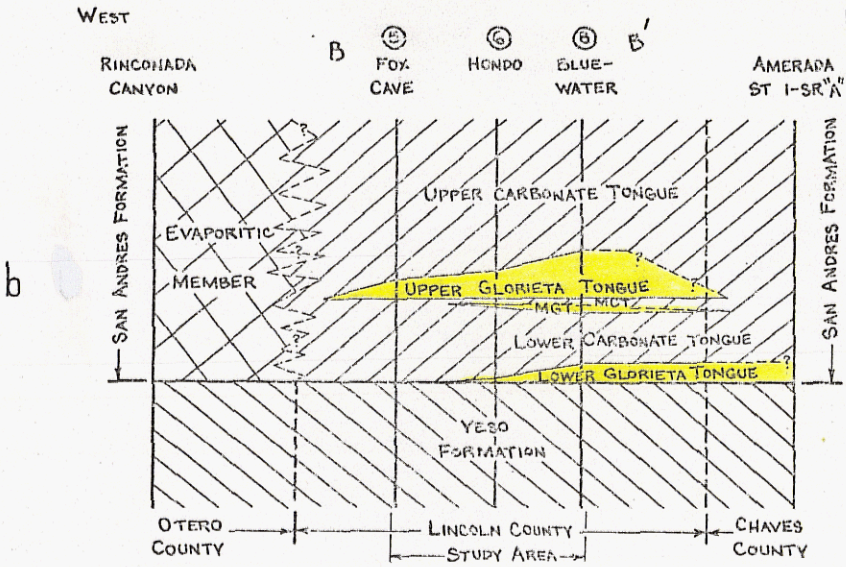
YESO FORMATION

The Yeso Formation underlies the San Andres Formation in central New Mexico. The contact between these formations is apparently gradational in the study area. No evidence of



MGT = Middle Glorieta Tongue
MCT = Middle Carbonate Tongue

Datum: Base Upper Glorieta Tongue South of Walker Ranch
Base Upper Carbonate Tongue at Walker Ranch & Duran Mesa



MGT = Middle Glorieta Tongue
MCT = Middle Carbonate Tongue

Datum: Base Lower Glorieta Tongue East of Fox Cave
Top Highest Siltstone in Fox Cave and Rinconada Canyon

Figure 4 Rock Units of the Yeso and Lower San Andres Formations in Central New Mexico

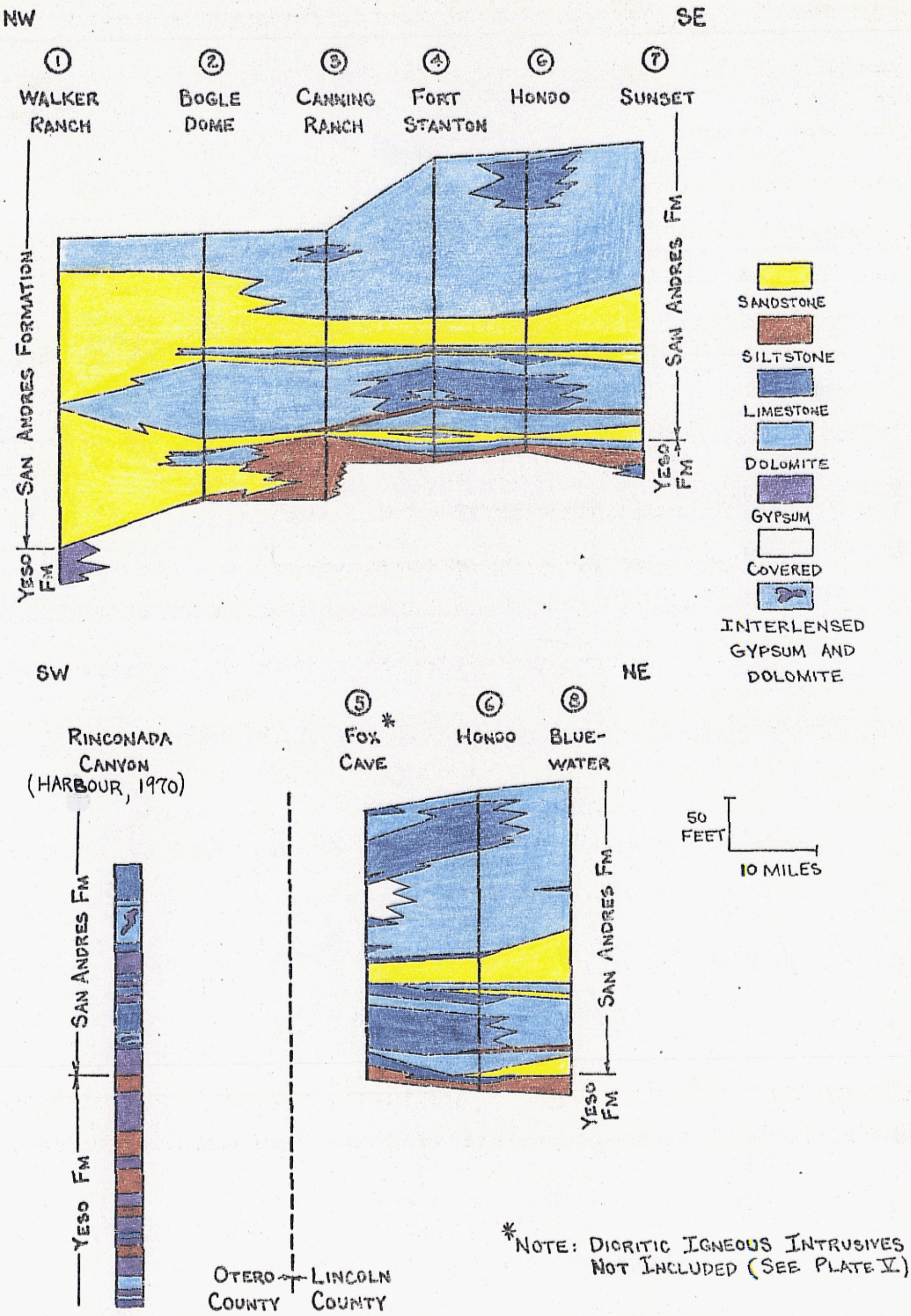


FIGURE 5 LITHOLOGY OF UPPER YESO AND LOWER SAN ANDRES IN STUDY AREA AND RINCONADA CANYON

unconformity has ever been reported in the published literature. The Yeso Formation in central New Mexico consists of sandstone, limestone, dolomite, gypsum, and siltstone. The Yeso outcropping in the Sacramento Mountains of south-central New Mexico is about 1200 feet thick (Kelley, 1971).

Only the very top (3 to 20 feet) of the Yeso is included in this study. Yellow, pink, and gray quartzose siltstone is the most common lithology, but 1) gypsum is present at Walker Ranch, 2) evaporitic dolomites are present at Fort Stanton and Hondo, and 3) a thick oolitic limestone and a thin partially laminated limestone are present at Sunset.

SAN ANDRES FORMATION

The San Andres Formation varies in thickness from about 800 feet in central New Mexico to as much as 1,700 feet in southeastern New Mexico. Kelley (1971) has recently subdivided the San Andres Formation into four members: Glorieta Sandstone Member, Rio Bonito Carbonate Member, Bonney Canyon Carbonate Member, and Fourmile Draw Evaporitic Member.

The Glorieta Sandstone Member forms the base of the San Andres Formation throughout most of the study area (figure 5). It is 280 feet thick at Duran Mesa and thins to about 240 feet at Walker Ranch. Three sandstone tongues extend southward and are informally termed the lower, middle, and upper Glorieta tongues of the San Andres Formation in this study (figure 5). The three tongues pinch out towards the western boundary of Lincoln County and thicken appreciably towards the eastern edge of the study area (e.g. Sunset and Bluewater, figures 4 and 5). This study accepts Kelley's (1971, 1972) inclusion of the Glorieta Sandstone as a member within the San Andres Formation.

Harbour (1970) suggests that the upper Glorieta tongue of this study should continue to be called the Hondo Sandstone Member of the San Andres Formation until a more positive demonstration of its relationship to the Glorieta is made. However, Harbour believes that this rock unit is probably a Glorieta tongue. Kelley (1971) concludes that there is little doubt of the correlation of this rock unit to the Glorieta and believes that the name Hondo should be dropped. This study supports Kelley's (1971) conclusions on the basis of the excellent continuity and lithologic identity of all three sandstone tongues over the 45 miles from Bogle Dome to Sunset. It is highly unlikely that these sandstones pinch out as they approach areas of nearly continuous sand deposition.

Kelley's (1971, 1972) Rio Bonito and Bonney Canyon Carbonate Members are differentiated entirely on the basis of bedding thickness. Whereas the lower carbonate rocks of the San Andres Formation are thicker bedded than the upper rocks, the actual contact between members is usually difficult to determine with the precision required for this study. Consequently, no attempt has been made to distinguish between these two members in the study area. In this study, 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 as the middle carbonate tongue, and the carbonates capping the upper Glorieta tongue as the upper carbonate tongue (figure 4). The three carbonate tongues are informally termed the carbonate member of the San Andres Formation in this study.

The Fourmile Draw Evaporitic Member (Kelley, 1971) is stratigraphically higher than the carbonate member in the study area and is not included in this study. In parts of Socorro, Otero, and western Lincoln Counties, that is, west of the study area, the lower San Andres is very evaporitic (e.g. Rinconada Canyon, figure 5).

AGE OF THE SAN ANDRES FORMATION

The Leonardian Series has its type section in the Glass Mountains of west Texas. The type section of the Guadalupian Series is at the northern margin of the Delaware Basin. Each series is characterized by the presence of distinctive fusulinids, ammonites, and brachiopods (Dunbar et al. 1960). Fusulinids are completely absent and datable ammonites and brachiopods have never been reported from the San Andres Formation in the study area. Dunbar et al (1960) concluded that in west Texas and southeastern New Mexico the lower part of the San Andres was Late Leonardian and the upper part was Early Guadalupian in age. The determination of the exact age of the lower San Andres in the study area has never been reported in the published literature of the San Andres Formation.

A minor attempt was made to find datable conodonts in a sample which had a good chance of containing them. A limestone sample with abundant normal marine fauna (Hondo, unit 35) was crushed, treated with glacial acetic acid, and the heavier fraction was separated using acetylene tetrabromide (S.G. 2.90). However, no conodonts were found in the residue.

PALEONTOLOGY

INTRODUCTION

The paleontologic emphasis in this study has been largely to use major types of trace and body fossils for environmental determination. No effort has been made to determine genera or species for taxonomic or age-dating purposes. Only invertebrate body fossils were found. No algal body fossils or plant remains were recognized.

The carbonate member of the lower San Andres Formation is divided into a number of depositional facies on the basis of the environments inferred present during deposition. The characteristic features of these facies are described later in this report in the section on carbonate depositional facies. Figure 6 illustrates an estimate of the relative frequency of occurrence of trace and body fossils present in the carbonate depositional facies of this study.

TRACE FOSSILS

Introduction

Three general types of trace fossils were recognized in the study area: 1) a general mottling of the rock surface, but without any clearly definable burrows, 2) unoriented, but distinct burrows, and 3) burrows of "Cruziana" type (i.e. burrows oriented obliquely or parallel to stratification; figure 11). No "Zoophycus" or "Nereites" types of burrowing were found (Seilacher, 1967). There is no evidence of boring, except within a few individual oncolites in the carbonate member at Hondo, unit 35.

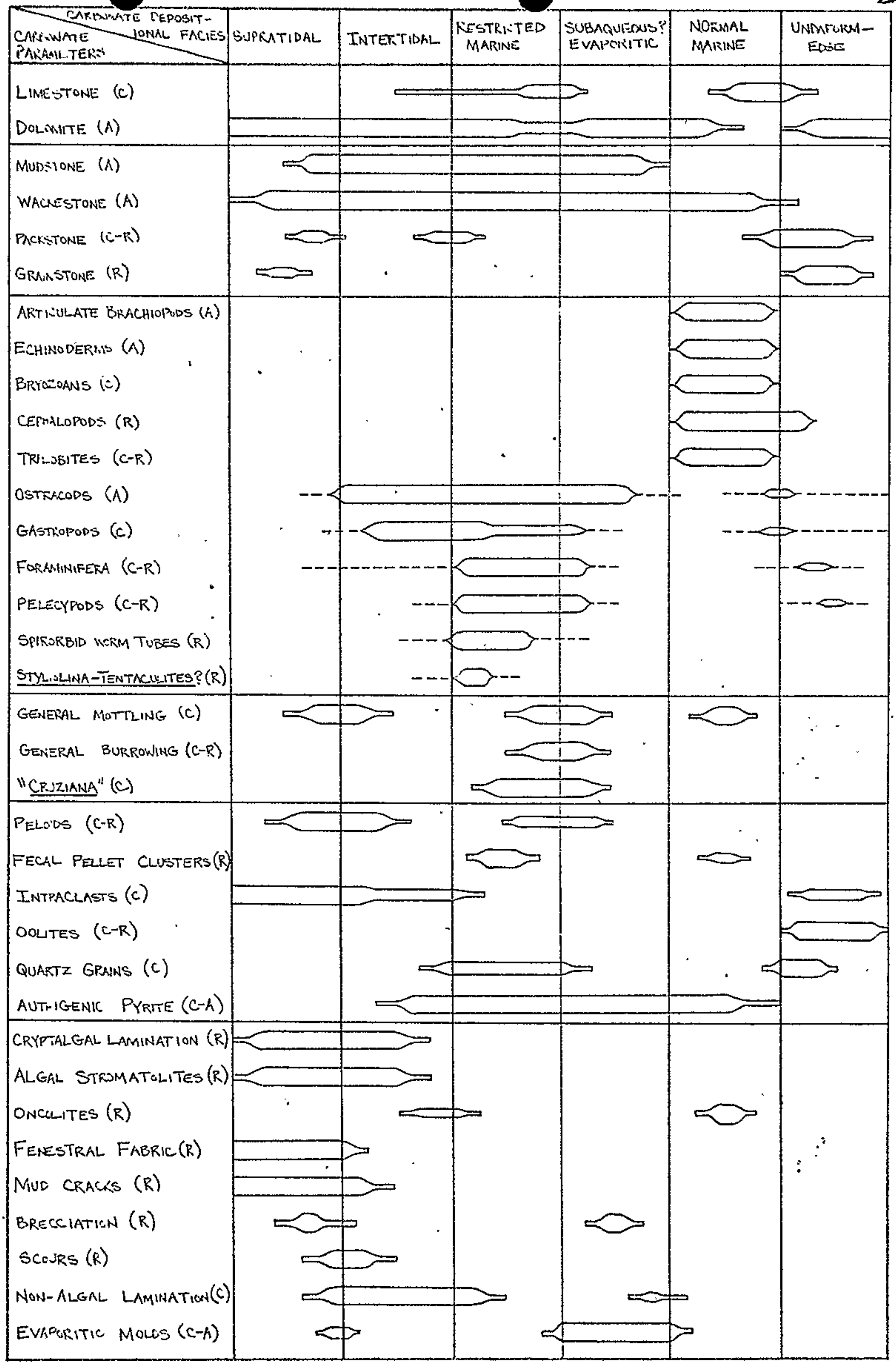


FIGURE 6 ESTIMATE OF RELATIVE FREQUENCY OF OCCURRENCE OF CARBONATE PARAMETERS WITHIN CARBONATE DEPOSITIONAL FACIES OF LOWER SAN ANDRES FORMATION. LETTERS (R=RARE, C=COMMON, A=ABUNDANT) REFER TO RELATIVE ABUNDANCE OF CARBONATE PARAMETERS WITHIN LOWER SAN ANDRES FORMATION. SEE APPROPRIATE SECTION OF TEXT FOR DISCUSSION OF CARBONATE DEPOSITIONAL FACIES LISTED ABOVE.

Carbonate Member

The type and amount of burrowing varies between different carbonate depositional facies. The supratidal and intertidal facies are in places slightly to moderately mottled. Burrowing in the normal marine facies is limited to a general mottling, which is common to rare in places. "Cruziana" type and distinctive unoriented burrows are almost completely confined to the restricted marine facies. Most burrows in this facies are of the "Cruziana" type.

"Cruziana" type burrows (figure 11) have the following characteristics in the carbonate member in the study area. In two dimensions, the "Cruziana" burrows are oriented obliquely to stratification. They are generally about 1 inch in diameter, but range from 1½ to ½ inches. The maximum apparent length in two dimensions is about eight inches. A few burrows are distinctly internally laminated with concentric U-shaped laminae (figure 11A). Locally, individual burrows give the impression of being part of a network, but this effect may be due to two or more distinct superimposed burrowing events (figure 11B). "Cruziana" type burrows are commonly filled with unidentifiable fossil debris, ostracodes, and peloids, whereas the host is a mudstone (figure 11A). Such fabrics result from the mixing of fossiliferous and unfossiliferous sediments by burrowing organisms.

The crustaceans Alpheus and Callianassa produce burrow networks in Recent carbonate sediments, whose segments are of the approximate diameter and length of most of the "Cruziana" type burrows of this study (figure 11B). Shinn (1968a, figure 16) illustrates a core slab from the San Andres Dolomite of west Texas and a Recent core slab with a Callianassa burrow. The burrows in both core slabs have a very similar, concentrically laminated structure, which is somewhat similar to structures found in a few of the "Cruziana" burrows examined in polished slabs in this study.

The usefulness of trace fossils among rocks of different ages is based on the principle that whereas organisms themselves have evolved through time, their behavioral reaction to similar environments has remained essentially the same (Heckel, 1972). Consequently, the similarity in size and structure between some of the "Cruziana" type burrows of this study and Recent Alpheus and Callianassa burrows suggests similar environmental conditions during deposition. "Alpheus" or "Callianassa" type burrowing in Recent sediments is found in intertidal to shallow subtidal environments (Shinn, 1968a; Weimer and Hoyt, 1964). "Cruziana" type burrows are dug in modern shallow subtidal environments for protection and as "feeding mines" for deposit feeders. These burrows are more common in quieter water where finer organic material settles out (Heckel, 1972). Consequently, "Cruziana" type burrowing in the restricted marine facies of this study suggests shallow subtidal to intertidal depths during deposition. Burrowing in the normal marine facies is too indistinct to provide depth information, but the lack of "Zoophycus" and "Nereites" burrowing suggests relatively shallow depths during deposition.

Glorieta Sandstone Member

Trace fossils are rare in the Glorieta Sandstone Member. Mottling is the most common evidence suggestive of burrowing and at least some of it may conceivably have an inorganic origin. "Cruziana" type burrowing was found on a piece of float from the upper Glorieta tongue at Bluewater and near the top of the lower Glorieta tongue at Fort Stanton. These burrows are about ½ inch in diameter and are oriented parallel to stratification. They suggest that at least some of the Glorieta Sandstone was deposited in a shallow marine environment. The general lack of burrowing coupled with the large number of tractive current sedimentary structures suggests that most of the Glorieta Sandstone was deposited in a non-marine environment or that sand movement was great enough to inhibit burrowers in a marine environment.

BODY FOSSILS

Carbonate Member

Introduction

Parts of the carbonate member are apparently barren of biota, whereas other parts are highly fossiliferous. The interest in biotics in the carbonate member is confined to the environmental inferences that may be drawn from the exclusive presence of members of either a normal or restricted marine fossil assemblage. Figure 6 illustrates an estimate of the relative frequency of occurrence of body fossils in the carbonate depositional environments inferred for the lower San Andres Formation in the study area.

Normal Marine Assemblage

The normal marine assemblage consists of biotic types, which are known or inferred to require normal marine conditions for life, especially normal marine salinities. The assemblage is generally found in very fossiliferous rock units. Rock units where relatively few of these biotics are present suggest less well-developed normal marine conditions. The normal marine assemblage consists, in order of decreasing relative abundance, of Productid brachiopods, crinoids, bryozoans, non-Productid articulate brachiopods, echinoids, trilobites, and cephalopods.

Productid brachiopods: the most common and, except for a very few cephalopods, the largest biotic constituent in the study area. Productid valves are not commonly disarticulated and fragments are angular with no evidence of abrasion. Productids are commonly partially silicified.

Productid spines are locally abundant even where valves are relatively rare.

Crinoids: the second most common biotic constituent. They are generally coarse sand to granule size disarticulated columnals. No crown fragments were recognized.

Bryozoans: included in this assemblage even though some modern types are tolerant of salinities slightly higher than that of normal marine waters because in the study area: 1) they are almost exclusively found in association with normal marine biota, and 2) they are only very rarely found associated exclusively with members of the restricted marine assemblage.

Non-fenestrate bryozoans are the most common type present. The only carbonate build-ups noted are bryozoan-ostracod bioherms in Canning Ranch, unit 9. The bioherms are about five feet thick and apparently had about 1½ feet of depositional relief.

Non-productid articulate brachiopods: relatively rare and found in abundance only at Fort Stanton, unit 13.

Echinoids: relatively rare. Both echinoid spines and plates were noted.

Trilobites: generally rare, except in Hondo, unit 37, where fragments are abundant. Trilobites are exclusively associated with biota of known or inferred normal marine affinities in the study area.

Cephalopods: the largest (6 to 8 inches) and among the rarest of biotic constituents. Only two specimens were found in place (Canning Ranch, unit 16 and Sunset, unit 15), whereas others were only observed in float.

Restricted Marine Assemblage

The restricted marine assemblage consists exclusively of biotic types which are known to be in some degree tolerant of adverse environmental conditions, especially large variations in salinity. The assemblage is generally found in barren to only slightly fossiliferous rock units in the field. In polished slab and thin section, some of these rock units were noted to have abundant microfauna. The restricted marine assemblage consists, in order of relative abundance, of ostracods, gastropods, Foraminifera, pelecypods, spirorbid worm tubes, and possible members of the <u>Styliolina-Tentaculites</u> group. Ostracods and gastropods are not infrequently found associated with normal marine biotic constituents.

Ostracods: the most abundant restricted marine biotic form. They are generally of sand size, but granule size ostracods are present in bryozoan-ostracod bioherms at Canning Ranch, unit 9.

Gastropods: common and range in size from about three inches in diameter to coarse sand size.

Foraminifera: generally rare, but are common in a few rock units. Apparently only calcareous types are present.

Pelecypods: not commonly noted. They usually appear as sparry calcite filled fragment molds, which are identified by their general morphology.

Spirorbid worm tubes: a close similarity between some biotic constituents noted in this study and spirorbid worm tubes identified by Laporte (1967). These biotic forms were only rarely observed in the lower San Andres Formation.

Styliolina-Tentaculites?: a gross similarity between some biotic forms noted in this study and fossils identified as possibly belonging to the Styliolina-Tentaculites groups by Wilson (1967). These biotic constituents are only very rarely observed in the lower San Andres Formation. The true biologic affinity of Wilson's fossils are unknown.

Glorieta Sandstone Member

No body fossils were found in the Glorieta Sandstone Member of the San Andres Formation. Organic films suggestive of dissolved fossils, such as in the Devonian Oriskany Sandstone of

New York (Pray, personal communication, 1974) have not been noted.

CARBONATE MEMBER OF THE LOWER SAN ANDRES FORMATION

INTRODUCTION

The carbonate member of the lower San Andres Formation in the study area consists of the lower, middle, and upper carbonate tongues. The three tongues thin to the north as the lower San Andres becomes dominantly sandstone.

About 75% of the rocks of the carbonate member in the study area are dolomite. There is a general increase in limestone at the expense of dolomite westward across the study area (figure 5). Limestone is important in the lower carbonate tongue at Hondo and Fort Stanton, in the middle carbonate tongue at Canning Ranch, in the upper carbonate tongue at Hondo and Canning Ranch, and in the entire section at Fox Cave.

Mudstones and wackestones (after Dunham, 1962) constitute almost all (94%) of the carbonate member. The predominance of mud-support rock fabrics strongly suggests that most of the dolomite crystals in the carbonate member represent original calcium carbonate mud precursors. Packstones and grainstones make up about 5% of the carbonate rocks present. They are generally found in the oolitic rock units at Canning Ranch and Bluewater, whereas they are very rare to absent in the other sections. Boundstones constitute less than 1% of the carbonate member and consist of cryptalgal laminates, algal stromatolites, and bryozoan-ostracod bioherms.

Well-defined, laterally continuous bedding planes are generally rare. Most of the carbonate member is very thickly to thickly bedded and internally massive. At the Sunset, Hondo, Fox Cave, and Bluewater sections, the carbonates above and locally below the Yeso/San Andres contact are commonly thinly bedded and internally indistinctly to distinctly laminated indicating environmental conditions inimical to the survival or development of burrowing organisms. Extreme salinity and/or low oxygen content of the water is the most likely cause of the absence of burrowing organisms, since no evidence of supratidal exposure was noted in these rock units. Towards the top of these four sections, obscure to distinct medium bedded rock units are interbedded with thick bedded units.

Most carbonate rocks are at least moderately petroliferous in that they have a darker aspect than is usual in shelf carbonates (Wilson, 1970) and they emit a fetid odor upon being struck with a hammer. Supratidal facies are usually much lighter than other facies and are essentially unpetroliferous. Two explanations for this pattern are possible depending on whether the hydrocarbons present were formed *in situ* or transported into the area. If they formed *in situ*, then the absence of hydrocarbons suggests the oxidation of organic material on supratidal flats and the reduction of organic material in all other environments. If the hydrocarbons migrated into the carbonate rock units, then relative porosities might be responsible for their localized absence. Subaerial cementation processes might have rendered the supratidal facies relatively impermeable compared with the other carbonate facies.

CARBONATE SEDIMENTARY STRUCTURES

Introduction

Organo-sedimentary structures and emergent desiccation features are the most common carbonate sedimentary structures present in the study area. Distinct cross-stratification is almost completely absent in the carbonate member, even in the undaform-edge facies, and hence is not discussed further in this report. Figure 6 is an estimate of the relative frequency of occurrence of sedimentary structures in the carbonate environments, which are inferred to be represented in the study area.

Organo-sedimentary structures

Organo-sedimentary structures consist of cryptalgal laminates, algal stromatolites, and oncolites. They are relatively very rare in the study area. These structures are inferred to have formed through the sediment binding activities of blue-green algae. No evidence of rhodolites (i.e. red algal encrusted balls; Bosellini and Ginsburg, 1971) was noted.

Cryptalgal laminates (Aitken, 1967) are rock units with undulatory laminae at least some of which are inferred to be due to the activity of blue-green algae. The cryptalgal laminates noted in this study (figure 21C) have the following characteristics: 1) they develop into recognizable algal stromatolites in a few rock units, and 2) they only very rarely contain evaporite molds. Cryptalgal laminates form in protected mud-flats in Recent carbonate settings (Aitken, 1967; Logan et al, 1964). The cryptalgal laminates of this study are compatible with formation in protected mud-flats, which generally had enough water circulation to prevent the formation or preservation (Shinn et al, 1965) of evaporite minerals.

Domal algal stromatolites (Aitken, 1967) are the most common type of algal stromatolite noted in the lower San Andres Formation. Domal stromatolites in the study area may be characterized as follows: 1) they consist of simple, undulatory laminations, a few of which show emergent desiccation features, 2) they are commonly associated with intraclasts, 3) they are not associated with evidence of evaporites, and 4) they range in size from about 3 to 8 inches in diameter. Domal stromatolites form in exposed intertidal mud flats, where the scouring action of waves and other interacting factors prevent the growth of algal mats between stromatolites (Logan et al, 1964), to shallow subtidal areas (3 to 25 feet deep in Bermuda; Gebelein, 1969) in Recent carbonate settings. The degree of desiccation present in the stromatolites observed in the study area has been used to help determine whether they were deposited in low supratidal/high intertidal or low intertidal/subtidal environments. The absence of evidence of evaporites suggests at least minimal amounts of water circulation in the intertidal/subtidal environments and not infrequent inundation of the supratidal environment during the formation of domal stromatolites.

Digitate algal stromatolites (Aitken, 1967) were noted only in Bogle Dome, unit 26 (figure 9B). There is no apparent coalescence upwards into laterally linked hemispheroids (Logan et al, 1964). The digitate stromatolites are about ½ inch in diameter and contain abundant tubules. Digitate stromatolites are generally thought to have formed only in low intertidal environments exposed to waves (Aitken, 1967). The digitate stromatolites of this study may well have formed in such an environment. However, the presence of well developed fenestral fabric (see text below) in the carbonate matrix between the stromatolites suggests subsequent subaerial exposure.

Practically the only occurrence of oncolites is near the top of Hondo, unit 35 (figure 21A). These oncolites are generally concentric (mode C of Logan et al, 1964). Gastropod, crinoid, and bryozoan fragments are the main nuclei. A few oncolites have been bored, with borings about 2mm in diameter. Oncolites form in very shallow subtidal areas exposed to waves to low intertidal areas exposed to agitated shallow water in modern carbonate settings (Logan et al, 1964). The oncolites of Hondo, unit 35 were probably deposited in a nearly continuously agitated shallow subtidal environment because of the concentric nature of the oncolite laminae and the lack of any intertidal features in the unit. The presence of crinoids and bryozoans suggests normal marine conditions during deposition. A single, leached oncolite was noted in Sunset, unit 10 (figure 10B). It was probably transported into the area during deposition.

Emergent Desiccation Features

Introduction

Evidence of subaerial exposure is relatively very rare in the lower San Andres Formation in the study area. The presence of fenestral fabric, mud cracks, and some brecciation is used in this study to recognize subaerial exposure during deposition or shortly thereafter.

Fenestral Fabric

Fenestral fabric is not common, but some is found in almost all measured sections (Plates I to VIII; figure 10). Fenestrae are defined as primary or penecontemporaneous gaps in rock framework, larger than grain supported interstices regardless of degree or character of subsequent filling (Tebbutt et al, 1965). Fenestral fabric in the study area is found only in dolomite hosts. Isolated bubble-like cavities indicative of a gas bubble origin were not observed. Fenestrae consisting of planar isolated cavities are inferred to have been made by shrinkage resulting from desiccation of subaerially exposed sediments. Sparry calcite cement is the most common fenestral filling, but sparry dolomite cement is present in Sunset, unit 45, Canning Ranch, unit 10, and Hondo, unit 24. No internal sediment or sheet cracks were noted. Fenestral fabric in the study area is commonly associated with abundant to common intraclasts and slight to moderate brecciation. It is rarely, if ever, associated with anhydrite nodule or gypsum molds. Fenestral fabric in modern carbonate settings is most abundant in supratidal dolomitic sediments, sometimes present in intertidal sediments, and never present in subtidal ones (Shinn, 1968b). Rock units with fenestral fabric in the study area are interpreted to have formed in supratidal or intertidal environments depending on the degree of emergent desiccation present.

Mud Cracks

The cracking of muddy sediment by desiccation most commonly occurs during subaerial exposure, but may happen subaqueously under special conditions (Heckel, 1972; Burst, 1965). Consequently, other evidence of subaerial exposure is desirable for environmental interpretation. Mud cracks were only found in two rock units in the study area, namely Hondo, unit 6 and Canning Ranch, unit 10. In Hondo, unit 6, distinct polygons about 2 to 4 inches in diameter and about 1½ inches thick are present. They are associated with fenestral fabric above and below them. The inter-polygonal areas are partially filled with intraclasts. In Canning Ranch, unit 10, sparry calcite filled mud cracks are present. Such mud cracks appear to be relatively rarely reported in the literature. However, similar mud crack filling has been described by Fischer (1964) and Matter (1967). Fischer (1964) invokes an algal mat mechanism to explain this type of filling: 1) cracks formed under the cover of a tough algal layer or 2) they formed at the surface and were overgrown by an algal mat before acquiring a mud filling. The presence of cryptalgal laminates and stromatolites in the rock unit is compatible with the foregoing explanation. Fenestral fabric in the overlying unit and algal stromatolites and cryptalgal laminates within the rock unit suggest a subaerial cause of mud cracking.

Brecciation

Brecciation (figure 9A) can form in a number of ways, environments, and times relative to deposition: 1) intense desiccation due to subaerial exposure, 2) an initial step in the calichification process (James, 1972; Reeves, 1970), 3) solution brecciation due to the leaching of evaporites, 4) associated with penecontemporaneous submarine cemented hard-grounds of the Persian Gulf (Shinn, 1969), 5) mild epeirogeny may brecciate weaker rock units, or 6) igneous intrusion frequently brecciates adjacent rock units. Consequently, brecciation *per se* is useless as an environmental indicator, but associated features may suggest possible causes of brecciation.

Brecciation in the study area is generally rare to common. Most brecciation is probably due to the Recent calichification of carbonate rocks in the lower San Andres Formation. Brecciation is generally found in the supratidal depositional facies (e.g. figure 9A), where it may most likely be related to intense desiccation during subaerial exposure. However, locally brecciation may have been conceivably caused by the solution of evaporite minerals or by the start of Permian calichification, although no evidence was found to support these hypotheses. Brecciation related to the emplacement of igneous intrusives is common at Fox Cave.

Conclusion

The preceding sections on carbonate sedimentary structures illustrate that individual sedimentary structures only rarely form in a single distinct environment of deposition. Consequently, combinations of sedimentary structures and paleontology were used to interpret supratidal, intertidal, and subtidal environments in this study.

The sedimentary structures and paleontology noted in the study area indicates that the environments of deposition of the lower San Andres Formation were predominately subtidal and that supratidal and intertidal environments were rare. The general absence of evidence of the former presence of evaporites in the supratidal and intertidal facies of this study suggests that sabkha environments of deposition were rare during lower San Andres time. The lower San Andres in the study area is located on the Pedernal positive element, which appears to have been active during lower San Andres time (see PALEOGEOGRAPHIC IMPLICATIONS OF STUDY). Hence, the paucity of supratidal and intertidal facies in the study area suggests that at least most of the lower San Andres Formation, which was deposited off of the Pedernal positive element, was probably deposited subtidally.

PETROGRAPHY

Introduction

The petrography of rock units during this study was confined to what was necessary to identify the types and sizes of grains present in order to aid in the environmental interpretation of the rock units. Figure 6 illustrates the relative frequency of occurrence of skeletal and non-skeletal grains in carbonate depositional facies. The petrographic parameters present in the measured sections are graphically portrayed in Plates I to VIII.

Skeletal Grains

The skeletal grains identified in the lower San Andres Formation in the study area have already been discussed (see BODY FOSSILS). These skeletal grains generally lack all evidence of transport and abrasion. Brachiopods are commonly not disarticulated and almost all skeletal fragments are angular. Hence, lower San Andres deposition appears to have been almost entirely in low-energy environments.

Peloids

The term peloid (Bathurst, 1971) is used to denote cryptocrystalline aggregates of unknown origin that are smaller than 0.2mm in diameter. Peloids, especially those suggestive of fecal pellet origin, are very rare in the study area. Yet they are abundant in both modern and many ancient shelf settings. This suggests that peloid boundaries have become merged and blurred beyond recognition (Beales, 1965) probably owing to the compaction of very poorly cemented or non-cemented peloids and/

or the effects of pervasive dolomitization. The term fecal pellet cluster is used to denote small clusters of rounded peloids, which at least superficially resemble clusters of fecal pellets found in modern carbonate environments.

Intraclasts

Intraclasts (Folk, 1959) refer to fragments of partially lithified carbonate sediment which are inferred to have been eroded from the sea bottom or adjacent tidal flats (Blatt et al, 1972). Intraclasts may be identical to peloids and are operationally separated by a 0.2mm boundary when no evidence of an intraclastic origin is present. Such grains larger than 0.2mm are intraclasts, whereas grains smaller than 0.2mm are peloids. Intraclasts in the study area are most commonly rounded to very rounded, but angular to subangular grains are present in places (Powers, 1953).

Oolites

Oolites are defined as subspherical, sand size carbonate particles that have concentric rings of carbonate surrounding a nucleus of another particle (after Blatt et al, 1972). The term "true" oolite is used in this study to denote an oolite whose nucleus constitutes less than 50% of the particle. The term "superficial" oolite is used in this study to denote an oolite whose nucleus constitutes more than 50% of the particle. Most true oolites in the study area have been recrystallized to the point where the rings are microscopically obscure or absent. However, enough grains with characteristic concentric rings are available for identification of oolitic rock units.

True oolite nuclei were indeterminable. Intraclasts, quartz grains, and Foraminifera tests, in decreasing order of abundance, are the most common nuclei in superficial oolites.

Terrigenous Grains

Terrigenous grains (mostly quartz and some feldspars) are identical to the ones present in the quartz arenites of the Glorieta Sandstone Member of the San Andres Formation. They were noted in rock fabrics that ranged from slightly sandy mudstone to very mud-lean wackestone. Carbonate rock units that are rich in terrigenous grains locally contain rip-ups and superficial oolites with quartz grain nuclei.

Porosity

Porosity in the carbonate member was described after the classification of Choquette and Pray (1970). Calcium carbonate mud deposited in modern carbonate settings contains porosities of 60 to 70%, whereas calcium carbonate mudstones (ancient limestones) generally have porosities of a few per cent at most. Early cementation is thought to reduce these very high initial porosities to about 5 to 10% and late stage cementation to eliminate the remaining porosity. Dolomitization (resulting in intercrystalline porosity), selective solution of carbonate grains or evaporites (resulting in moldic porosity), formation of fenestrae (resulting in fenestral porosity), fracturing (resulting in fracture porosity), and/or random solution of carbonate rocks (resulting in vugs and/or channels) may increase porosity in rock units, but late stage cementation also frequently eliminates these porosities. Almost all former porosity in the lower San Andres Formation in the study area is now completely or partially filled with calcite cement. However, sparry dolomite and quartz cements were observed locally. The dolomite cements were only noted filling fenestrae in supratidal rock units.

The most common porosity type in the lower San Andres is dolomite intercrystalline porosity. Fossil moldic porosity is the second most abundant porosity type. Evaporite and oolite moldic porosity and vug and channel porosity are only locally significant and are completely or partially filled with calcite cement. Inter- and intraparticle porosity is rare, calcite filled, and chiefly present in the undaform-edge sand facies.

Interconnected porosity is practically confined to dolomite intercrystalline porosity and the inter- and intraparticle porosity of the undaform-edge facies. These porosity types are almost without exception filled with calcite cement in the study area. However, open porosity is locally present. The petroleum potential of the lower San Andres in the vicinity of the study area, in terms of interconnected porosities sufficient for reservoir development, appears to be confined to 1) undaform-edge rock units inferred to be present in the subsurface in eastern Lincoln and western Chaves Counties (see PALEOGEOGRAPHIC IMPLICATIONS OF STUDY), and 2) dolomitic rock units, which are most likely interbedded with the undaform-edge rock units.

CARBONATE DIAGENESIS

Introduction

Most carbonate rocks, including those of this study, have been profoundly modified by post-depositional or diagenetic changes. Cementation, dolomitization, iron sulfides and iron oxides, dedolomitization, silicification, and stylolitization are the carbonate diagenetic features considered in this study.

Cementation

Practically nothing is known about cementation in the matrix of mudstones and wackestones. However, Recent carbonate mud contains porosities of 60 to 70%, whereas mudstones and wackestones contain at most only a few per cent porosity. The lower San Andres Formation in the study area contains mudstone and wackestone almost entirely and hence little emphasis was placed on cementation during this study.

The study of carbonate cementation has generally been focused upon sparry calcite cements. Such cements were noted in the study area in molds of evaporites and carbonate grains, in vugs and channels, in inter- and intraparticle porosity, in fenestrae, and as fracture filling (after Choquette and Pray, 1970). Only sparry calcite consisting of equant crystals was noted in the 100 thin sections of the carbonate member examined during this study. The equant crystals imply precipitation from a range of possible waters whose end members are connate subsurface and meteoric phreatic waters (Folk, 1974).

Sparry dolomite and quartz cements were observed locally. The dolomite cements were only noted filling fenestrae in supratidal rock units.

Dolomitization

Most lower San Andres Formation rock units are completely dolomitized and many are partially dolomitized, but limestones are locally very important (figure 5). Practically all dolomite crystals are 0.01 to 0.02mm in diameter and are inferred to have formed from original calcium carbonate mud. Dolomite pore-filling crystals are locally present and are very variable in size ranging from about 0.01 to 0.10mm in diameter.

Murray (1960) describes a very common sequence of selective dolomitization in carbonate rocks with both mud and grains, which results from the cannibalization of local calcite to form dolomite crystals and leave intercrystalline porosity. Examples of all phases of this sequence are present in the lower San Andres Formation (figure 7). The most common phase of the sequence in the study area is the complete selective dolomitization of mud matrices and preservation of calcitic fossil fragments in most dolomites. The final stages of the selective dolomitization process in the lower San Andres usually resulted in the leaching of fossil fragments and the formation of moldic porosity. However, less commonly, echinoderms were dolomitized whereas other biotics were leached.

Modern carbonate tidal flats commonly contain varying amounts of dolomite. Supratidal flat environments produce conditions necessary for sea—water evaporation to the point where dolomitizing waters are produced. The heavy hypersaline water moves down from the supratidal surface and dolomitizes

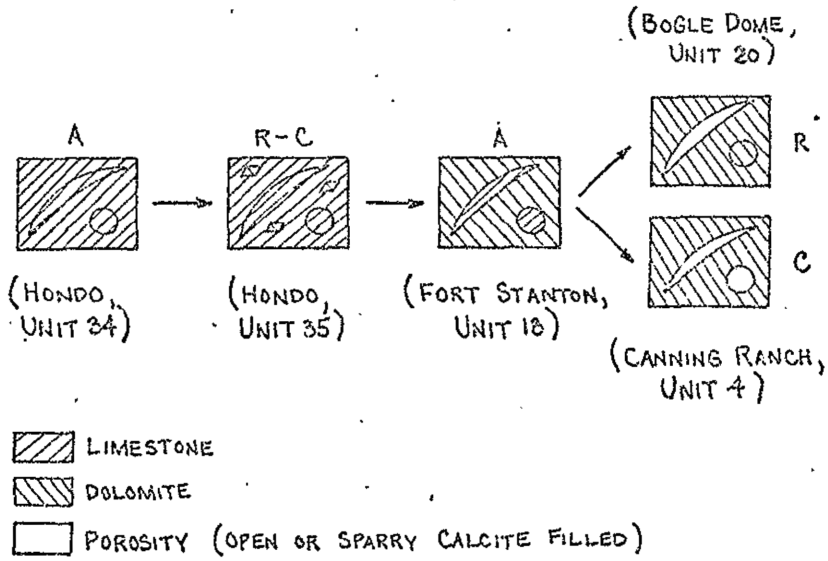


FIGURE 7 SEQUENCE OF SELECTIVE DOLOMITIZATION OBSERVED IN LOWER SAN ANDRES FORMATION WITH EXAMPLES OF EACH PHASE. LETTERS REFER TO RELATIVE ABUNDANCE OF DIFFERENT PHASES (A= ABUNDANT, C= COMMON, R-C = RARE TO COMMON, R=RARE)

the underlying sediments (Lucia, 1972). Whether or not the evaporation results in the formation of preservable evaporites is dependent on climate. The Bahamas are in a tropical climate and evaporites, which are probably formed, are not preserved (Shinn et al, 1965). The Trucial Coast is in an arid climatic zone and the formation of evaporites accompanies dolomitization (Bebout and Maiklem, 1973).

The patterns of dolomitization in the lower San Andres are almost entirely consistent with an emergent tidal-flat dolomitization model: 1) the greatest amount of limestone is found at Fox Cave, which is the only section lacking recognizable supratidal or intertidal facies, 2) conversely, for example, Sunset has evidence of four separate periods of subaerial tidal flat deposition and Bluewater one period; furthermore, both sections are almost completely dolomitized, including some dolomite-cemented sandstones, 3) at Hondo, Fort Stanton, Fox Cave, and to a lesser extent Canning Ranch, normal marine units tend to be limestones, whereas other facies tend to be dolomites, 4) at Hondo, Fox Cave, and Canning Ranch, the upper parts of normal marine rock units tend to be dolomitic and grade up into pure dolomites, suggesting that a limited gravity sinking of later penesaline brines was responsible for dolomitization, and 5) with only a few exceptions, evidence of the former presence of evaporites is found in dolomitic hosts, suggesting that an increase in the Mg/Ca ratio was due to the precipitation of gypsum and anhydrite. No convincing evidence for a regional permeability or reflux model of dolomitization was recognized. The patterns of dolomitization are generally incompatible with a lateral movement of dolomitizing brines hypothesis. Depositional facies control of dolomitization suggests that it was an early diagenetic process.

Iron Sulfides and Iron Oxides

Microscopic hematite pseudomorphs after pyrite are common in the lower San Andres Formation. In the evaporitic facies, they are usually found as parts of red rims that form the outer portion of anhydrite nodule molds. The pseudomorphs are found as widely disseminated individual crystals and clusters of intergrown crystals in the carbonate depositional facies of this study, except the supratidal, some of the intertidal, and the undaform-edge sand facies. Their presence suggests reducing conditions existed at or just below the sediment-water interface penecontemporaneously with deposition.

Dedolomitization

Dedolomitization was only noted in one rock unit in the study area. Sunset, unit 11 is thin, irregularly laminated, and has a fabric of calcite crystals, which are very similar to pseudospar calcite from the neomorphism of carbonate mud (Folk, 1965). A possible dedolomite origin is suggested by a number of textural and stratigraphic criteria. The thin limestone is in a section that is practically all dolomite (figure 5). The unit is not unlike the underlying laminated dolomite rock unit, if diagenetic effects are not considered. Features typical of the clotted or "grumeleuse" dedolomite texture of Evamy (1967) are present: 1) several sharp, partial rhombohedral margins, 2) cavities partly filled with apparent blocky calcite (psuedospar of Folk, 1965?), but lacking partial mud fillings, and 3) dark clots within individual calcite crystals. The clots are suggestive of original dolomite rhombohedra with dark centers, which are likely to be the product of dolomitization of mud. This interpretation is consistent with the inferred presence of an original mud-supported fabric.

Dedolomitization can only proceed at or near the earth's surface (Evamy, 1967). The dedolomite unit is in an intertidal depositional facies, which is stratigraphically equivalent to a well developed supratidal facies at Hondo. This stratigraphic selectivity suggests a Permian origin for the dedolomitization. However, a Recent origin cannot be discounted on the available evidence.

Silicification

Silicification in the lower San Andres Formation in the study area is relatively uncommon. It occurs as chert nodules, fossil replacing silica, and pore-filling chalcedony. Chert nodules are most common in the lower, but are also very common in parts of the upper and middle carbonate tongues. Chert nodules usually constitute no more than about 5 to 10% of the rock units in which they appear. They range from coarse sand to large cobble size in diameter. Biota, especially brachiopods, are commonly selectively partially silicified in well developed normal marine facies. Chalcedony is only common locally in Canning Ranch, unit 10. All chalcedony found (present in six out of one hundred thin sections examined) was optically length slow.

Fossils are preserved in chert nodules in dolomite rock units where the biotics have been leached from the carbonate. This proves that silicification preceded dolomitization. Hence, silicification must have been an early diagenetic process, because of the evidence already cited (see Dolomitization) that dolomitization in the lower San Andres was an early diagenetic process.

Stylolitization

Stylolites are abundantly present in the study area. Many, if not most, bedding planes in the carbonate member are along stylolitized contacts. The stylolites vary in relief from about 4 inches to microscopic dimensions, with most amplitudes less than about ¼ inch.

Very thin red clay seams are almost universally present along styolites. However, much thicker red seams about ½ inch thick were found in the upper carbonate tongue at Bogle Dome. Charles Walker, formerly of the New Mexico Bureau of Mines and Mineral Resources, suggested that these thick red seams might be insoluble residues left behind by the solution of evaporites (pers. comm., 1973). However, no independent evidence of evaporites was observed in the upper carbonate tongue at Bogle Dome.

EVIDENCE OF EVAPORITES

Introduction

Stratified evaporites are often associated with shelf carbonates (Lucia, 1972), but none are recognized in the lower San Andres Formation in the study area. There is also but little evidence in the study area of the former presence of evaporites prior to their removal by solution. Meteoric water commonly leaches out any evaporites that may be present in rock units, thereby frequently resulting in outcrops with collapse brecciation of a typically dolomitic host, if stratified evaporites had been present, and molds of evaporitic crystals or nodules (Lucia, 1972). Brecciation in the study area is local, small scale, and not demonstrably due to the leaching of evaporites. However, there is local evidence of salinities high enough to form evaporite minerals. Evidence of the former presence of evaporites in the study area consists of: 1) common to abundant occurrences of molds, which are the solution products of former nodules and which shall henceforth be termed anhydrite nodule molds (figures 13B, 14), 2) rare occurrences of evaporite crystal molds, and 3) rare occurrences of optically length-slow chalcedony. The very limited evidence of evaporites in the lower San Andres in the study area coupled with the arid climate inferred for Permian time suggests sufficient water circulation to prevent the precipitation of stratified evaporites.

Anhydrite Nodule Molds

Major occurrences of anhydrite nodule molds are practically always confined to dolomitic hosts which are almost to completely barren of biota, but lack all indication of subaerial exposure, such as fenestral fabric, mud cracks, algal mats, and abundant intraclasts. The exceptions to this are as follows. There are a few occurrences of anhydrite nodule molds in subtidal facies overlain by supratidal facies, but in almost each case the supratidal facies itself is free of evidence of evaporites. This suggests the possibility that evaporite nodules may have formed subaqueously prior to the advent of supratidal conditions. Only one occurrence of anhydrite nodule molds intimately associated with emergent desiccation features was found (Canning Ranch, unit 10). Anhydrite nodule molds in a laminated, unfossiliferous limestone host were found in Fox Cave, units 10 (figure 14A) and 24. Some were noted in a few rock units with a normal marine biota. ere the anhydrite nodule molds increased in relative abundance upward in the units, suggesting formation from hypersaline brines, which were concentrated during later, more restricted environments of deposition.

No gypsum or anhydrite crystals or nodules are preserved in the study area. Most cavities or former cavities of evaporite nodule origin are now partially or completely filled with calcite (silica in one rock unit) and few are completely empty. Anhydrite nodules in the San Andres Formation in the subsurface (Murray, 1960, p. 517, figure 4) appear at least superficially similar to most of the anhydrite nodule molds noted in the study area. Anhydrite nodule molds in the lower San Andres Formation range from about 1/16 to 2 inches in diameter. Rarely, a few nodules appear to have coalesced to form vertical features about 6 to 8 inches long (figure 14B). Evidence of the calcitized replacement of anhydrite nodules was sought in eight thin sections and about twenty polished slabs containing anhydrite nodule molds, but the characteristic calcite crystal morphology and inclusions of small dolomite crystals were not recognized.

Most anhydrite nodule molds in the study area are characterized by lobate outlines (figures 13B, 14A), internal septa, and red, hematite rims (figure 14A) forming the outside of the molds. Lucia (1972) reports that rarely, evaporite nodules have a rectangular outline with straight sides. Such anhydrite nodule molds were noted in a sample from Fort Stanton, unit 22. Anhydrite nodules in a core slab from the San Andres Formation of west Texas were observed by the author to contain pyrite rims (pyrite is used in a generic sense in this study to include marcasite). The hematite rims forming the outside of most anhydrite nodule molds in the study area most likely represent similar pyrite precursors, which were later oxidized. Hematite rims are almost always very thin with respect to the nodules in which they appear, except in Sunset, unit 15, where anhydrite nodule molds are completely to almost completely filled with hematite.

A relatively few rock units have calcite-filled pores or former pores, which have the general aspect of anhydrite nodule molds, but lack red rims. These pores have lobate outlines, internal septa, are associated with the same types of sediment hosts as red rimmed nodule molds, and hence probably are anhydrite nodule molds. Red rimmed and unrimmed anhydrite nodule molds were never observed together in the same rock unit in the study area. Geochemical considerations of pyrite formation (Berner, 1971) suggest, by the process of elimination, that iron concentration or reactivity was probably the limiting factor in pyrite formation in the anhydrite nodule molds lacking hematite rims. However, no convincing explanation has emerged from this study to explain the absence of hematite rims in these probable anhydrite nodule molds.

Evaporite Crystal Molds

Evaporite crystal molds in the lower San Andres Formation appear scarce and most appear to originally have been gypsum crystals. Evaporite crystal molds are recognized by straight sides and rectangular re-entrants (Lucia, 1972). Calcite-filled molds are present in a calcite host in Fort Stanton, unit 11. Empty molds are present in a calcite host at Hondo, unit 8. These empty molds are confined to layers about 1 inch thick, which are interstratified with layers about 1½ inches thick consisting of possible cryptalgal laminates (figure 13A). A few molds are confined to a burrow in a dolomitic normal marine rock unit (Fort Stanton, unit 13). No lath-shaped molds typical of anhydrite crystals were found in the three aforesaid occurrences. These evaporite crystal molds most likely represent original gypsum crystals. Calcite-filled molds suggestive of the fabric formed by the displacive growth of anhydrite crystals (Shearman and Fuller, 1969) were only noted in a Productid brachiopod from Fort Stanton, unit 23.

Length-Slow Chalcedony

The presence of optically length-slow chalcedony is suggestive of precipitation from hypersaline brines (Folk and Pittman, 1971). All chalcedony noted in the study area (found in six out of one hundred thin sections examined) is optically length-slow, suggesting formation from hypersaline brines. Most of the chalcedony fills non-evaporitic former pores, but one occurrence was noted coating evaporite crystal molds in a burrow in Fort Stanton, unit 13.

The presence of length-slow chalcedony in a rock unit is an ambiguous criterion to infer an evaporitic depositional history if used alone. Optically length-slow chalcedony may form in semi-arid soils such as those in central New Mexico today. And the hypersaline brines recorded by the presence of length-slow chalcedony may not have originated near the rock units where it is noted. This latter explanation for the length-slow chalcedony in the study area cannot be discounted because stratified evaporites are present in the overlying upper San Andres in the study area and in the stratigraphically equivalent lower San Andres west of the study area.

CARBONATE DEPOSITIONAL FACIES

Introduction

Wilson (1970) outlined an idealized scheme of carbonate environments following a pattern widely developed in the geologic record ranging from open deep marine to evaporitic shoreface environments. The carbonate environments inferred to have been responsible for deposition of the carbonate member of this study are approximately equivalent to the following five of Wilson's general shelf depositional environments: 1) tidal shelf facies, 2) winnowed platform edge sands, 3) open marine platform facies, 4) facies of restricted circulation on marine platform, and 5) platform evaporite facies (figure 25).

Figure 6 illustrates the estimate of relative frequency of occurrence of carbonate parameters within the carbonate depositional facies discussed in this section. Plates IX and X and figure 8 illustrate the lateral and vertical distribution of carbonate depositional facies in the study area.

Tidal Flat and Lagoonal Environments

The tidal flat environment is the most common shoreline environment in modern carbonate settings (Lucia, 1972). About 55% of the carbonate member of this study is interpreted to have been deposited in a tidal flat and shallow lagoonal setting. The tidal flat environment may correspond to either Wilson's (1970) restricted circulation on a marine platform (non-evaporitic) environment or platform evaporite environment. Non-evaporitic tidal flat and lagoonal rock units constitute about 35% and evaporitic tidal flat and lagoonal rock units about 20% of the

Specimen
U.W. 1589/1

A

Specimen
U.W. 1589/2

B

Supratidal Depositional Facies

Figure 9 A. Sunset, unit 47: brecciation probably due to solution of evaporites or intense desiccation.
B. Bogle Dome, unit 26: dark masses are digitate stromatolites (D).

of the carbonate member of the lower San Andres in the study area.

Climate and physical setting determine which of the two tidal flat end-members will dominate in a given area (Kinsman, 1969). The presence of bedded evaporites in the upper Yeso Formation in the study area, in the lower San Andres Formation west of the study area, and in the upper San Andres in the study area suggests a uniformly arid climate during Late Yeso and throughout San Andres time. Therefore, physical setting appears to have largely controlled evaporite formation in San Andres seas.

Both non-evaporitic and evaporitic tidal flats share certain basic features in modern carbonate settings. Tidal flats are commonly separated into three major sub-environments on the basis of daily tidal fluctuations: the supratidal, intertidal, and subtidal sub-environments. The marine environment is the main source of sediment deposited on the tidal flat. Sediment is carried onto the tidal flat by tidal and storm currents. If the rate of sediment accumulation is greater than relative sea-level rise, then the tidal flat will prograde out. Consequently, subtidal deposits would be overlain by intertidal deposits, which would in turn be overlain by supratidal deposits. Two types of flow often result in a topography of flats and channels: regular on- and offlap of tides and funneling of tides into channels. Channels may be found in all three sub-environments of tidal flats in non-arid settings, but are rare in arid settings (Roehl, 1967).

Non-Evaporitic Tidal Flat and Lagoonal Facies

The non-evaporitic tidal flat and lagoonal facies of this study consists mostly of shallow subtidal deposits with only small amounts of supratidal or intertidal deposits.

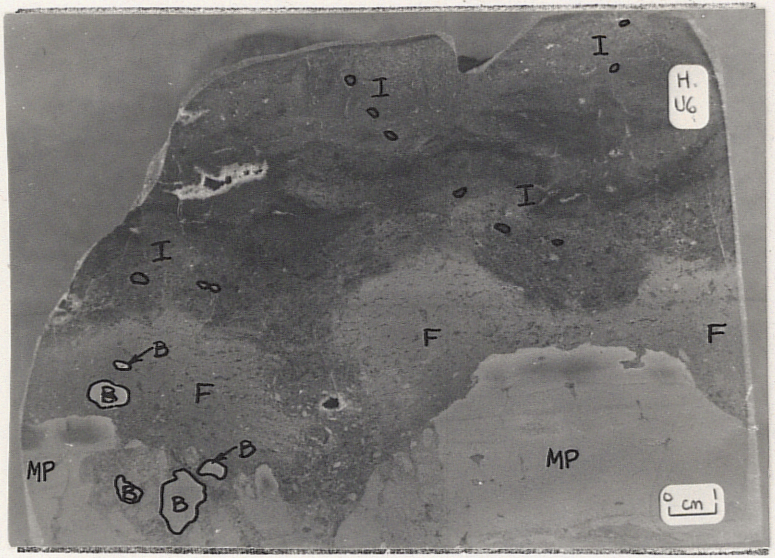
Supratidal Facies

The supratidal facies of this study (figures 9 and 10A) consists of tidal flat carbonates deposited above mean high-tide and consequently subaerially exposed for long periods of time between spring and/or storm tides, which occasionally inundated them. This facies makes up only about 2% of the carbonate member. The supratidal facies has been recognized in the study area by the presence of various combinations of the following emergent desiccation features: 1) fenestral fabric, 2) mud cracks, 3) abundant intraclasts, and 4) brecciation. The following rock types, in order of decreasing relative abundance, are characteristic of the supratidal facies: 1) intraclastic, slightly fossiliferous to unfossiliferous mudstones and mud-rich wackestones, 2) unfossiliferous mudstones, and 3) intraclastic grainstones.

Intertidal Facies

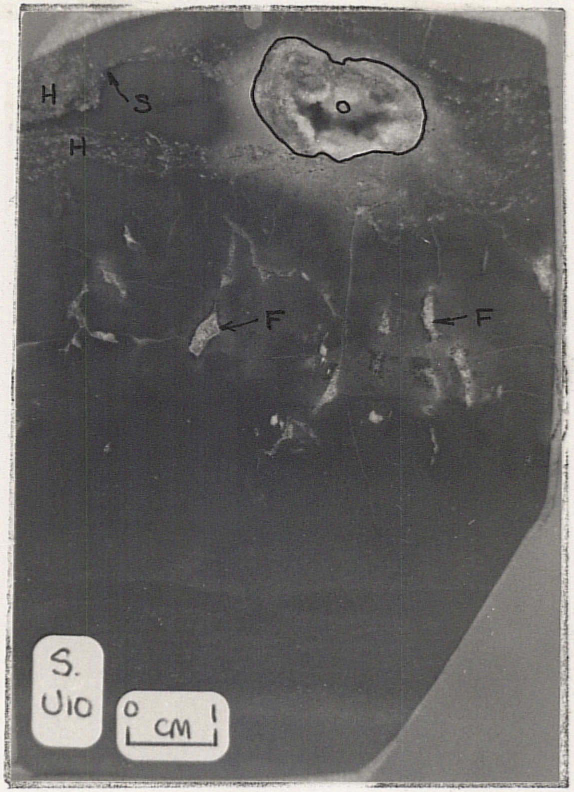
The intertidal facies of this study (figures 10B and 21C) consists of carbonates that were deposited between daily mean high- and low-tide, and hence, were daily subjected to inundation and emergence. This facies makes up about 2% of the carbonate member.

The supratidal facies is environmentally much more distinctive than the intertidal facies and normally directly over-



Specimen U.W. 1589/3

A



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B

Supratidal and Intertidal Depositional Facies

Figure 10 A. Supratidal facies (Hondo, unit 6): mudcrack polygons (MP) with intraclasts between polygons (B), layer with fenestral fabric in packstone (F), layers of abundant rounded intraclasts (packstone and grainstone) (I).

B. Intertidal facies (Sunset, unit 10):

lower $\frac{1}{2}$: faintly rippled mudstone

upper $\frac{1}{2}$: fenestral fabric in mudstone (F), scour (S), leached oncolite (O), fossil hash in laminae (mud-lean wackestone to packstone) (H).

lies it. Hence, the best way to recognize intertidal deposits is often to first find the supratidal facies. However, it is possible to have no intertidal deposits below a supratidal facies, and no supratidal facies over an intertidal deposit. The tidal range might have been very small and the tidal effect essentially absent or an "abrupt" relative fall in sea level might have resulted in supratidal deposits being underlain by subtidal deposits. And supratidal deposits need not always prograde over intertidal deposits. Hence, care must be exercised in identifying intertidal deposits solely by the use of supratidal rock units.

It is frequently difficult to differentiate low intertidal from restricted marine deposits. Shallow subtidal sediments are transported to the intertidal environment by storms and tides resulting in similar sedimentary fabrics in each environment (Roehl, 1967). Laporte (1967) handled this difficulty by using intertidal to "denote a sedimentary regimen that is regularly and periodically flooded by marine water for an unspecified duration." Hence, his intertidal facies appears to include at least some of the subtidal facies of this study.

The intertidal facies was recognized in the study area by the presence of slightly desiccated to undesiccated cryptalgal laminates and algal stromatolites or by position underneath supratidal deposits if shrinkage cracks or many gastropods were present. The following rock types are characteristic of the intertidal facies in the study area: 1) cryptalgal laminate or algal stromatolite boundstone, 2) gastropod mud-rich wackestone, and 3) alternating laminae of peloidal mudstone and peloidal, fossiliferous mud-lean wackestone to packstone.

Restricted Subtidal (Lagoonal) Facies

The subtidal facies (the infratidal of Roehl, 1967) consists of tidal flat and lagoonal carbonates that were deposited below daily mean low-tide level, but might have been subaerially exposed during extreme spring and storm tides. Two sub-facies are recognized in this study. The restricted marine facies, which was probably deposited in tidal flat and lagoonal environments and is discussed in this section and the normal marine facies, which is discussed in this report as a separate major environment.

The restricted marine facies of this study (figures 11 and 12A) includes the "open marine platform facies" and part of the "restricted circulation on a marine platform facies" of Wilson (1970). It consists of carbonates deposited in a subtidal environment, which was not conducive to the development or survival of biota inferred to require normal marine conditions. The restricted marine facies makes up about 35% of the carbonate member.

Two sub-facies of the restricted marine facies are recognized, namely unfossiliferous and fossiliferous sub-facies. The unfossiliferous sub-facies is essentially barren of all biota and may represent physical-chemical precipitation of carbonate minerals in a penesaline environment. Unfossiliferous mudstone and quartz sand mudstone to mud-lean wackestone are the characteristic rock types. The fossiliferous sub-facies

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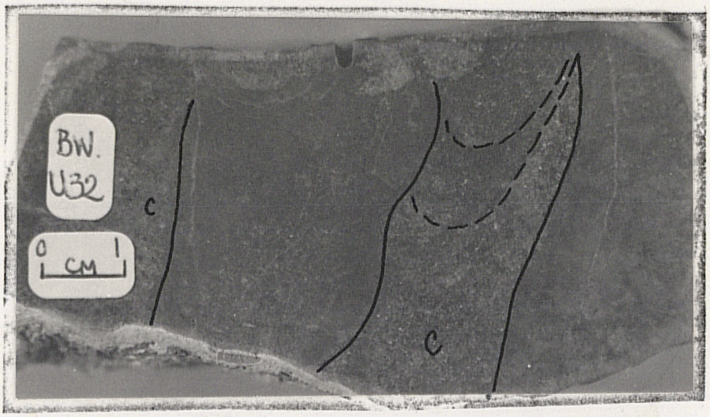
U.W. 1589/5



A

B

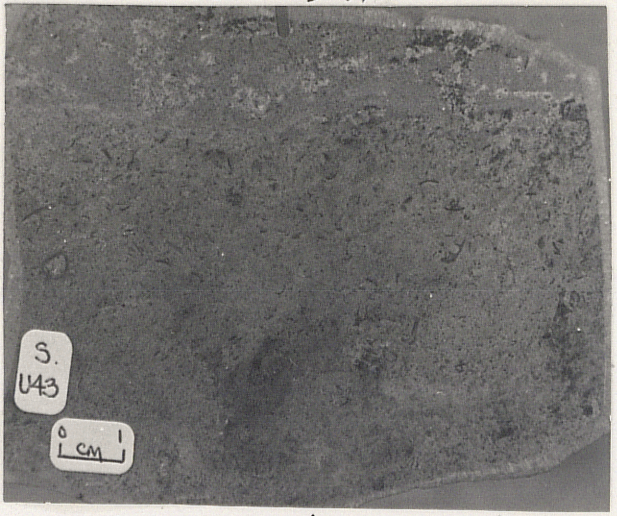
Burrows in the Restricted Marine Depositional Facies

Figure 11 Bluewater, unit 32: mud-lean wackestone burrows (C), mudstone host

A. "*Cruziana*" type burrows

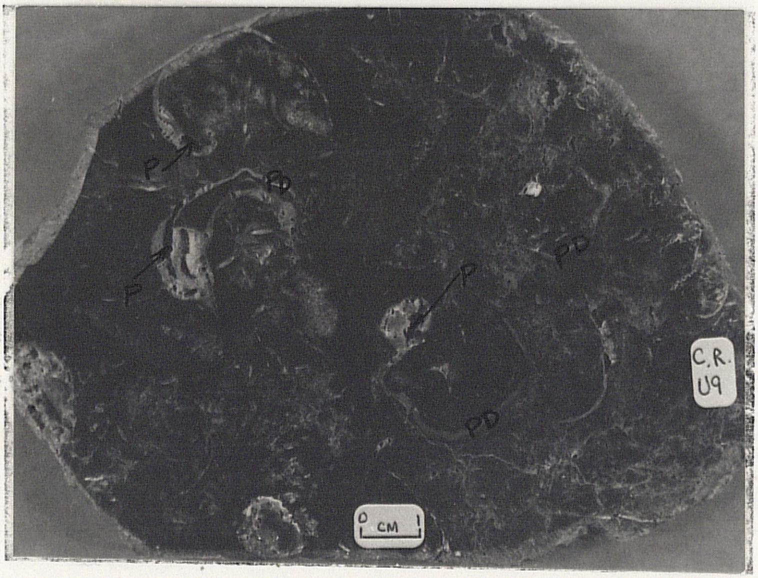
B. "*Cruziana*" type burrows which, at least superficially, appear to be part of a "*Callianassa*"-"*Alpheus*" type burrow network (mechanical pencil, MP, is ¼ inch in diameter)

Specimen
U.W. 1589/6



A

Specimen
U.W. 1589/7



B

Restricted and Normal Marine Depositional Facies

Figure 12 A. Restricted marine facies (Sunset, unit 43): abundant fossil debris (wackestone)
B. Normal marine facies (Canning Ranch, unit 9): abundant Productids (PD) and intraparticle porosity (P)

contains only biotic types which are inferred to be tolerant of such adverse enviromental conditions as abnormal salinity, great turbidity, extreme temperature variations, or stagnation. Hence, restricted marine does not imply that abnormal salinities were alon responsible, although they commonly play a dominant role in the Recent (e.g. Persian Gulf, Clarke and Keij, 1973). The arid climate inferred for lower San Andres time suggests that abnormally low salinities were unlikely. Tolerant fauna generally represent a lowered species diversity than normal marine assemblages, but the number of individuals can vary greatly (Laporte, 1967).

All of the following criteria were required for inclusion of rock units within the restricted marine facies of this study: 1) unfossiliferous or if fossiliferous, then only ostracods, Foraminifera, gastropods, and/or pelecypods are present, 2) absence of biota inferred to require normal marine conditions for life, 3) absence of intertidal or supratidal characteristics, and 4) evidence of evaporites is absent (or rare, if common to abundant in the overlying unit). Geographically, the restricted marine environment in modern carbonate settings corresponds to open and cut-off lagoons, straits, bays, and cut-off ponds (Wilson, 1970).

<u>Evaporitic Tidal Flat and Lagoonal Facies</u>

Introduction

The absence of stratified evaporites or convincing evidence of their former presence in the study area precludes a physical setting during Early San Andres time conducive to the sedimentation of bedded evaporites out of a standing body of water. The limited evaporitic features found in the rocks of this study are of the type produced by precipitation from interstitial water within sediment and hence represent a diagenetic, not a sedimentary environment. These features suggest the presence of hypersaline water "within" the sediment. Hypersaline water "within" sediment occurs associated with hypersaline bodies of water or is found under supratidal flats (Lucia, 1972).

Modern Sabkha Environments

The best studied environment in which evaporites are precipitated within carbonate sediments is the coastal sabkha or salt flat of the southern Persian Gulf, especially the Trucial Coast (Kinsman, 1969). Sabkhas are exposed, level, salt-encrusted surfaces that are only occasionally inundated. Sedimentary evidences of emergence and desiccation are abundant (Kinsman, 1969; Illing et al, 1965; Curtis et al, 1963; Shinn, 1968b). The two components of sabkha diagenesis are: 1) interstitial precipitation of evaporitic minerals within the host sediment, 2) changes in the host sediment such as dolomitization. Evaporites are restricted to the upper levels of the sabkha because the major recognized mechanism of brine concentration is evaporitive pumping of interstitial fluids upward to the sabkha surface. Dolomitization may extend in depth as dense brines move downward and seaward through the sediment. Sabkha anhydrite is typically nodular. Gypsum crystals in the upper 4 to 5cm of the sabkha are replaced in situ by anhydrite resulting in pseudomorphs. The pseudomorphs lose their shape in time ending up as variously shaped anhydrite nodules. A fossilized sabkha will not necessarily contain all minerals or even traces that developed during early diagenesis. Precipitation of diagenetic aragonite, gypsum, and anhydrite increases the Mg/Ca ratio resulting in the penecontemporaneous, prelithification dolomitization of fine grained sediments (Kinsman, 1969).

There is a spectacular development of intertidal algal mats along many inner lagoon shores in the southern Persian Gulf. They are absent on more exposed parts of the coast. Small lenticular gypsum crystals scattered within the algal mats and underlying sediments are apparently characteristic of intertidal zone diagenesis. The gypsum crystals are flattened in the plane approximately normal to the c-crystal axis. Consequently, these crystals typically have lozenge shapes in cross-section (Shearman, 1966).

Origin of Evaporites in Lower San Andres Formation

A sabkha-like origin for the evaporite molds in the lower San Andres Formation in the study area can only be invoked for some of the evaporitic rock units present. Supratidal shrinkage cracks are intimately associated with anhydrite nodule molds only in the upper part of Canning Ranch, unit 10. And three supratidal rock units at Sunset are underlain by anhydrite nodule mold-bearing units, but no evidence of evaporites is present within the supratidal rock units themselves. Some apparent gypsum crystal molds are scattered within possible cryptalgal laminates suggesting intertidal zone diagenesis (Shearman, 1966; figure 13A of this study).

Many evaporitic rock units in the study area are inconsistent with a sabkha-like origin. They most commonly show little to no evidence of subaerial exposure either: 1) within the rock units, 2) above the rock units prior to the deposition of non-evaporitic marine rock units, or 3) adjacent to the rock units at equivalent or stratigraphically slightly higher levels in nearby measured sections. The only two occurrences of anhydrite nodule molds in calcite showing no evidence of dolomitization or of dedolomitization fail to suggest a sabkha-like origin because dolomitization of limy sediment typically takes place concurrently with the precipitation of evaporites in modern sabkhas (Bebout and Maiklem, 1973).

The lack of emergent desiccation features in most evaporitic rock units in the study area may be explained in several ways: 1) subaqueous origin of diagenetic evaporites, 2) removal of emergent features by erosion, and 3) source of brines outside of the lower San Andres Formation in the study area.

A strong bias exists in modern carbonate sedimentology in favor of a sabkha origin for evaporites, especially nodular anhydrites (e.g. Kendall, 1969; Shearman and Fuller, 1969). This bias is the result of there being no recognized modern analogue of completely subaqueous diagenetic anhydrite nodule formation. However, recent work on the Middle Devonian Winnipegosis and Prairie Formations of south-central Saskatchewan presents considerable evidence of submarine bedded and nodular anhydrite formation in a basinal setting (Davies and Ludlam, 1973; Wardlaw and Reinson, 1971). In the recent literature, dolomite hosts are more commonly associated with supratidal evaporites, while calcite hosts, such as the aforementioned two occurrences of anhydrite nodule molds in calcite in the study area, are more commonly associated with evaporites of inferred subaqueous origin (Kendall, 1969; Bebout and Maiklem, 1973).

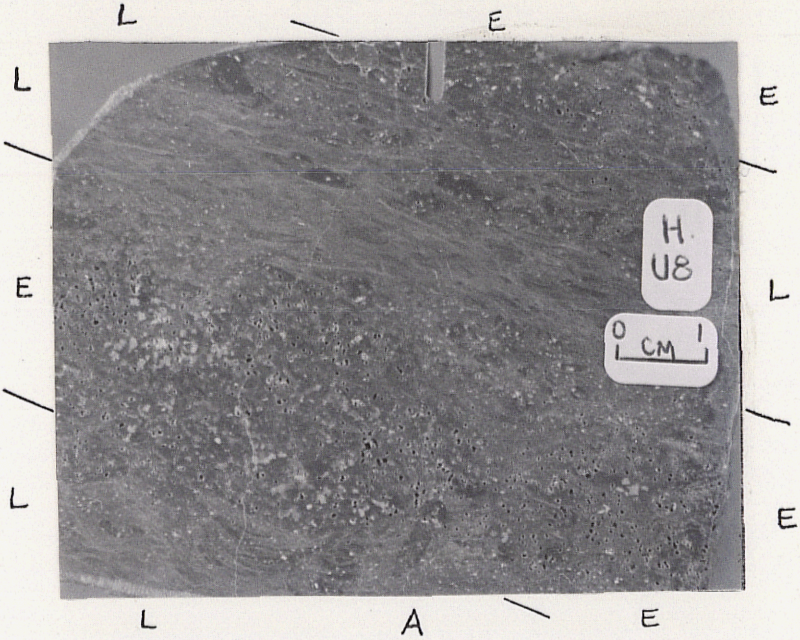
Erosion of subaerially desiccated supratidal and high intertidal portions of an evaporitic tidal flat, and preservation of the underlying evaporite-bearing low intertidal and subtidal facies is a possible way to explain the dissociation of evidence of subaerial exposure and evidence of diagenetic evaporites in the same rock units. Evidence of such erosion might be less conspicuous if it took place underwater. For example, there would be no building of a soil profile, and the erosional surface might be less pronounced. Relative rises in sea level and the accompanying shelfward migration of a high-energy zone (Shaw, 1964; Irwin, 1965) might result in submarine erosion. Such a possibility is suggested in the study area by: 1) evaporitic rock units are not uncommonly directly overlain by normal marine rock units, 2) at Canning Ranch and Bluewater, evaporitic rock units are directly overlain by oolitic rock units, which indicate high-energy conditions at deposition, and 3) some evaporitic rock units are overlain by sandstone and siltstone rock units with undulatory contacts. Hence, there is a distinct possibility that at least some of the evaporitic rock units in the study area may have been formed by brines concentrated on a sabkha-like surface, the evidence of which was subsequently removed by submarine erosion.

Abundant bedded evaporites in the lower San Andres Formation west of the study area and in the upper San Andres in the study area indicate hypersaline environments, which might have been the source for at least some of the concentrated brines responsible for the formation of diagenetic evaporites in the study area. However, no evidence was found to support this hypothesis. Occurrences of abundant evaporite molds are stratigraphically controlled and do not increase in thickness westward or upward in the study area. And abundant evaporite molds are found in hosts that are consistent with a penesaline local environment of deposition. They are almost always dolomitic and essentially unfossiliferous.

Evaporitic Facies in Lower San Andres Formation

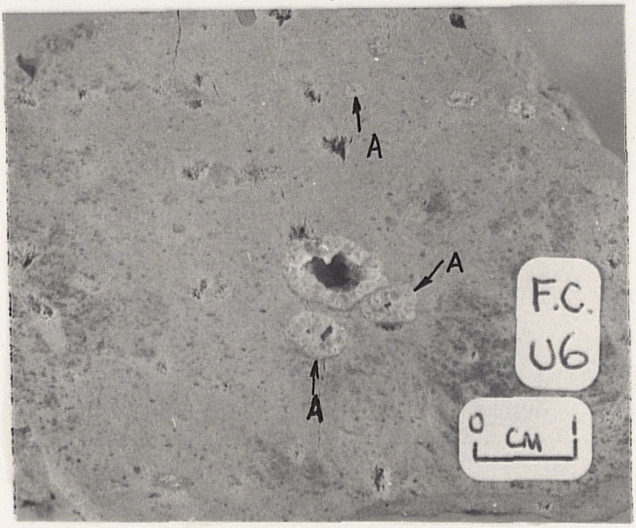
The evaporitic facies of this study is essentially a restricted marine, intertidal, or supratidal facies characterized by the presence of evaporite molds. Two sub-facies are recognized. An evaporitic emergent tidal flat facies (figures 13A and 14B) composed of evaporitic rock units, which show evidence of subaerial exposure or which are overlain by supratidal rock units. And a subaqueous? evaporitic facies (figures 13B and 14A) consisting of evaporitic rock units with no evidence of associated subaerial exposure within or above the units.

Specimen
U.W. 1589/8



A

Specimen
U.W. 1589/9

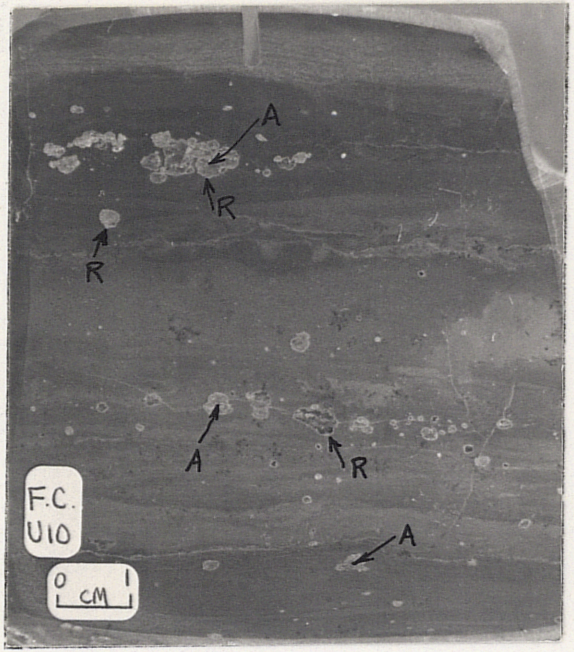


B

Evaporitic Depositional Facies

Figure 13 A. Evaporitic emergent tidal flat facies (intertidal?; Hondo, unit 8): layers of evaporite crystal molds (E) alternate with possible cryptalgal laminates (L) in a calcite host

B. Subaqueous? evaporitic facies (Fox Cave, unit 6): calcite-filled anhydrite nodule molds (A) in a dolomite host



Specimen
U.W. 1589/10

A

B

Evaporitic Depositional Facies

Figure 14 A. Subaqueous? evaporitic facies (Fox Cave, unit 10): abundant anhydrite nodule molds (A) with distinct hematitic rims (R) in a calcite host

B. Evaporitic emergent tidal flat facies (overlain by supratidal facies; Hondo, unit 24): coalesced anhydrite nodule molds (A) (white circle is 2 cm in diameter)

The evaporitic emergent tidal flat facies makes up about 5% and the subaqueous? evaporitic facies about 15% of the carbonate member. Relatively minor amounts of evaporite molds are present in some normal marine rock units (figure 16A). These appear to be related to the concentration of brines during later periods of hypersalinity.

Normal Marine Subtidal Facies

The normal marine facies of this study (figures 12B, 15, 16A, and 21A) corresponds to the tidal shelf facies of Wilson (1970). It consists of carbonates deposited in a subtidal environment which closely approximates normal open marine conditions. The facies is recognized by the presence of biota inferred to require an open, normal marine environment for development and survival, mainly articulate brachiopods and echinoderms. The rock types noted in this facies range from fossiliferous mudstone to mud-rich packstone. The normal marine facies makes up about 40% of the carbonate member.

Skeletal carbonate build-ups, that is skeletal boundstones, are apparently almost completely absent in the lower San Andres Formation in the study area. They were recognized only in Canning Ranch, unit 9, which consists largely of bryozoan-ostracod bioherms (figure 15). These bioherms are about 5 feet thick, but only about 1 to 2 feet of depositional relief is apparent. The bioherms are exposed for about 200 feet along the outcrop and are laterally equivalent to a rock unit containing abundant Productid brachiopods (figure 12B). Subtidal

Specimen
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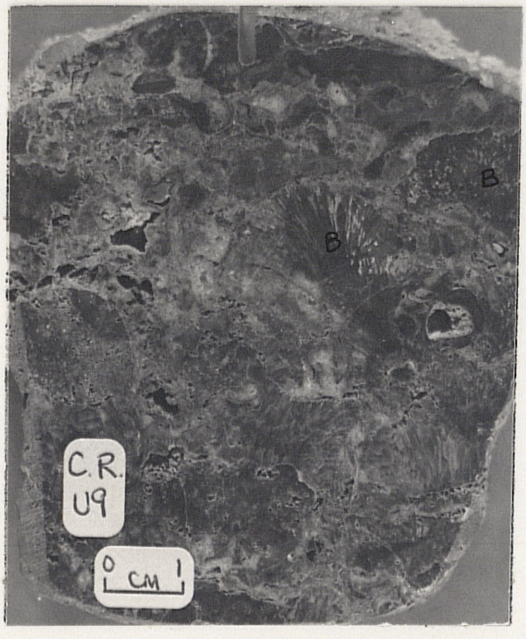
A

Specimen
U.W. 1589/12



B

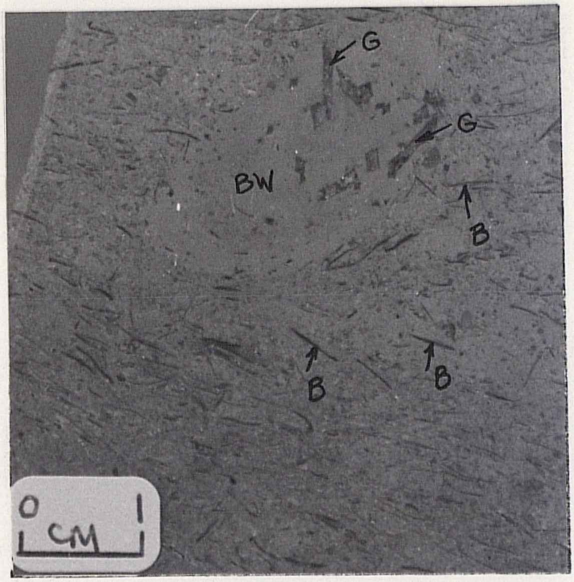
Normal Marine Facies

Figure 15 Rocks of bryozoan-ostracod bioherms in normal marine facies (Canning Ranch, unit 9):

A. Sharp contact between bryozoan (B) bioherm (BM) and fill material (F) covering bioherm

B. Bryozoans (B) and interparticle porosity (P) in biohermal rock

Specimen
U.W. 1589/13



A

Specimen
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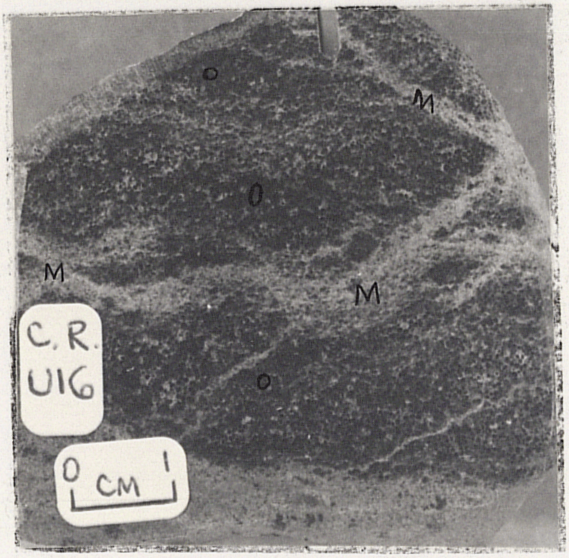


B

Normal Marine and Undaform-Edge Depositional Facies

Figure 16 A. Normal marine facies (Fort Stanton, unit 13): abundant non-Productid brachiopods (B) and a burrow (BW) with probable gypsum crystal molds (G) filled with length-slow chalcedony and calcite cement

B. Undaform-edge facies (Canning Ranch, unit 16): oolitic grainstone (O) with lighter colored, muddier stringers of oolites (M) (packstone to mud-lean wackestone) skeletal banks may be present at Fort Stanton about 10 feet laterally from where unit 13 was measured. However, the poor accessibility of these questionable banks precluded further examination of a possible bank origin.

Undaform-Edge Facies

The undaform-edge facies of this study (figure 16B) corresponds to Wilson's (1970) platform-edge sand facies. It consists of winnowed oolitic and intraclastic sands inferred to have been deposited along an undaform margin. In the study area, it consists mainly of oolitic and some intraclastic sands. There are relatively few abraded bioclasts, and intraclasts and quartz grains are oolitically coated in places. Obscure, small-scale planar cross-stratification is locally present, but the facies is generally massive. Mud-rich tongues of oolites ranging in thickness from about 6 to ½ inches are present in places (figure 16B). The facies is recognized by the presence of oolitic, and less commonly, intraclastic packstone and grainstone rocks. The undaform-edge sands may have been deposited as shoals, beaches, offshore or tidal bars in fans or belts, or eolianite dune islands (Wilson, 1970). The depths of such marginal sands today may range from sea level to 20 to 30 feet. Salinity is commonly normal marine and the environment is well oxygenated, but it is not hospitable to benthonic marine life because of the shifting substrate (Wilson, 1970). The undaform-edge facies of the lower San Andres makes up about 5% of the carbonate member in the study area as a whole. However, it comprises 20% of the carbonate member at the Canning Ranch and

Bluewater sections in the northeastern portion of the study area.

Correlation by Carbonate Depositional Facies

Detailed carbonate sedimentology, as reflected in the carbonate depositional facies of this study, provides a valuable method of correlating parts of the lower San Andres Formation across the study area (about 250 square miles) and probably in adjacent areas. Correlation of the lower San Andres in Lincoln County prior to this report depended upon the use of sandstone tongues within the San Andres. This study not only confirms the continuity of sandstone tongues within the study area, and hence their validity for correlation, but also provides a supplement to the use of sandstones for correlation purposes. The applicability of using the carbonate depositional facies of this study for correlation of the lower San Andres outside of the study area is unknown. However, the persistence of some of the carbonate depositional facies, especially the normal marine and restricted marine facies, across the study area suggests that these facies continue into areas adjacent to the study area. See the "TRANSGRESSIVE-REGRESSIVE" CYCLE section of this report for more information on the possibilities of detailed correlation within the lower San Andres Formation.

GLORIETA SANDSTONE MEMBER OF THE LOWER SAN ANDRES FORMATION

FIELD DESCRIPTION

The Glorieta Sandstone Member of the lower San Andres Formation is generally a fine-grained, very well to moderately sorted, calcite cemented quartz arenite. It is generally less well exposed than the carbonate member. Gross lithology is almost always apparent, but sedimentary structures are not uncommonly indeterminable. The Glorieta Sandstone is generally very thickly (>5 feet) to medium bedded ($\frac{1}{2}$ to $1\frac{1}{2}$ feet), and commonly contains internal cross-stratification, wavy bedding, or even, planar stratification.

The Glorieta Sandstone is yellow and light gray colored on fresh surfaces. It weathers to shades of yellow, gray, brown, and orange in decreasing order of relative abundance. The lower part of the upper Glorieta tongue at Bogle Dome is oil stained dark gray to black.

GENERAL PETROLOGY

Texture

Eleven representative samples from wavy bedded, cross-stratified, and comparatively well sorted massive units were disaggregated using a rubber pestle, soaked in dilute hydrochloric acid, and sieved using $\frac{1}{4}\phi$ sieve intervals down to and including 4ϕ. Statistical parameters were calculated (Folk and Ward, 1957) and are tabulated in Table 1. There is no apparent systematic variation in grain size in the study area.

The small number of samples studied precludes meaningful statistical treatment to test the significance of differences

TABLE 1 STATISTICAL PARAMETERS OF ELEVEN SIEVED SAMPLES FROM THE GLORIETA SANDSTONE (AFTER FOLK AND WARD, 1957)

	SAMPLE NUMBER	MEAN, φ UNITS	MEDIAN, φ UNITS	STANDARD DEVIATION	SKEWNESS	COARSEST 1 PERCENTILE mm	% GRAINS <4φ	SEDIMENTARY STRUCTURES
	W6	2.60	2.50	±.87	+.30	.47	12.53	WAVY BEDDING
	W8	2.34	2.13	±.67	+.45	.33	4.57	CROSS-STRATIFICATION
	W9	1.58	1.65	±.37	+.54	.38	1.42	CROSS-STRATIFICATION
	W15	1.82	1.76	±.30	+.31	.47	1.00	"WELL" SORTED MASSIVE
	W30	2.17	2.12	±.56	+.17	.38	2.68	WAVY BEDDING
	W31	1.79	1.66	±.47	+.35	.54	.82	CROSS-STRATIFICATION
	W32	1.93	1.90	±.44	+.30	.50	.42	"WELL" SORTED MASSIVE
	S2	2.46	2.40	±.52	+.42	.29	7.36	WAVY BEDDING
	S4	2.28	2.35	±.33	−.86	.38	2.54	CROSS-STRATIFICATION
	S24	2.13	2.13	±.45	+.13	.41	2.78	CROSS-STRATIFICATION
	S33	1.60	1.56	±.23	+.35	.38	<.01	CROSS-STRATIFICATION
AVERAGES	W6, W30, S2	2.41	2.34	±.65	+.30	.38	7.52	AVERAGE OF 3 WAVY BEDS
AVERAGES	W8, W9, W31, S4, S24, S33	1.97	1.90	±.42	+.16	.40	2.02	AVERAGE OF 6 CROSS-STRATIFIED UNITS
AVERAGES	W15, W32	1.88	1.83	±.37	+.31	.49	.71	AVERAGE OF 2 MASSIVE UNITS

W6: WALKER RANCH SECTION — ROCK SAMPLE NUMBER (SEE PLATE I)

S2: SUNSET SECTION — ROCK SAMPLE NUMBER (SEE PLATE VII) between calculated statistical moments. However, on an inspection basis, the statistical moments generated suggest the following conclusions: 1) there is no significant difference between average mean and median size diameters of cross-stratified and comparatively well sorted massive units, 2) average mean and median diameters of wavy bedded units are probably significantly smaller than these values for cross-stratified and comparatively well sorted massive units, 3) the average percentage of grains finer than 4ø in wavy bedded units is probably significantly larger than this percentage in cross-stratified and comparatively well sorted massive units, 4) there seems to be no significant difference in average coarsest one percentile in cross-stratified and comparatively well sorted massive units, and 5) the average sorting (i.e. standard deviation) of wavy bedded units is probably significantly larger than that of cross-stratified and comparatively well sorted massive units. These conclusions suggest that there is a definite sorting difference between wavy bedded units, and cross-stratified and comparatively well sorted units. This sorting difference is used in this report to help interpret depositional flow regimes.

Grain roundness is generally a function of grain size. The smaller grains are uniformly sub-angular to sub-rounded (Powers, 1953). Most larger grains are very well rounded to rounded, indicating a texturally very mature source. However, a relatively few large grains are sub-rounded suggesting a second, less mature source.

Composition

Light Minerals

Sixteen thin sections from the three types of units (wavy bedded, cross-stratified, and comparatively well sorted massive) were point counted (table 2) and another eleven were examined qualitatively. All sandstone thin sections were stained for orthoclase and plagioclase after the method of Bailey and Stevens (1960). Orthoclase should have been stained yellow and plagioclase red. However, both feldspars were stained pink. As a result, plagioclase was identified by its characteristic twinning and orthoclase by its feldspar characteristics and lack of twinning. The number of points counted generally varied between 300 and 450, depending on the apparent variability in each sample. Point intervals exceeded the diameters of the largest grains present. A 95% confidence interval for each constituent was determined graphically as an indication of variability (Van der Plas and Tobi, 1965).

The Glorieta Sandstone is almost entirely a quartz arenite, but a few units at Walker Ranch are feldspathic arenites (i.e. >10% feldspar). The feldspars (orthoclase, microcline, and sodic plagioclase) are restricted to the finer grain sizes. Compositional maturity generally increases upward in the measured sections and southward along the inferred paleocurrent direction. The former increase in maturity may be explained by increased maturity of the sediment source and/or greater abrasion of terrigenous grains during transport and deposition. The latter increase in maturity may be due to the additional

TABLE 2 MODAL ANALYSIS OF SELECTED SAMPLES FROM WALKER RANCH (W), SUNSET (S), AND FOX CAVE (FC) SECTIONS

MINERAL CONSTITUENT \ SAMPLE NUMBER	W8	W10	W12	W18	W21	W25	W28	W32	S2	S4	S8	S24	S29	S33	FC9	FC10
	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±4.6	56.7±4.7	67.7±4.7	59.6±3.0	63.5±4.8	67.8±4.7	80.5±4.0	62.2±4.8	48.8±5.8	69.7±5.4	70.1±5.3	52.2±5.7	63.9±5.5	67.3±5.4	70.9±5.2	63.5±5.6
(STRAINED)[1]	(13.5±3.1)	(6.2±2.2)	(5.5±2.2)	(5.2±1.3)	(2.0±1.2)	(2.3±1.4)	(4.8±2.0)	(3.3±1.6)	(1.3±1.0)	(3.0±1.9)	(5.9±2.7)	(3.4±2.0)	(5.0±2.3)	(6.0±2.7)	(9.4±3.2)	(6.3±2.3)
(UNSTRAINED)[2]	(47.5±4.7)	(50.5±4.7)	(62.2±4.8)	(54.4±3.1)	(61.5±4.8)	(65.5±4.8)	(75.7±4.3)	(58.9±4.9)	(47.5±5.7)	(66.7±5.4)	(64.2±5.5)	(48.8±5.7)	(58.9±5.7)	(61.3±5.6)	(61.5±5.6)	(57.2±5.7)
POLYCRYSTALLINE QUARTZ	3.1±1.5	2.7±1.3	1.5±1.0	.5±<1	1.0±<1	3.3±1.5	2.5±1.4	2.3±1.3	2.3±1.1	1.3±<1	1.6±1.0	2.7±2.0	3.3±2.0	3.0±2.0	4.4±2.2	4.0±2.1
QUARTZ OVERGROWTHS	9.4±2.5	5.7±2.1	14.3±3.4	4.6±1.3	10.3±3.0	3.3±1.5	.5±<1	13.5±3.3	4.3±2.0	5.7±2.7	5.3±1.5	*	5.6±2.5	9.0±3.1	11.1±3.7	8.9±3.2
CHERT	.7±<1	.6±<1		*	.3±<1	.5±<1	.3±<1	.5±<1				*	.7±<1	.3±<1	.3±<1	
ORTHOCLASE	5.7±2.0	7.8±2.5	.8±<1	3.0±1.0	2.3±1.5	.5±<1		.3±<1	1.0±<1	1.3±1.0	1.0±<1					
MICROCLINE	.5±<1	.9±<1	.3±<1	.1±<1					*							
SODIC PLAGIOCLASE	.2±<1	.2±<1		.1±<1												
FINE GRAINED MICA	17.9±3.5	16.0±3.4	1.7±1.0	4.0±1.1	6.4±2.3	4.3±1.9	12.8±3.3	3.2±1.5	.6±<1	2.7±1.3	5.9±2.6			4.7±2.3	.7±<1	
CLAY	1.4±1.0	1.0±<1	*	.1±<1	.3±<1	.2±<1	1.2±1.0	*	*	*	*			*	*	
MUSCOVITE	*	.5±<1			*	.3±<1	*	.5±<1		*		*			*	
ZIRCON	*									*						
TOURMALINE	*	*		*						*						
RUTILE	*															
HEMATITE	*	1.3±1.0	.3±<1	1.0±<1	.3±<1		2.0±1.0	.3±<1		1.0±<1						
CALCITE CEMENT		6.4±2.2		26.8±2.7	14.5±3.4	12.5±3.3			42.9±5.6	17.7±4.4	7.9±3.0	45.1±5.7	26.5±5.0	5.6±2.6	9.0±3.2	15.6±4.0
POROSITY			13.5±3.3		1.3±<1	7.8±2.5	.3±<1	17.3±3.7		.7±<1	8.2±3.1		.7±<1	10.0±3.4	3.7±2.0	9.9±3.4
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

n = NUMBER OF POINTS COUNTED

* = TRACE AMOUNTS PRESENT

1 EXTINCTION POSITIONS > A FEW DEGREES

2 EXTINCTION POSITIONS < A FEW DEGREES

NOTE: MEASURE OF VARIABILITY OF AMOUNT OF EACH CONSTITUENT INDICATED BY ± 2 STANDARD DEVIATIONS sediment transport distance along the inferred paleocurrent direction.

Heavy Minerals

Samples for heavy mineral separation were taken from the lower and upper Glorieta tongues at Sunset and units 3 and 20 at Walker Ranch. These four samples were concentrated using acetylene tetrabromide (S.G. 2.90). Table 3 lists the heavy minerals identified. The same heavy mineral types are apparently present in about the same relative amounts in all four samples. Non-opaque heavy minerals never appear in more than trace amounts in unconcentrated samples. Some units appear to have slightly more heavy minerals than others, however there appear to be no concentrations of heavy minerals into stringers or lenses in the study area.

TABLE 3 HEAVY MINERALS IN THE GLORIETA SANDSTONE

	HEAVY MINERAL	RELATIVE ABUNDANCE	REMARKS
NON-OPAQUES	TOURMALINE	ABUNDANT	BLUE, GREEN, YELLOW, PINK, BROWN, SLATE BLUE
	ZIRCON	COMMON	LOW AND HIGH BIREFRINGENT VARIETIES
	RUTILE	RARE	
OPAQUES	HEMATITE	ABUNDANT	PSEUDOMORPHS AFTER "PYRITE"
	LEUCOXENE	COMMON	ILMENITE ALTERATION PRODUCT

Cements

Calcite cement is abundant and the most common cement type in the Glorieta Sandstone. Dolomite cement is locally very important (e.g. Sunset, unit 17). Only one sample (Bogle Dome, unit 31) out of thirty-seven sandstone thin sections examined had chalcedony cement. It showed optically length slow. Clay frequently coats quartz grains in many units and may act as a cement.

Diagenetic Features

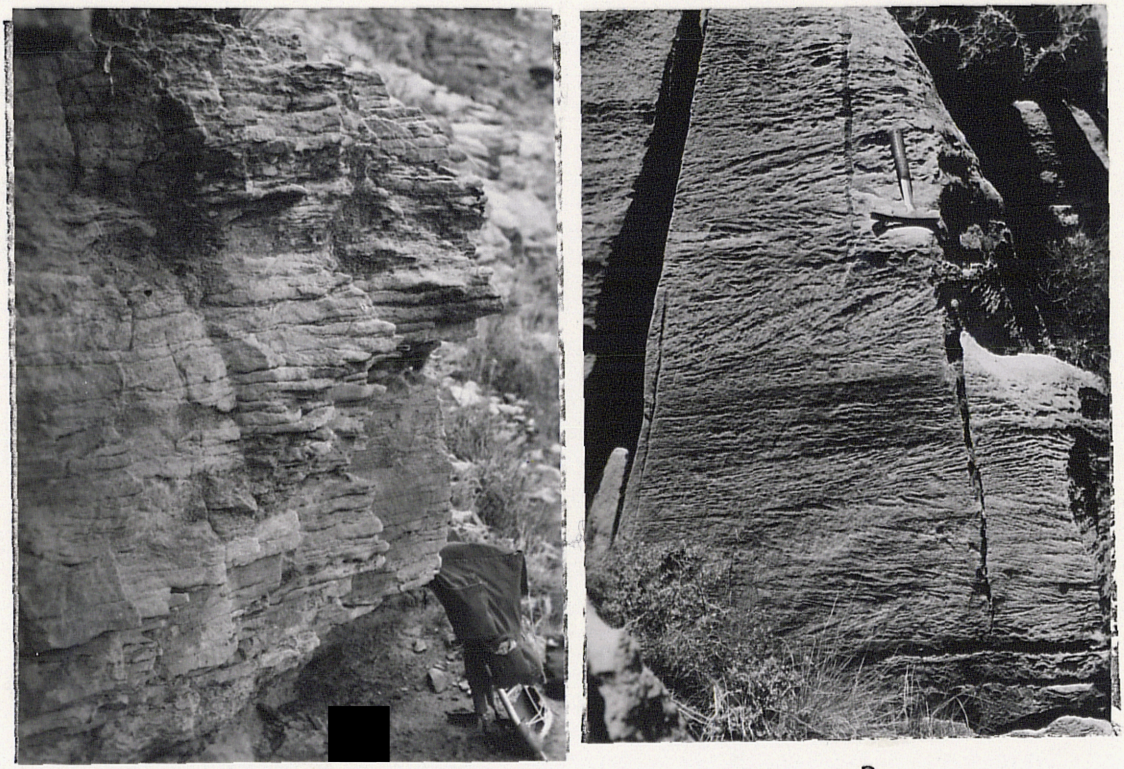
Quartz overgrowths are common, especially in the better sorted units. Orthoclase overgrowths and terrigenous grains with sutured pressure solution contacts are very rare. Calcite-cemented spherules or concretions ranging from about 1/16 to 2 inches in diameter are abundant in many units. The spherules are more resistant than the host rock and weather out in relief to produce a distinctive knobby appearance on the outcrop surface.

SEDIMENTARY STRUCTURES

Wavy Bedding

The term wavy bedding (figure 17A) is used in this study to describe rock units consisting of irregular sandstone lenses of varying length, which are separated by undulatory, distinct to indistinct bedding planes ½ to 2 inches apart (very thin bedding of this study). These units are comparatively the most poorly sorted in the Glorieta Sandstone, having the largest percentage of grains finer than 4ϕ (table 1).

Wavy bedding is interpreted as a weathering phenomenon



A B

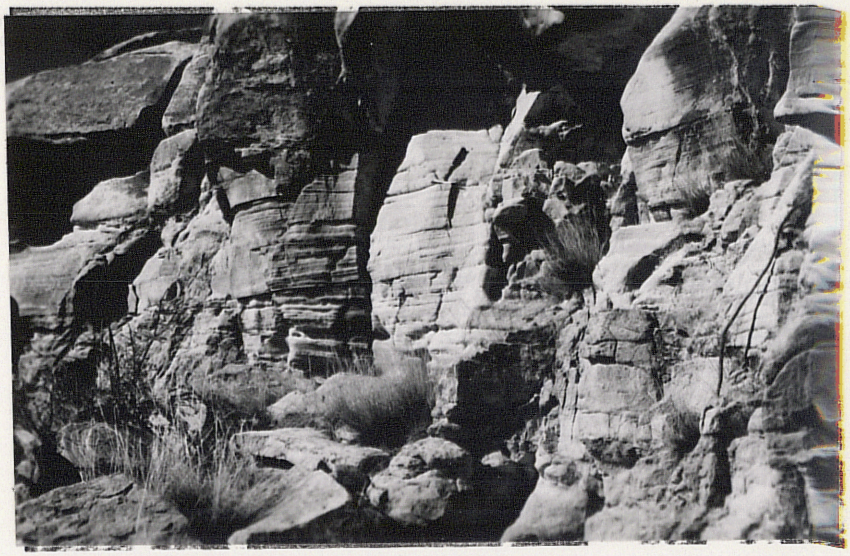
Figure 17 A. Wavy bedding in thick Glorieta tongue below lower Glorieta tongue (Bogle Dome, unit 1; backpack in lower right hand corner of photograph is about 3 feet high)
B. Bimodally cross-laminated (non-trough) channel sandstone in middle Glorieta tongue (Sunset, unit 17)

resulting from the presence of ripple marks, which are invisible in outcrop or hand specimen. Hamblin (1962) illustrates several apparently homogeneous sandstones in outcrop and hand specimen, whose radiographs show well-defined lamination and cross-lamination. Consequently, the lack of visible sedimentary structures in a sandstone does not preclude their presence. The general lack of mottling and the presence of very thin bedding suggests no disturbance by burrowing organisms.

Several independent lines of evidence suggest that wavy bedding has a ripple mark origin. A polished slab from the lower Glorieta Sandstone at Walker Ranch has questionable ripple marks with amplitudes of about 1mm and wave lengths of about 7mm. Wavy bedding, very similar to much of the wavy bedding in the Glorieta Sandstone, is present in an outcrop of the Jordan Sandstone in Madison, Wisconsin. There an overlying dolomite bed permits discernment of the original rippled upper surface of the sandstone. The comparatively poorer sorting in wavy bedded units (table 1) is more suggestive of lower flow regime conditions than the relatively better sorted cross-stratified units. Such very low flow conditions result in the formation of ripple marks, where sand grains are less than 0.6mm in diameter. The thickness of beds in wavy-bedded units in the study area includes the amplitudes of most ripple marks described in the geologic literature.

<u>Cross-Stratification</u>

Different types of cross-stratification (figures 17B and 18) are present in the study area, but no wedge-shaped sets



A

B

Cross-Stratification

Figure 18 Low-angle cross-lamination truncating low angle cross-lamination suggests possible beach foreshore deposition (note hammer in center of each photograph for scale)
A. Walker Ranch, unit 3
B. Bluewater, unit 16

(McKee and Weir, 1953) were noted. Tabular cross-sets are most abundant. Most cross-sets are 1 to 2 feet thick (ranging from 6 inches to 5 feet), about 3 feet long (ranging from about 2 feet to about 15 feet), and medium angle (10 to 25 degrees). However, many cross-sets are low angle (<10 degrees) or high angle (>25 degrees). Most cross-sets are planar (or angular), but many are curved and tangential at the bottom. These two types were not observed together in the same rock units in the study area. Planar cross-sets form in environments where there is little suspended load or where the height of the lee face is large compared with total flow depth. Curved cross-sets form where there is a large amount of sediment in suspension or if the height of the lee slope is small compared with the total flow depth (Blatt et al, 1972). The absence of appreciable silt and clay size terrigenous material in cross-stratified sandstones in the study area suggests that the height of the lee slope relative to the total flow depth was responsible for curved cross-sets.

Trough cross-sets were only found in Bogle Dome, unit 32. These sets are apparently 1 to 2 feet thick and about 2 feet by 4 feet in plan view. Cross-stratification is apparently somewhat symmetrical, but it is difficult to be certain. The cross-sets consist entirely of doubly-plunging troughs, which probably represent the fillings of canoe-shaped depressions (Dott, 1973). The long axes of these troughs are oriented essentially east-west. However, the underlying planar cross-sets dip toward the south-southwest, as do the planar cross-sets in the upper Glorieta tongue at Walker Ranch (unit 20), Canning Ranch, Fort Stanton, and Sunset (figure 19). Consequently, the short axes of these troughs appear to be in the paleocurrent direction unlike most trough axes studied heretofore.

Even,Planar Stratification

Even, planar stratification is comparatively rare in the study area, except for its occurrence in the lower part of the Bogle Dome section, suggesting the absence of upper flow regime conditions during the deposition of most of the Glorieta Sandstone. Strata range in thickness from lamination (<½ inch) to thick bedding (1½ to 5 feet).

Massive

Massive units are characterized by the apparent lack of sedimentary structures. Hamblin's (1962) work suggests that sedimentary structures probably are present, although invisible. Two types of massive units are recognized: 1) silty units with the comparatively poorer sorting associated with wavy bedded units, and 2) clean sandstones with the better sorting associated with cross-stratified and even, planar stratified units. The better sorted units lack any evidence of burrowing, whereas the comparatively poorer sorted units are locally mottled, although no distinct burrows were found.

Soft Sediment Deformation

Evidence of soft sediment deformation (Potter and Pettijohn, 1963) is very unusual in the Glorieta Sandstone and only has been noted in the lower Glorieta tongue at Sunset. Soft sediment deformation is suggested by the confinement of deformation to a single bed between undeformed beds. Locally, unit 6 is twice as thick as usual (about 4 inches) along the outcrop, whereas unit 7 (about 2 feet thick) is tilted at about 35 degrees. Units 5 and 8 (1 and 3 feet thick respectively) are apparently unaffected by this deformation. The instantaneous compaction of loosely packed sand or flowage of sand while liquefied ("quick") are the most probable mechanisms of deformation. The "shock" that initiated deformation was apparently of a very local character and may possibly have been related to rapid sediment influx increasing overburden pressure past a threshold value required for deformation.

PALEOCURRENT ANALYSIS

Cross-stratification orientations were measured in all sections except Fox Cave and Hondo (figure 19). No other sedimentary structures revealing paleocurrent information were noted in the study area. However, the general increase in compositional maturity southward in the study area is compatible with the paleocurrent directions inferred from cross-bed orientations.

A general southward transport direction is recorded for the currents that deposited the upper Glorieta tongue (figure 19 and 23). The five cross-stratified units at Walker Ranch all indicate a general west-southwest transport direction (figure 19). Paleocurrent directions, statistics, and corrections for structural tilt were calculated by computer using a

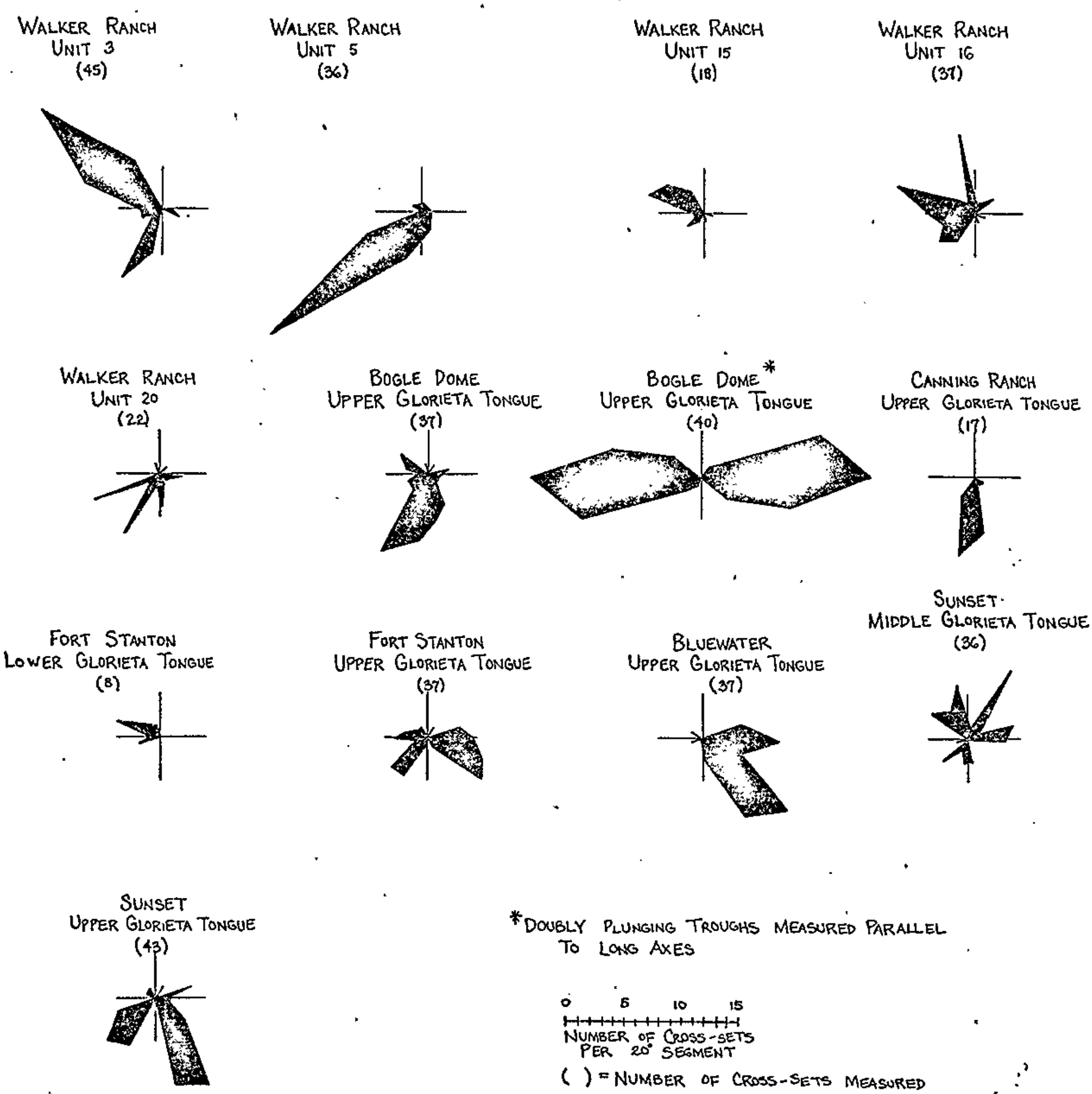


FIGURE 19 ROSE DIAGRAMS FOR CROSS-STRATIFIED UNITS IN GLORIETA SANDSTONE

program developed by Doe (1973). The statistics were determined by the vector summation technique (Curray, 1956).

PROVENANCE AND DISPERSAL OF THE SAND

Inferred Glorieta paleocurrent directions clearly suggest that the terrigenous sand was supplied from the north-northeast. Both the Ancestral Rockies of Colorado (figure 2) and cratonic areas farther to the north and northeast are possible sources. The extreme textural and compositional maturity of the Glorieta suggests a pre-existing sandstone source (Pettijohn et al, 1972). The Ancestral Rockies were stripped to crystalline Precambrian basement long before Glorieta time (McKee et al, 1967) and Todd (1964) has calculated that the Ancestral Rockies were not extensive enough to have supplied all the sand present in the Late Paleozoic blanket sandstones of which the Glorieta forms a southern feather-edge. These considerations strongly suggest that the Ancestral Rockies probably did not supply any more than a tiny fraction of the Glorieta sands. However, the larger sub-rounded quartz grains present in most Glorieta Sandstone samples may have come from this source. The primary sources of terrigenous sand were probably Lower Paleozoic sandstones in cratonic areas to the north of the study area. The lack of Permian terrigenous clay deposits in the southwest of the United States suggests a source area poor in clays, such as the Lower Paleozoic of the central craton (Doe, 1973).

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 the study area (Kelley, 1972). However, none were found in the vicinity of the Precambrian knob about 5 miles north of Corona (figure 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 it is remarkable how little detritus seems to have been supplied by the Corona knob.

DEPOSITIONAL PROCESS FACIES

The use of bed forms and bed-form internal structures (figure 20) to interpret flow regimes is based on recent work with flumes and streams (Simons et al, 1965; Harms and Fahnestock, 1965). The flow regime concept is a valuable way to define process facies because it emphasizes the fact that assemblages of bed forms are controlled not by a single hydraulic variable, such as depth or slope, but by a complex of variables (Blatt et al, 1972). This study uses the flow regime concept with the recognition that at least two distinct environments may have been responsible for deposition, namely the offshore marine and "shoreline" environments.

Plates IX and X illustrate the vertical and lateral distribution of depositional process facies on the basis of flow regime as recognized by: 1) bed-forms and bed-form internal structures present or inferred present, and 2) comparative sorting in apparently massive units (figure 20). There is a good correlation between the degree of comparative sorting and the associated sedimentary structures, where the latter are visible. Comparatively poorer sorting is associated with wavy

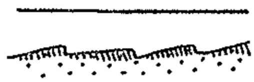
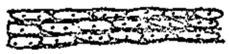
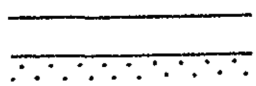
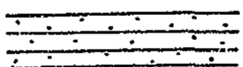
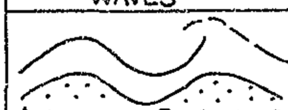
Flow Regime		Ideal Sequence of Bed Forms in Alluvial Channels	Corresponding Features in Study Area	Associated Comparative Sorting
Lower	Lower	 Ripples	 Wavy Bedding	"Poorer" (Large Percentage of Grains $<4\phi$)
		 Dunes with Ripples	Absent	
	Upper	 Dunes	 Tabular and Trough Cross-Stratification	"Better" (Small Percentage of Grains $<4\phi$)
Transition		 Transition	Absent	
Upper	Lower	 Plane Bed	 Even Planar Stratification	"Better" (Small Percentage of Grains $<4\phi$)
	Upper	 Antidune Standing Waves	Absent	
		 Antidune Breaking Waves	Absent	
		 Chutes and Pools	Absent	

Figure 20 Ideal Sequence of Bed Forms in Alluvial Channels (Simons et al, 1965) and Corresponding Features in Study Area with Associated Comparative Sorting

bedding, whereas better sorting is associated with cross-stratification and even, planar stratification.

ENVIRONMENTAL INTERPRETATION

Interpretation of the environments of deposition of the Glorieta Sandstone using sedimentary structures, grain size distribution, and surface textures of individual sand grains has yielded mixed results.

The following aspects of internal cross-stratification in the Glorieta Sandstone are similar to those reported from both modern subaerial dunes (McKee, 1967; McBride and Hayes, 1962) and the non-barred high energy nearshore subaqueous environment (Clifton et al, 1971). Higher-angle cross-sets are not infrequently truncated by low-angle cross-stratification or even, planar stratification in the study area. In unit 3 at Walker Ranch, high-angle, large scale sets pass laterally into very low-angle cross-lamination and even, planar lamination. Some Glorieta rock units are dominated by high-angle cross-stratification, which is characteristic of at least some coastal dunes (McBride and Hayes, 1962). However, the almost complete lack of information on the internal structures of offshore subaqueous dunes precludes choosing between nearshore or aeolian environments of deposition without other evidence. However, the long, low angle cross-stratification in Walker Ranch, units 3 (figure 18A) and 20, and in Bluewater, unit 16 (figure 18) suggests possible beach foreshore deposition (Clifton, 1969).

Inferred ripple marked units, that is wavy bedded units, do not apparently represent tidally-influenced sand deposits because fine material is not segregated into recognizable flaser bedding patterns (Reineck and Wunderlich, 1968).

Various methods have been proposed to infer physical processes or environments of deposition from parameters based on grain size distribution: 1) Passega (1957) plotted median against coarsest one percentile values of a number of samples, 2) Visher (1969) recognized sub-populations within individual log-normal grain size distributions, and 3) Friedman (1961, 1962, 1967) plotted various combinations of statistical parameters against each other. Table 4 lists the environmental inferences made for the eleven samples of table 1 using these methods. The results of the grain size analyses are conflicting and ambiguous. There is very little if any correlation between different types of sedimentary structures and the processes or environments inferred by the above methods. Grain size analysis appears to have, at best, only a very limited utility in the environmental interpretation of such pure quartz sandstones as the Glorieta Sandstone.

Various combinations of detailed surface textures, as revealed by scanning electron microscope (SEM), are believed characteristic of sand grains deposited in different Holocene environments (Krinsley and Doornkamp, 1973). Grain mounts from four samples representing three cross-stratified and one wavy bedded unit were examined on the SEM. Ten to fifteen grains per grain mount were closely examined. All original

ROCK SAMPLE NUMBER	SEDIMENTARY STRUCTURE	DEPOSITIONAL PROCESS OR ENVIRONMENT				
		PASSEGA, 1957	VISHER, 1969	FRIEDMAN, 1961, 1962, 1967		
				SKEWNESS VS. STAND. DEV.	SKEWNESS VS. MEAN SIZE	STAND. DEV. VS. MEAN SIZE
W6	WAVY BEDDING	BEACH	MARINE; REWORKED	TRACTIVE CURRENTS	WIND	TRACTIVE CURRENTS
W8	CROSS-STRATIFICATION	BEACH	MARINE; REWORKED	TRACTIVE CURRENTS	WIND	MIXED
W9	CROSS-STRATIFICATION	NO FIELD	MARINE; REWORKED	SURF	WIND	MIXED
W15	"WELL" SORTED MASSIVE	NO FIELD	BEACH	SURF	WIND	WIND
W30	WAVY BEDDING	BEACH; RIVER OR TRACTIVE CURRENT	?	SURF OR TRACTIVE CURRENT	WIND	MIXED
W31	CROSS-STRATIFICATION	BEACH; RIVER OR TRACTIVE CURRENT	BEACH; REWORKED	SURF	WIND	MIXED
W32	"WELL" SORTED MASSIVE	BEACH; RIVER OR TRACTIVE CURRENT	MARINE; REWORKED	SURF	WIND	MIXED
S2	WAVY BEDDING	BEACH	FLUVIAL	SURF OR TRACTIVE CURRENT	WIND	WIND
S4	CROSS-STRATIFICATION	BEACH	BEACH	SURF	SURF	WIND
S24	CROSS-STRATIFICATION	BEACH; RIVER OR TRACTIVE CURRENT	BEACH; REWORKED	SURF	WIND	MIXED
S33	CROSS-STRATIFICATION	NO FIELD	BEACH; REWORKED	SURF	SURF	WIND

TABLE 4 ENVIRONMENTAL INTERPRETATION OF GLORIETA SANDSTONE BASED ON GRAIN SIZE DISTRIBUTION

W6: WALKER RANCH SECTION ← W → 6: ROCK SAMPLE NUMBER (SEE PLATE I)

S2: SUNSET SECTION ← S → 2: ROCK SAMPLE NUMBER (SEE PLATE VII) grain surfaces were covered with thick diagenetic quartz overgrowths. The common occurrence of such overgrowths and other diagenetic effects in ancient sandstones suggests that this method has at best only a very limited utility in the environmental interpretation of ancient sandstones like the Glorieta.

At least some of the Glorieta Sandstone is probably of shallow marine origin because of the presence of local shallow marine type burrows and interbedded shallow marine carbonates. However, the study of modern continental shelves suggests that migration of a strand line seems more likely as a mechanism for spreading an extensive, thin marine sand sheet than does simultaneous deposition across an entire area. Yet distinct ancient shoreline sand bodies are seldom recognized (Pettijohn et al, 1972). The possible foreshore beach deposit at Walker Ranch, unit 20 is at about the same stratigraphic horizon as supratidal carbonate depositional facies along depositional strike at Canning Ranch, Bluewater, and Sunset, suggesting that this is a reasonable environmental interpretation. Cross-stratified sandstones are also present at about the same horizon as supratidal and intertidal facies in the lower carbonate tongue at Canning Ranch, Fort Stanton, Hondo, Sunset, and Bluewater, suggesting that at least Walker Ranch units 5, 14, 15, and 16 may also represent "shoreline" deposition. The "shoreline" environment in this report includes the coastal dune to nearshore environments because, as already discussed, criteria for differentiation of these individual environments are most commonly ambiguous and conflicting for clean quartz sandstones. It seems likely that most or all of the lower flow regime wavy bedded units were deposited in comparatively lower energy shallow lagoonal environments, whereas at least some of the cross-stratified and even, planar stratified rock units were deposited in the shoreline environment.

PALEOGEOGRAPHIC IMPLICATIONS FOR EARLY SAN ANDRES TIME IN CENTRAL NEW MEXICO

"TRANSGRESSIVE-REGRESSIVE" CYCLES

Introduction

Shaw (1964) proposed that rock units were fundamentally diachronous because they were the direct result of the migration of sedimentary facies in time in response to eustatic sea level fluctuations. Hence, vertical changes of carbonate depositional facies in ancient rocks might be the result of changes in sea level during deposition. However, many vertical changes in carbonate facies do not require sea level fluctuations for explanation. Thus, it is frequently difficult, on a detailed scale, to determine the cause of vertical sedimentary facies changes. Yet the terms used to describe sequences of such changes often have genetic connotations (e.g. transgressive and regressive). Consequently, the terms used in this study are defined below to avoid misunderstanding.

"Transgressive" or "deepening upwards" refers to an upward change in sedimentary facies that is consistent with, but not necessarily caused by, a migration of facies in response to a relative sea level rise. A major marine or eustatic transgression refers to an apparent absolute sea level rise that resulted in normal marine conditions over most or all of the study area. A minor transgression refers to an apparent relative sea level rise that resulted in less restrictive depositional environments in the study area, except for normal marine environments, which were only locally present when not absent. "Regressive" or "shoaling upwards" refers to an upward change in sedimentary facies that is consistent with, but not necessarily caused by, a migration of facies in response to a relative sea level drop. "Marine" or "eustatic regression" indicates that an absolute sea level drop was apparently responsible for the deposition of a "shoaling upwards" sequence. "Sedimentary regression" indicates that an effectively constant sea level was coupled with a rate of carbonate accumulation that was faster than the rate of local subsidence. The term "sedimentary regression" includes the progradation of tidal flat environments.

Both "transgressive" and "regressive" rock sequences may be explained by other than absolute sea level fluctuations. A relatively high rate of regional subsidence coupled with a relatively low rate of carbonate accumulation may explain some aerially extensive "transgressive" rock sequences, whereas storm piercement of an undaform-edge barrier may explain more local "transgressive" changes. "Sedimentary regression" may explain many "regressive" rock sequences. However, eustatic sea level shifts are frequently invoked to explain large scale vertical facies changes in Permian deposits in the southwestern United States (e.g. Wanless, 1972; Meissner, 1972). Glaciation, global tectonics and storage of water in lakes are some of the possible mechanisms. Alternating glacial and interglacial periods in Gondwanaland are often suggested as the most likely cause because they can account for the repeated sea level fluctuations inferred for Early and

Middle Permian time. However, a change in the size of ocean basins due to shifting crustal plates could account for some shifts. A less likely possibility is the temporary storage of large volumes of water in fresh-water lakes (Wanless, 1972). Only several of the "transgressive-regressive" cycles discussed in the next section can be confidently attributed to absolute sea level fluctuations.

Cycles in the Upper Yeso and Lower San Andres Formations

The upper Yeso and lower San Andres Formations of this study appear to have been deposited in seventeen "transgressive-regressive" cycles. In general, the "regressive" portions of these cycles tend to be prolonged, resulting in thick deposits and indicating a gradual "marine" and/or "sedimentary regression," whereas the "transgressive" portions tend to be "rapid," resulting in thin deposits and in an abrupt change from more saline to less saline-water deposits, similar to those discussed by Irwin (1965). These abrupt changes or "kicks" have been used to recognize correlative points to establish approximate time equivalents on Plates IX and X. For example, the lower boundary of "transgression-regressive" cycle 7 was placed at the base of the first normal marine rock unit present in most of the measured sections on Plates IX and X. A relatively thick line was used for this boundary to indicate that this cycle begins with a major marine transgression. The lower boundary of cycle 8 was positioned on the basis of the three measured sections that contain an abrupt change from relatively restricted to relatively unrestricted depositional environments.

The cycle's lower boundary is marked by a relatively thin line, which indicates a minor transgression and which is dashed where it passes through measured sections with no evidence of transgressive deposits at the approximate horizon.

Three major transgressive "kicks" (beginning cycles 7, 13, and 15) in the lower San Andres Formation are traceable over most or all of the study area. These "kicks" are attributed to major marine or eustatic transgressions. Thirteen minor transgressive "kicks" (beginning cycles 2,3,4,5,6,8,9,10,11, 12,14,16, and 17) are traceable over some to all of the study area. No convincing way was found to differentiate between individual "kicks" predominately caused by a rise in absolute sea level and those predominately caused by a rate of subsidence greater than the rate of sediment accumulation. The influx of terrigenous sand to depositional centers is commonly associated in the geologic literature with low sea level stands resulting from eustatic sea level fluctuations. Cycles 5, 9, and 10, which begin with the influx of terrigenous sand south of Walker Ranch, thus may reflect absolute sea level fluctuations. The deposits of cycle 1 were noted only at Walker Ranch, where the transgressive portion of the cycle was not exposed. Hence, very little may be inferred about the origin of cycle 1.

The Glorieta Sandstone Member at Walker Ranch consists of five cyclic repetitions of strata, each involving lower flow regime deposits. These consist of upper-lower flow regime deposits, which are interpreted to represent transgressive phases, that cap lower-lower flow regime deposits, which are interpreted to represent regressive phases. These interpretations permit a good correlation between transgressive "kicks" inferred in the sandstone at the boundary between these two different types of flow regime deposits and those "kicks" noted in the carbonate member (Plate IX).

No general method was found in this study to distinguish between regressive rock sequences deposited by marine or eustatic regression and those deposited by sedimentary regression. However, the "shoaling upwards" sequence in the middle carbonate tongue at Canning Ranch is suggestive of marine (or eustatic) regression. There, normal marine rock units pass up into intertidal rock units in a vertical distance of about one foot. Assuming that sedimentary regression was responsible would imply that about a foot depth of water at low tide was sufficient for well developed normal marine conditions to exist. However, it is unlikely that the varied and abundant normal marine biota present in the normal marine facies (figure 12B) could have survived and prospered in such shallow depths for the following reasons. A one foot depth suggests that only minimal circulation, if any, was possible. And tropical storms, which would have occurred frequently on a geological time scale, would most likely have uncovered such shallow sediments periodically.

Figure 21 illustrates a well-developed "shoaling upwards" sequence present in the Hondo section.

Significance of "Transgressive-Regressive" Cycles

The seventeen "transgressive-regressive" cycles of this report, which follow naturally from the detailed carbonate sedimentology of this study, provide a valuable method of detailed correlation within the lower San Andres Formation. The method is independent of the continuity of individual carbonate depositional facies or the presence of terrigenous sand. Hence, it has great applicability both in and adjacent to the study area. These cycles lend themselves to correlation with similar cycles in the lower San Andres in outcrop and in the subsurface outside of the study area. Hence, the cycles permit the prediction of carbonate depositional facies where no other information is available. These cycles also offer a method of correlating the carbonate member of the San Andres Formation into the Glorieta Sandstone Member, a correlation which has apparently never been successfully made in the published literature.

PEDERNAL POSITIVE ELEMENT

The study area occurs on the Pedernal positive element (figure 22). The Pedernal seems to have been the most active tectonic element in central New Mexico at least in Middle and Late Pennsylvanian, and Early Permian time (Dixon, 1967). Continuation of the rise of the Pedernal during Wolfcampian time resulted in denudation well into the Precambrian basement (Kelley, 1971) and deposition of the conglomerates of the Laborcita and Abo Formations of Otero County (Pray, 1961; Otte, 1959). The regional tendency during the Early Permian, especially during Wolfcampian time, was to eliminate much of the relief of the Late Pennsylvanian/Early Permian basins: the Orogrande, Delaware, and Midland basins and the Central basin platform (figure 2).

The structure of the Pedernal positive element is not well known, but it appears to have been a broad upwarp in some places and fault-bounded blocks in others (Kelley, 1971). The first-order broad surface of the Pedernal was highly irregular with second order knobs of differing elevations. One such Precambrian knob is now exposed just north (T.1N., R.13E.) and another just south (Pajarito Mountain, T.12S., R.15E. and R.16E.) of the study area (Kelley, 1971, 1972). The outcrop of these two knobs is about 1 to 2 miles in diameter. These knobs appear to have been islands at least several hundred feet high in Middle Permian seas, which became covered with sediments as regional subsidence and deposition continued through Permian time. Regionally (Kelley, 1971, 1972) arkosic sandstone

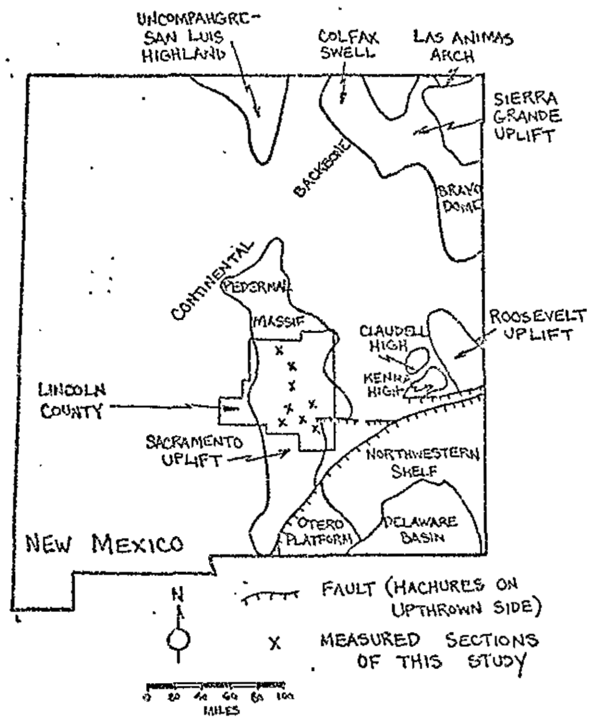


FIGURE 22 TECTONIC ELEMENTS OF CENTRAL AND EASTERN NEW MEXICO AT BEGINNING OF PERMIAN TIME AFTER HILLS, 1967. PEDERNAL POSITIVE ELEMENT CONSISTS OF PEDERNAL MASSIF, SACRAMENTO UPLIFT, AND OTERO PLATFORM. NOTE TREND AND POSITION OF EASTERN EDGE OF PEDERNAL POSITIVE ELEMENT.

and conglomerate are present in the basal parts of the Yeso Formation and Glorieta Sandstone where these units lap onto or are in proximity to Precambrian exposures.

Kelley (1971) found evidence in the Capitan--Ruidoso area of Lincoln County (figure 1) of repeated activity of the Pedernal positive element from Permian well into Tertiary time. Even though deposition covered most of the Pedernal positive element during Glorieta and San Andres time, it appears to have acted as a buried, yet relatively positive feature. Hock (1970) found that the Yeso Formation wedges out, whereas the San Andres Formation, including the Glorieta Sandstone Member, thins drastically as they onlap the Pedernal in the area around northeastern Torrance County, north of the study area of this report. Kottlowski (1963) invoked a relatively positive Pedernal element as one possible way to explain the complex problem of the age of the San Andres. He suggested that the entire Permian section may change facies going from west to east across the Pedernal. A buried, yet relatively positive Pedernal element is also used in this study to explain the distribution of lower San Andres lithologies in and adjacent to Lincoln County. Included are bedded evaporites and carbonates west of the study area, carbonates and sandstones in the study area, and carbonates east of the study area (figure 5).

DETAILED PALEOGEOGRAPHY

Introduction

Most of New Mexico during Middle Permian time, including Lincoln County and adjacent areas, is considered to have been a paleogeographic shelf province (Meissner, 1972). Analysis of the carbonates and sandstones in the study area on the basis of recent depositional models, and the principles of carbonate sedimentology and physical sedimentation suggest that the Permian shelf in central New Mexico may be subdivided into "deeper" and "shallower" parts, that is below and above wave base.

Rich (1951) coined the terms undaform, clinoform, and fondoform, which are analogous to the general terms of shelf, slope, and basin, except that they are independent of scale. The root unda refers to the relatively horizontal part of the sea floor within the depth of effective wave action, and clino to the more steeply sloping part of the sea floor that extends down to the more level deeper part below wave base, the fondo. These terms are very useful for subdividing a recognized shelf province free of any basinal character.

Several independent lines of evidence lead to the hypothesis that most of the lower San Andres Formation in the study area was deposited on an undaform, which was west of an undaform-edge barrier environment that trended generally north-south in eastern Lincoln and western Chaves County (figure 23). These include: 1) the nature and distribution of carbonate rock types and recognized depositional facies, 2) the trend of the eastern edge of the Pedernal positive element and thickness trends in the lower, middle, and upper Glorieta tongues, and 3) paleocurrent analysis of the upper Glorieta tongue. The entire study area was presumably below wave base during high sea level stands and hence, in the fondo environment. Measured sections in the northern, southern, and western sides of the study area are not sedimentologically distinctive enough to permit any but the most general paleogeographic extrapolation outside the study area. This extrapolation is included in the later section that proposes models for lower San Andres deposition.

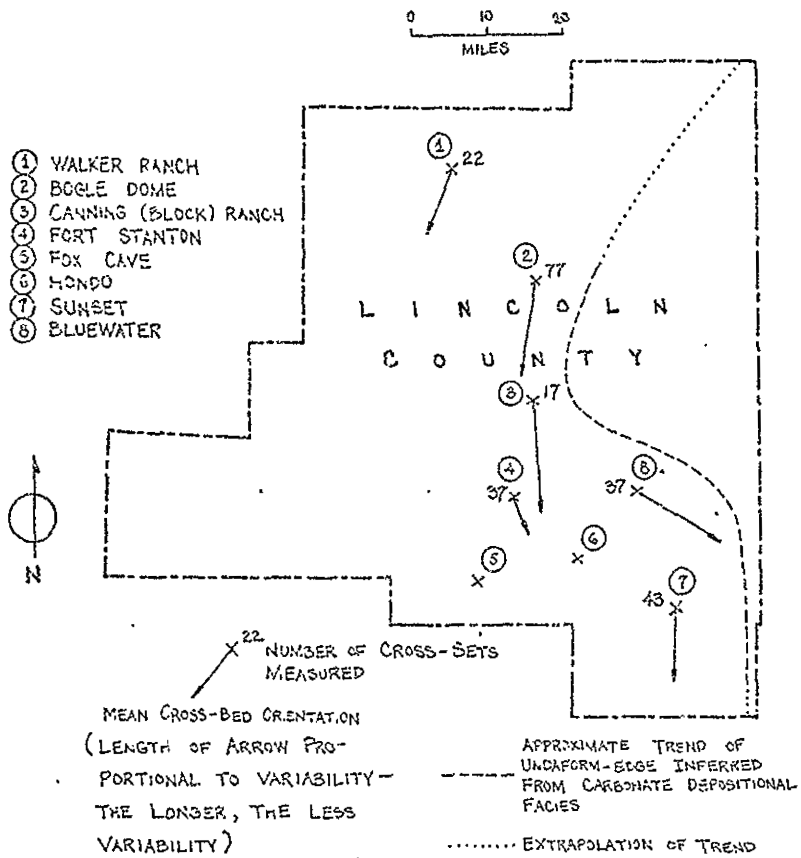


FIGURE 23 CROSS-BED ORIENTATIONS (UPPER GLORIETA TONGUE, LOWER SAN ANDRES FORMATION) AND APPROXIMATE TREND (NOT POSITION) OF THE UNDAFORM-EDGE INFERRED FROM CARBONATE DEPOSITIONAL FACIES

Nature and Distribution of Carbonate Rocks and Facies

The formation of spheroidal, well rounded carbonate oolites, such as are present in the Canning Ranch and Bluewater sections of this study, requires water supersaturated with calcium carbonate and an environment with strong and consistent agitation. Modern large-scale oolite formation is known only from very shallow, warm-water environments in which tidal currents keep the grains in nearly constant agitation (Heckel, 1972). Oolitic sediments are found in the more shoreward extent of the agitated zone in which effective wave base intersects the bottom surface in the southern Persian Gulf, in the Great Salt Lake of Utah, and on the margins of the Bahamas Platform. This location is explainable on theoretical grounds (Irwin, 1965), and oolitic rock units in most ancient carbonate sequences should represent deposition in similar environments. Low-energy carbonate deposition commonly proceeds on both sides of this agitated oolite-forming zone; on the low (fondo) side because sediments are below wave base and on the high (unda) side because the kinetic energy of waves and currents are dampened in the agitated zone (Heckel, 1972). Oolitic sand bodies generally form discontinuous to continuous trends roughly parallel to the high-energy zone, whose position is determined by the position of the undaform-edge, that is the break in slope (Ball, 1967).

Mud-supported carbonate fabrics indicative of low-energy deposition characterize about 95% of the lower San Andres Formation in the study area. Of the remaining 5%, oolitic, grain-supported fabrics indicative of high-energy deposition are only found in the easternmost sections in the study area, where they form 20% of the Bluewater and Canning Ranch sections, are common about 5 miles southeast of Bluewater, and are abundant in the upper Yeso Formation at Sunset. They are reported from the upper carbonate tongue at Sunset by Kelley (1971), although such were not found by the author. Emergent tidal flat carbonate facies present in all sections except Fox Cave and Walker Ranch suggest that the study area would have to be on the high (unda) rather than the low (fondo) side of the clinoform. The presence of abundant mud-supported rock units interbedded with the oolitic units and the association of decreased water restriction and more open marine conditions at most measured sections (Plates IX and X) with the appearance of oolitic rock units at Bluewater and Canning Ranch may reasonably be interpreted as follows: 1) mud-supported sediments were deposited at Bluewater and Canning Ranch, while grain-supported sediments were deposited along an undaform-edge east of the study area during much of lower San Andres time, and 2) the undaform-edge environment migrated westward to deposit oolitic sediments at Bluewater and Canning Ranch during relatively limited periods of lower San Andres time in response to relative rises in sea level that were not large enough to place the entire study area below wave base in the fondo environment.

Extrapolation northwestward of the linear trend of sections with oolites (Bluewater and Canning Ranch) would mean that the Bogle Dome and Walker Ranch sections were deposited on the low (fondo) side of the undaform-edge. However, the correlation of carbonate depositional facies (Plate IX) suggests that Bogle Dome and Walker Ranch were deposited on the undaform. Hence, we may deduce that if an undaform-edge trend continues northward, then it would have to swing to the northeast from Canning Ranch forming an embayment. Figure 23 illustrates the undaform-edge trend inferred from the distribution of the carbonate depositional facies of this study.

Eastern Edge of the Pedernal Positive Element

Introduction

The trend of the eastern edge of the Pedernal positive element (figure 22; after Hills, 1967) and the thickness trends of the lower, middle, and upper Glorieta tongues may be independent evidences for the existence of an undaform-edge. However, they are grouped together in this section because Hills (1967) does not indicate whether the trend and position of the eastern edge of the Pedernal is based on isopach data, in which case these evidences would not be independent.

Trend of the Eastern Edge of the Pedernal Positive Element

Figure 22 illustrates the trend of the eastern side of the Pedernal positive element during Early Permian time with respect to the position of Lincoln County and the measured sections of this study. This trend is subparallel to the trend of the undaform edge predicted from the distribution of carbonate depositional facies (figure 23). The parallelism of trends may be explained by the Pedernal having acted as a buried, yet relatively positive feature. Thus, the seas over the Pedernal high would have been shallower than to the east and west. During lower sea level stands, the sediment-water interface would likely be above wave base over most of the Pedernal and below wave base to the east and the west. This would result in an oolitic undaform-edge trend such as the one inferred to be present east of the study area.

Thickness Trends in the Three Glorieta Tongues

An isopach map (figure 24) illustrates the general thickening of the upper Glorieta tongue west to east across the study area. The lower and middle Glorieta tongues thicken similarly across the study area (figure 8). However, only a relatively very thin basal sandstone is present in the lower 1,000 feet of the San Andres Formation in the subsurface approximately 24 miles due east of Bluewater (Amerada ST1-SR"A"; Meissner, 1972). It is very difficult to devise a model that accounts for the sandstone thickening and yet is compatible with the other observations made during this study without invoking an undaform-edge environment east of the study area.

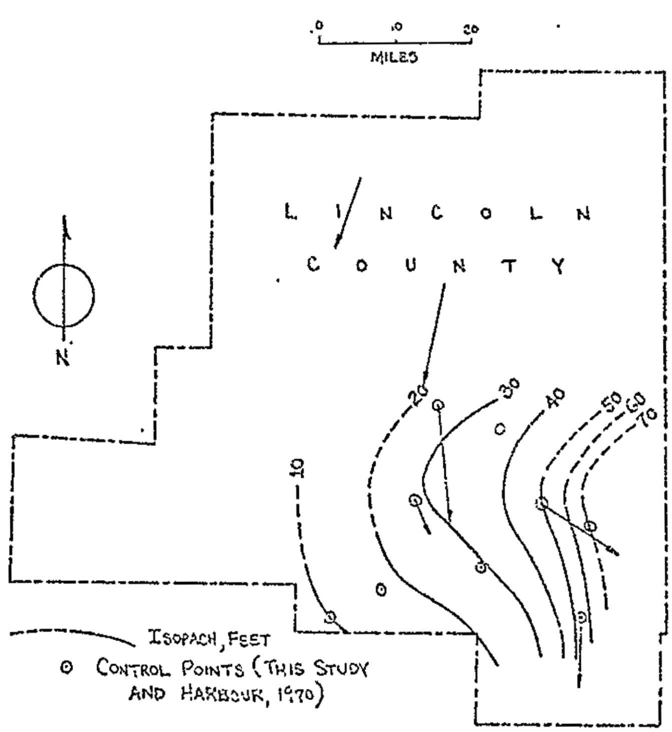


FIGURE 24 ISOPACH MAP AND CROSS-BED ORIENTATIONS, UPPER GLORIETA TONGUE, LOWER SAN ANDRES FORMATION

Paleocurrent Analysis of the Upper Glorieta Tongue

Analysis indicates that the paleocurrent directions inferred for the upper Glorieta tongue are sub-parallel to the undaform-edge trend inferred from the study of carbonate depositional facies (figure 23). This suggests that either the currents responsible for quartz sand transport and deposition were controlled by the trend of the undaform-edge or vice versa.

DEPOSITIONAL MODEL FOR LOWER SAN ANDRES TIME

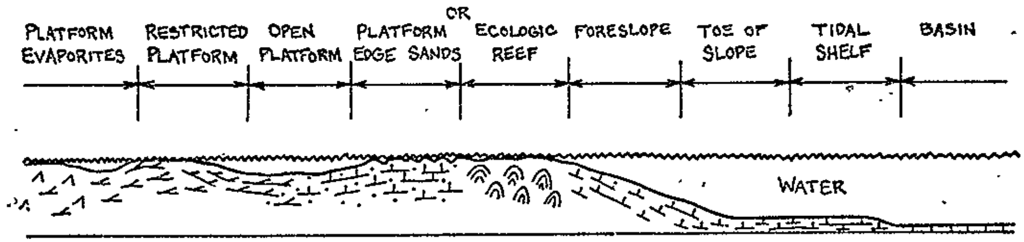
INTRODUCTION

Major objectives of this study are the examination of the facies mosaic of the lower San Andres Formation and its environmental interpretation. The depositional models proposed in this report are compatible with the observations made in the study area and with reasonable inferences based upon these observations. These models are also compatible with the gross lithologies of the lower San Andres Formation in western Lincoln and eastern Socorro Counties (after Harbour, 1970) and in western Chaves County (Meissner, 1972). However, it is recognized that subsequent detailed surface and subsurface study of the lower San Andres may provide prospectives that will invalidate aspects of these models.

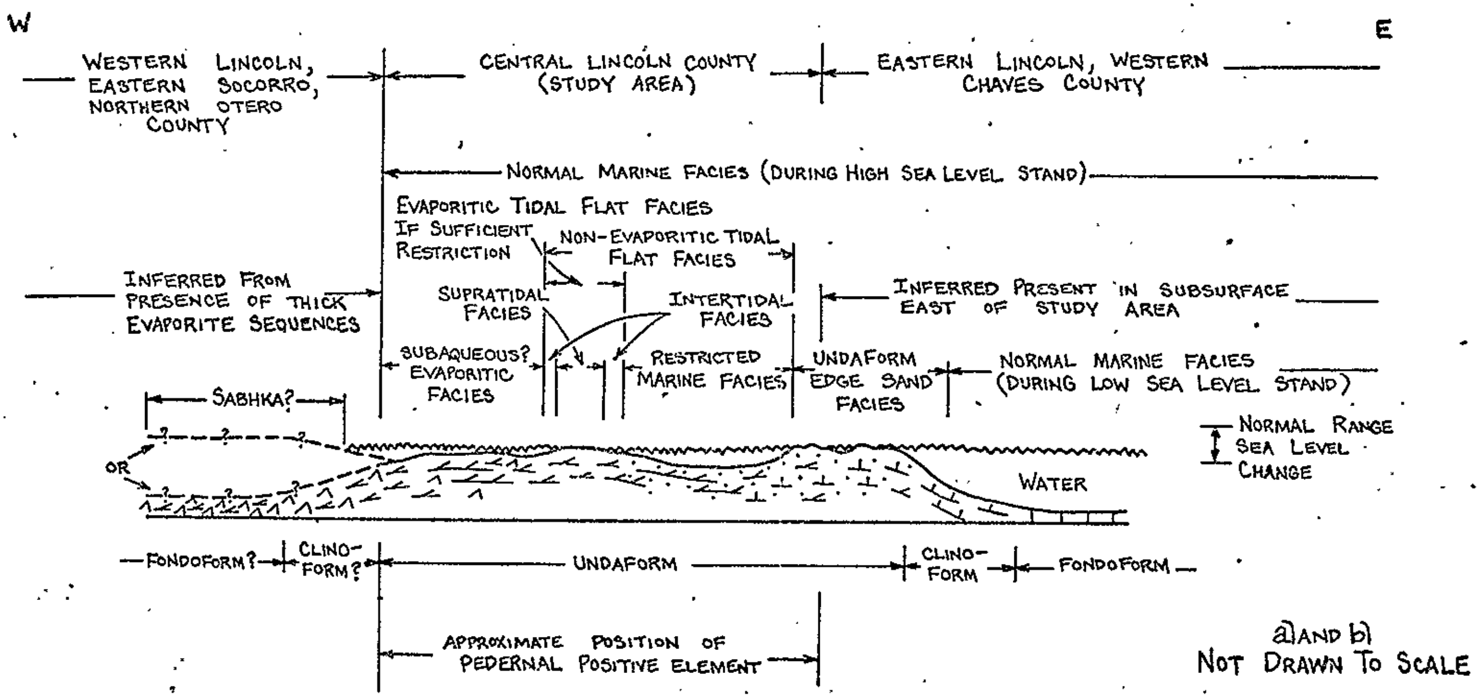
CARBONATE DEPOSITIONAL MODEL

Introduction

The cross-section of figure 25 illustrates both the idealized model of carbonate deposition of Wilson (1970) and the interpreted depositional model for lower San Andres Formation deposition in southern Lincoln County, that is south of Walker Ranch. Terrigenous sand deposition was predominant in the vicinity of Walker Ranch and north of it and is discussed separately in the next section. The interpreted carbonate model applies to deposition in an east-west direction through Lincoln County and into adjacent areas. The applicability of this model south of the study area is unknown.



a) Idealized Cross-Section of Environments of Carbonate Deposition (After Wilson, 1970)



b) Interpreted Carbonate Depositional Model for Lower San Andres Formation

Figure 25 Idealized and Interpreted Carbonate Depositional Models.

Carbonate sediments and terrigenous sand were apparently deposited in response to relative sea level fluctuations. Hence, deposition of the lower San Andres Formation is discussed below in terms of low, high, and intermediate sea level stands.

Low Sea Level Stands

Low sea level stands in early San Andres seas occurred as the result of sea level drops (marine or eustatic regression) or the accumulation of carbonate sediments towards "fill level" (sedimentary regression). The undaform-edge barriers inferred to be present to the east inhibited water circulation in the study area, resulting in restricted, low-energy environments. There was sufficient circulation to prevent the precipitation of bedded evaporites in the study area, suggesting that the undaform-edge barriers may have been somewhat discontinuous and/or that "freshening" waters from the north, west, and/or south regularly entered the study area. However, water levels were temporarily low enough to create sufficient restriction to form some emergent tidal flat and possibly even subaqueous diagenetic evaporite nodules and crystals. Most of the "regressive" portions of the seventeen "transgressive-regressive" cycles of this study were deposited during such low sea level stands.

The influx of terrigenous sand south of Walker Ranch to form the lower, middle, and upper Glorieta tongues is treated at length in the next section, however it appears to be related to low sea level stands in the study area. This relationship has also been noted in other Permian formations in the southwest of the United States (Ball *et al*, 1971; Meissner, 1972).

Undaform-edge carbonate units tens of feet thick are postulated to have been deposited in present day eastern Lincoln and western Chaves County during low sea level stands. Normal marine conditions are inferred to have been present on the low (fondo) side of the undaform-edge barriers, where water circulation should have been good at least in the vicinity of the undaform-edge. The "abrupt" appearance of normal marine fauna in the study area following major transgression is compatible with the inferred presence of normal marine conditions in the fondo environment east of the undaform-edge. And the absence of evaporites in the lower 1,000 feet of the San Andres Formation in western Chaves County (Amerada ST 1-SR "A", figure 1) proves that circulation was sufficient to prevent the precipitation of stratified evaporites in the fondo environment.

The lower San Andres Formation in western Lincoln, eastern Socorro, and northern Otero Counties is characterized by the presence of stratified evaporites tens of feet thick (e.g. Rinconada Canyon section of Harbour, 1970; figure 5 of this report). Such stratified evaporites are believed to form either by the sedimentation of evaporite minerals in restricted subtidal environments or diagenetically underneath evaporitic tidal flats (e.g. coastal sabkhas; Lucia, 1972). These lower San Andres evaporites occur directly west of the Pedernal positive element and hence are interpreted to have formed in a fondo environment there because of the evidence presented earlier that the Pedernal acted as a buried, yet relatively positive feature. This conclusion is consistent with the interpretation of a fondo environment east of the Pedernal and with the following observation. Deposition at Fox Cave, the most westward section in the study area, appears to have been deeper and less emergent than in the other sections, because Fox Cave is the only section, except for Walker Ranch, to lack any evidence of supratidal or intertidal carbonate deposition. This observation suggests at least an initial deepening of the lower San Andres seas westward across Lincoln County. However, a sabkha origin for these evaporites can not be completely discounted on the available evidence. Consequently, both possible origins are indicated in figure 25b.

High Sea Level Stands

After major marine transgressions, central Lincoln County was covered by enough water for normal marine conditions to predominate in the study area. The thin transgressive portions of "transgressive-regressive" cycles 7, 13, and 15 were deposited during these high sea level stands. Bathymetrically higher areas were the first to shoal as the result of subsequent marine (eustatic) or sedimentary regression. The undaform-edge barriers postulated present in eastern Lincoln and western Chaves Counties during low sea level stands may have been drowned by these major transgressions, resulting in both the former undaform and fondoform being below wave base. The carbonates interbedded with the stratified evaporites in western Lincoln and eastern Socorro Counties may have been deposited during this time as a result of the dilution of hypersaline brines by the transgression.

Intermediate Sea Level Stands

In central Lincoln County, following minor transgressions that lead to intermediate sea level stands, it appears that water circulation was sufficient to "freshen" restricted environments, but not enough for normal marine conditions to be anything but local. The transgressive portions of all "transgressive-regressive" cycles, except 1, 7, 13, and 15, were probably deposited during intermediate sea level stands. The oolitic rock units at Bluewater and Canning Ranch may be reasonably interpreted to have formed by the migration westward of the undaform-edge environment, which was present to the east during low sea level stands, in response to comparatively minor relative rises in sea level.

In western Lincoln and eastern Socorro Counties, the hypersaline brines formed during low sea level stands may have been diluted by these comparatively minor rises in relative sea level, resulting in either carbonate or evaporite deposits depending upon the amount of relative sea level rise and local conditions. However, no evidence is available to support this hypothesis or to rule out the possibility that relative sea level fluctuations in western or southern New Mexico were responsible for the evaporite and carbonate deposits present in western Lincoln and eastern Socorro Counties.

SANDSTONE DEPOSITIONAL MODEL

Regional Aspects of Glorieta Sandstone Deposition

A depositional model to explain the genesis of the Glorieta Sandstone in the study area must be compatible with the aerial distribution, cross-bed orientations, possible shorelines, paleowind directions, and other available data on the Glorieta Sandstone outside the study area. Figure 26 illustrates much of what is known of the Glorieta Sandstone in New Mexico. The southern limit of the Glorieta Sandstone in central New Mexico is placed at the approximate location at which the Glorieta begins to tongue southward as the lower San Andres Formation becomes dominantly carbonate (e.g. between the Walker Ranch and Bogle Dome sections in the study area). The Glorieta Sandstone, excluding its tongues, has a major east-west component and a major northeast-southwest component (Meissner, 1972). The northeast-southwest component includes the Glorieta Sandstone in the northern 1/3 of Lincoln County. This component extended southward to form the lower, middle, and upper Glorieta tongues of this study during periods of increased terrigenous sand influx.

Tanner (1963) postulated a northeast-southwest-trending Permian shoreline in northern New Mexico (figure 26) on the basis of the many assumed shoreline characteristics present: ripple marks, cross-bedding, bars and channels, fossils, beach rock, facies changes, gypsum, supposed halite prints, mud cracks, trails, pebble sizes, and rock thicknesses. Tanner

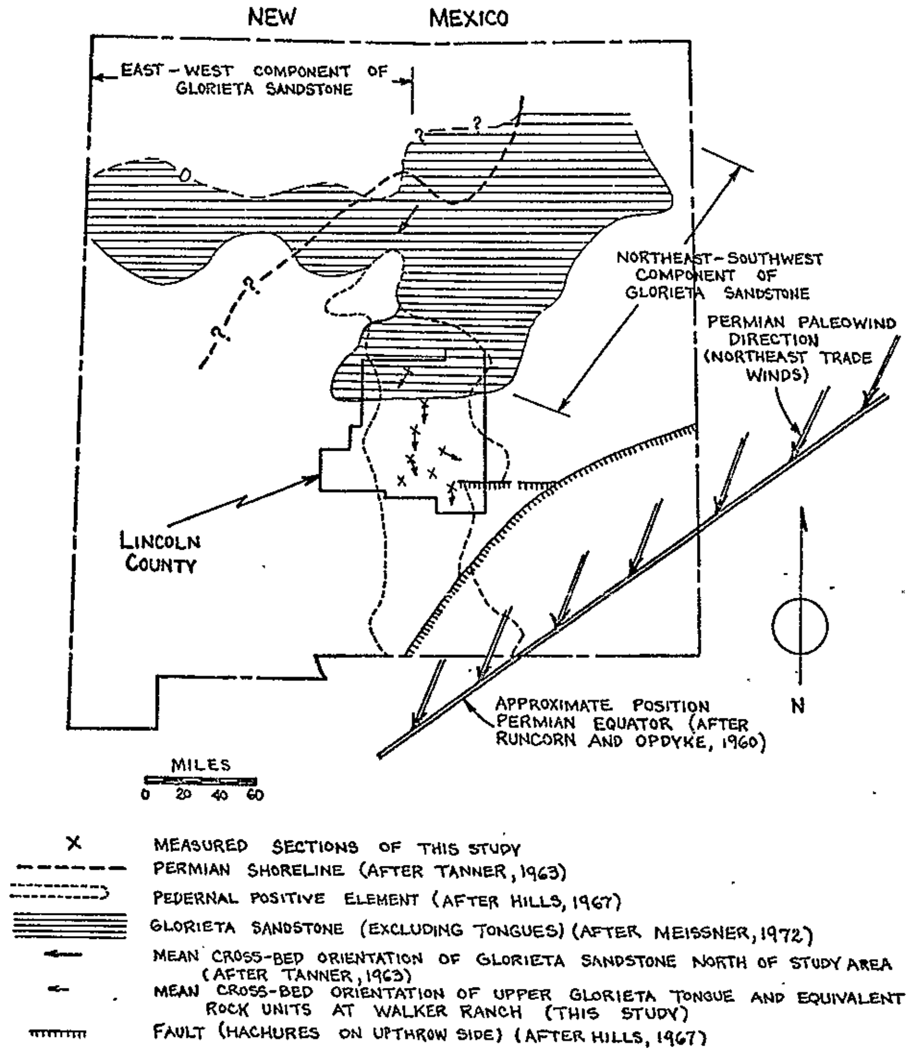


FIGURE 26 REGIONAL ASPECTS OF GLORIETA SANDSTONE DEPOSITION

does not consider the possible migration of this shoreline in time in response to relative sea level fluctuations. However, such migrations were probably not infrequent on a geological time scale. He interpreted the Glorieta Sandstone southeast of this shoreline (but north of the area of this study) to be an offshore sand. The Glorieta Sandstone studied by Tanner has many cross-beds, most of which are oriented dominantly to the southwest.

The paleowind direction during Permian time was probably from the northeast (figure 26). This direction is inferred on the basis of the position of the equator during Permian time as inferred from paleomagnetic data (after Runcorn and Opdyke, 1960, in Meissner, 1972) and idealized wind circulation paths on an earth without major land-masses (Leet and Judson, 1971). The inferred paleowind direction is sub-parallel to the northeast-southwest component of the Glorieta Sandstone and to the Permian shoreline of Tanner (1963). And it is oriented in the inferred mean paleocurrent direction of the Glorieta Sandstone as determined from cross-bed orientations in the area of this study and north of the study area (figure 26). These relationships suggest that paleowinds were the dominant means of transporting terrigenous sand into northern and central New Mexico. However, little evidence of aeolian deposition was noted in the Glorieta Sandstone in the study area or has been reported in the published literature.

Fewer criteria are available in the Glorieta Sandstone than in the associated carbonate member of the San Andres Formation for detailed environmental interpretation. Indeed, the directly associated carbonate rocks provide the most powerful tools for inferring the environments of deposition of the Glorieta terrigenous sands. The following discussion of Glorieta genesis is, therefore, necessarily hypothetical. It represents the author's attempt to provide the most comprehensive explanation of all evidence from carbonate as well as terrigenous rock units.

Marine Origin of the Glorieta Sandstone

Terrigenous sand influx is popularly related to low sea level stands (Ball *et al*, 1971), and Silver and Todd (1969) have postulated an aeolian dune origin for many of the Permian sandstones of southeastern New Mexico. Wind-driven processes, for the reasons enumerated in the preceeding section, must have been important in transporting the terrigenous sand of the Glorieta Sandstone into northern and central New Mexico. However, at least much of the Glorieta in the study area appears to have been deposited and/or reworked by marine processes for several reasons. These include the presence of: 1) shallow marine burrows in the upper Glorieta tongue at Bluewater and in the lower Glorieta tongue at Fort Stanton, 2) interbedded marine (subtidal) carbonates, 3) comparatively poorly sorted wavy bedded and massive rock units, which are imcompatible with the excellent sorting expected of aeolian processes, and 4) interpreted marine channel deposits in the middle Glorieta tongue at Sunset.

Carbonate rock units underlying the lower, middle, and upper Glorieta tongues in the study area suggest that at least much of the terrigenous sand in the Glorieta Sandstone was not originally deposited in aeolian dunes and then later reworked by marine processes. First, subtidal carbonate depositional facies underlie the three Glorieta tongues in almost all sections, and no evidence of subaerial sand scour is present in these subtidal facies. Second, a thin (2 feet), very silty sandstone at the base of the upper Glorieta tongue at Canning Ranch directly overlies an evaporitic tidal flat facies, which shows evidence of subaerial exposure (shrinkage cracks and dolomite pore-filling cement). The comparatively poor sorting of this thin sandstone is incompatible with aeolian processes, which should have winnowed out the fine terrigenous grains. Hence, evidence gathered in this study suggests that marine deposition rather than aeolian deposition and/or the marine reworking of aeolian dunes was responsible for the genesis of at least much of the Glorieta tongues in the study area. Evidence suggesting the marine origin of the Glorieta Sandstone at Walker Ranch, where terrigenous sand deposition was predominant during early San Andres time, is presented in the following section.

Depositional Model for the Glorieta Sandstone North of Bogle Dome

A detailed depositional model for the Glorieta Sandstone north of the Bogle Dome section is not possible because only one outcrop (Walker Ranch) was examined during this study.

However, a general model is proposed, which is compatible with many of the characteristics of the Glorieta Sandstone both inside and outside of the study area.

Analysis of carbonate depositional facies in the lower San Andres Formation suggests that about seventeen relative sea level fluctuations apparently influenced deposition in late Yeso and early San Andres seas. Evidence from trace fossils and carbonate depositional facies in the study area suggests that early San Andres seas were relatively shallow and that most deposition was subtidal. The combination of inferred relative sea level fluctuations and shallow marine depths during early San Andres time suggests that the cyclic repetition of lower-lower and upper-lower flow regime deposits in the Glorieta at Walker Ranch are related to repeated sea level fluctuations. This apparent control of terrigenous sand deposition by repeated sea level fluctuations suggests that at least much of the Glorieta at Walker Ranch was not originally deposited as aeolian dunes. This conclusion is compatible with the observation that almost half of the volume of sandstone at Walker Ranch consists of comparatively poorly sorted wavy bedded or massive rock units (Plate I). These comparatively poorly sorted rock units are incompatible with an aeolian origin for the following reason. The absence of almost all evidence of burrowing and the presence of abundant sedimentary structures suggest that post-depositional mixing of well sorted aeolian sands and marine silts or silty sands by burrowing organisms could not have been an important process in forming the comparatively poorly sorted sandstones at Walker Ranch. Tanner's (1963) interpretation of the Glorieta Sandstone north of the study area as an offshore sandstone is compatible with the interpretation that the Glorieta in the study area is predominately a marine sandstone which was probably occasionally built up above sea level as beaches and coastal dunes.

In summary, transportation of terrigenous sand into the study area was apparently controlled by wind-induced marine currents and possibly some aeolian transport of sand grains into the marine environment. Deposition of the Glorieta at Walker Ranch, except for some possible coastal dunes, appears to have been entirely sub-littoral to littoral.

Depositional Model for the Glorieta Sandstone South of Walker Ranch

Introduction

The Glorieta Sandstone south of Walker Ranch consists chiefly of the lower, middle, and upper Glorieta tongues of this study. These tongues appear to be southern extensions of the northeast-southwest component of the Glorieta Sandstone in New Mexico (figure 26). The influx of terrigenous sand south of Walker Ranch is closely associated with low sea level stands in the study area. A reasonable explanation for this association is that source areas to the north were more exposed following eustatic sea level drops, resulting in more sand detritus being available for transportation southward into the study area. It is inferred that dispersal of this sand within the study area was largely by marine processes, whereas aeolian dispersal must have been important to the north.

The lower, middle, and upper Glorieta tongues are characterized by a significant thickening eastward (figure 8) towards the inferred undaform-edge. A model termed the "oolite barrier" model in this report is compatible with all of the major observations made during this study. In this model, the influx of terrigenous sand from the north-northeast resulted in transport southward along the inside of pre-existing oolitic barriers. The wind-induced current regimes interpreted to be responsible for sand transport and for sand deposition were strongest near the oolitic barriers, and hence sandstone thickness decreases westward. Eastward the sand body would be expected to eventually pinch out against the oolitic barriers. The consistent thickening of sandstone tongues eastward in the study area requires that this pinching out take place east of the study area where the strata are not exposed. The "oolite barrier" model is compatible with the building up of terrigenous sand into topographically higher deposits, probably by wind-induced wave and current action. The lower and upper Glorieta tongues at Sunset and Bluewater appear to have acted as topographic highs following their deposition relative to the sections to the west. This is suggested by the subsequent carbonate deposits, which are generally shoaler at Sunset and Bluewater, and by the series of approximate time lines based on transgressive "kicks" which suggest this by their shapes below and above the lower and upper Glorieta tongues on Plates IX and X. The "oolite barrier" model is also compatible with the following observation. Abundant spheroidal, well rounded oolites with quartz sand nuclei are present in the dolomitic rock unit (2 feet thick) directly above the lower Glorieta tongue at Bluewater. This transition from quartz sand to carbonate oolites may be explained by the migration of the oolitic barriers inferred to be present east of the study area during low sea level stands westward in response to a rise in eustatic sea level that also resulted in the drowning of terrigenous sand source areas. The "oolite barrier" model is very similar to the one proposed by Ball _et al_ (1971) for the deposition of the

Shattuck Sandstone Member of the Queen Formation in the Guadalupe Mountains.

A model, which may be termed the "quartz sand barrier" model, was considered as an alternate way to explain the thickening of the lower, middle, and upper Glorieta tongues in the study area. In this model, the influx of quartz sand from the north-northeast is postulated to have overwhelmed oolite production at the undaform-edge so that quartz sand barriers would have replaced the oolitic ones. The model is based on the observation that "moving water reacts in the same fashion to a given topographic setting, regardless of the nature of the sedimentary particles upon which it acts" (Ball, 1967). Hence, once quartz sand arrived at the undaform-edge, it would be exposed to the same physical processes that produced oolite barriers prior to sand influx. The "quartz sand barrier" model is also able to explain many of the characteristics of the lower, middle, and upper Glorieta tongues. However, this model is rejected in this report because it does not take into consideration the effects of the pre-existing oolitic undaform-edge barriers, which are inferred to have controlled both carbonate and terrigenous sand deposition in early San Andres seas.

Lower Glorieta Tongue

The lower Glorieta tongue is generally characterized by the presence of silty sandstones, which are structureless except for local areas of wavy bedding. These features suggest low-energy lagoonal deposition for most of the lower Glorieta tongue. The subaqueous origin of the lower Glorieta tongue is also indicated by the presence of shallow marine burrows at Fort Stanton and localized soft sediment deformation at Sunset.

The lower Glorieta tongue at Sunset and Bluewater is more than twice as thick as to the northwest and west. At Sunset, the lower part of the lower Glorieta tongue is typically silty and massive, but the upper part is very well sorted and medium scale cross-stratification is overlain by even, planar stratification. The sedimentary structures and sorting indicate a consistent increase in flow regime energy during deposition. This energy variation is compatible with the following interpretation. The lower part of the lower Glorieta tongue represents low-energy lagoonal deposition behind inherited oolitic barriers, whereas the upper part may be explained as follows. Depositional processes characterized by comparatively higher flow regime energies were probably dominant near the oolitic barriers inferred to have been present to the east, whereas comparatively lower flow regime energies were probably dominant farther away from the barriers. A eustatic sea level rise, which would have ended terrigenous sand influx into Lincoln County south of Walker Ranch by partially drowning source areas, might have caused the oolitic barriers of the undaform-edge and the associated higher flow regime energies near them to migrate westward. This migration would have resulted in the deposition of relatively higher flow regime deposits over relatively lower flow regime deposits. Such a migration would also explain the transition from quartz sand to carbonate oolites at Bluewater, as discussed in the preceeding section.

The lower Glorieta tongue does not extend westward to Fox Cave. This suggests a western limit of sand influx beyond which there were not enough quartz grains arriving to overwhelm carbonate production.

Middle Glorieta Tongue

The middle Glorieta tongue is generally thin (3 to 12 feet) and poorly exposed. The thickest, best exposed, and environmentally most diagnostic unit is present at Sunset. In regions where tidal or wave action is very intense, tidal sand bars or flats may be formed, with individual bars separated by a network of large tidal channels (Blatt _et al_, 1972). The middle Glorieta tongue at Sunset can best be interpreted as having been deposited in such a channel, rather than as a bar with topographic relief because: 1) a scoured lower contact with about one foot of relief is present, 2) overlying carbonate depositional facies do not suggest deposition on a topographic high, and 3) the middle Glorieta tongue rests directly on normal marine carbonate deposits, whereas at all other sections, it rests on more restricted carbonate facies, suggesting that the restricted carbonate facies has been cut out. The sides of the interpreted channel were not noted in a 250 feet traverse across the outcrop. Hence, very little is known about the possible dimensions of this channel. There is a bipolar distribution of cross-bed orientations (figure 17B); northward is dominant, but a strong southern component is present (figure 19). Bipolar paleocurrent orientations are a common characteristic of channel deposition influenced by tidal currents

(Blatt et al, 1972). This observation suggests the influence of tidal currents during the deposition of the middle Glorieta tongue at Sunset.

Upper Glorieta Tongue

The upper Glorieta tongue is present throughout the study area as a thin blanket sand. It thickens eastward across the study area (figure 8). The upper Glorieta tongue at Sunset and Bluewater is about twice as thick (about 50 feet) as at Hondo, Fort Stanton, Fox Cave, and Canning Ranch. Subsequent carbonate deposits tended to be "shoaler" at these two sections, suggesting the influence of inherited depositional relief. This relief is also suggested by the shapes of the approximate time lines on Plates IX and X.

The upper Glorieta tongue at Sunset, Hondo, Fort Stanton, and Bogle Dome reflects a decrease in flow regime upwards in the units. At Bluewater and Canning Ranch, an upward increase in flow regime is apparent. The lower-lower flow regime deposits towards the bottom of the upper Glorieta tongue at Bluewater and Canning Ranch probably represent lower energy lagoonal deposition behind pre-existing oolitic barriers. The upper Glorieta tongue at the other sections and above the lower-lower flow regime deposits at Bluewater and Canning Ranch consists entirely of upper-lower and lower-upper flow regime deposits. Hence, relatively little evidence of lower energy lagoonal deposition is present in the upper Glorieta tongue. The position of the Bluewater and Canning Ranch sections along the northwest-southeast segment of the inferred undaform-edge trend (figure 23) coupled with a paleowind direction dominantly towards the southwest suggests the following interpretation. The Bluewater and Canning Ranch sections may have been protected from wind-induced waves and currents by the oolitic barriers of the undaform-edge resulting in lower energy lagoonal deposition initially, whereas the other sections appear to have been unprotected from the effects of wind-induced waves and currents, resulting in comparatively higher energy deposits. The upper parts of the upper Glorieta tongue at Bluewater and Canning Ranch also consist of comparatively higher energy deposits suggesting that the pre-existing oolitic barriers no longer effectively blocked the formation of wind-induced waves and currents.

CONCLUSIONS

The following conclusions are based on detailed study of the lower San Andres Formation of central New Mexico.

1) Subtidal carbonate depositional facies make up about 95% of the carbonate member, whereas supratidal and intertidal facies only about 5%.

2) Evaporite minerals were not noted in the lower San Andres Formation in the study area, although they are present in the upper Yeso Formation. However, evaporite molds in the lower San Andres Formation indicate the former presence of diagenetic evaporites. Little evidence was observed of an emergent tidal flat or sabkha origin for most of the former evaporites.

3) The carbonate depositional facies of this report permit detailed correlation throughout the study area. The normal marine facies is commonly very persistent and is thus probably useful for correlation of the lower San Andres Formation outside the study area.

4) Seventeen "transgressive-regressive" cycles were noted in the lower San Andres Formation. Only three cycles are demonstrably due to absolute sea level fluctuations. The "regressive" deposits of these cycles are relatively much thicker than the "transgressive" deposits. The cycles permit detailed correlation throughout the study area independently of the the continuity of individual carbonate depositional facies. Most of these cycles should be present in the lower San Andres outside the study area. The Glorieta Sandstone

at Walker Ranch has been correlated to the carbonate member by the use of these cycles.

5) Sedimentation in the lower San Andres Formation in the study area appears to have been controlled by the Pedernal positive element, which acted as a buried, yet positive feature.

6) Most of the lower San Andres in the study area was apparently deposited on an undaform behind undaform-edge barriers that were present east of the study area in eastern Lincoln and western Chaves Counties during low sea level stands.

7) The majority of the lower San Andres carbonate member was deposited in low energy tidal flat and shallow lagoonal environments behind the oolitic barriers of the undaform-edge.

8) The Glorieta Sandstone does not have any convincing aeolian or deltaic characteristics within the study area. Its genesis must be inferred largely from the associated carbonate depositional facies. At least much of the Glorieta in the study area was probably deposited in relatively shallow marine environments.

9) The terrigenous sands of the lower, middle, and upper Glorieta tongues appear to have been transported southward across the study area along the inside of pre-existing oolitic barriers of the undaform-edge environment during low sea level stands. The terrigenous sands in northern Lincoln County may also have been transported along the inside of pre-existing oolitic barriers. However, no independent evidence is available to support this hypothesis.

APPENDIX I

LOCATION OF MEASURED SECTIONS

Figure 27 illustrates the location of the eight sections measured during this study on portions of the General Highway Map of Lincoln County, New Mexico.

Walker Ranch (NE$\frac{1}{4}$, section 17, T.2S., R.13E.)

The section was measured about $\frac{1}{2}$ mile northeast of the dirt road between Gallinas and Walker Ranch headquarters about 3.3 miles east of Gallinas.

Bogle Dome (Outcrop A: E $\frac{1}{2}$, section 19, T.4S., R.15E. and outcrop B: SW $\frac{1}{4}$, section 20, T.4S., R.15E.)

Three outcrops were initially measured to form a composite section. The outcrops are located along a dirt ranch road, which appears as a stream bed on area maps. This dirt road intersects a heavy duty dirt road in section 19. The lower part of the composite section (outcrop A) was measured about .8 miles from this intersection, the middle part about .75 miles from the lower, and the upper part (outcrop B) about .2 miles from the middle. Subsequent analysis of carbonate depositional facies indicated that the outcrop between outcrops A and B (figure 27) was a repetition of facies already measured at outcrop A and hence, it was not included in the final graphic section of this report.

Canning (Block) Ranch (Outcrop A: SW$\frac{1}{4}$, section 6, T.7S., R.16E. and outcrop B: NW$\frac{1}{4}$, section 1, T.7S., R.15E.)

The lower Glorieta tongue and the lower five feet of the lower carbonate tongue were measured in outcrop A about one

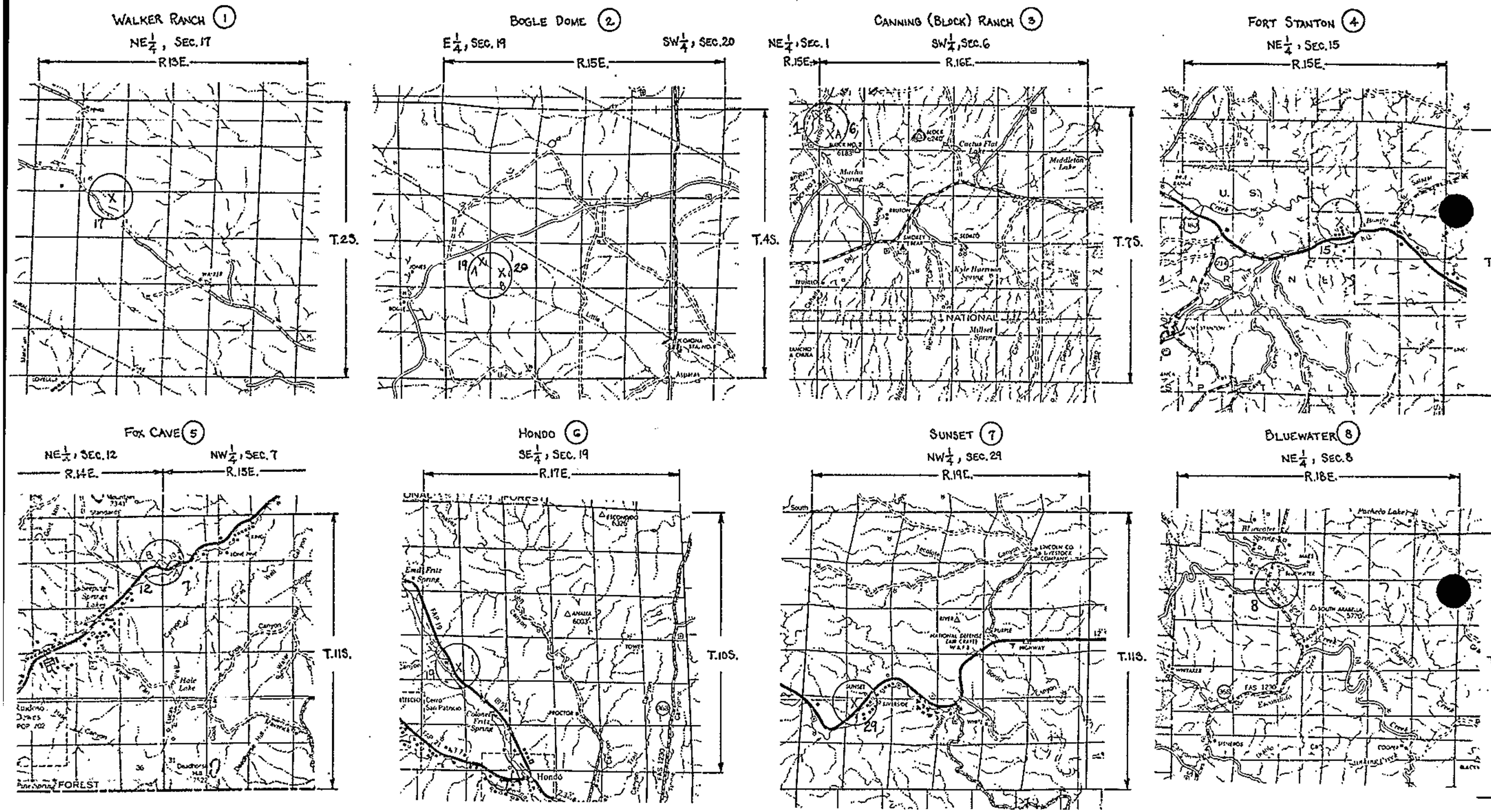


FIGURE 27 LOCATION OF MEASURED SECTIONS, LOWER SAN ANDRES FORMATION, LINCOLN COUNTY, NEW MEXICO. FROM GENERAL HIGHWAY MAP, LINCOLN COUNTY, NEW MEXICO, 1969. MAP AVAILABLE FROM STATE HIGHWAY ENGINEER, NEW MEXICO STATE HIGHWAY DEPARTMENT.

mile north of the Canning Ranch headquarters (called Block No. 2 on the map in figure 27) near the top of the east peak of the two prominent peaks in the area. The ranch headquarters is located along a dirt road about two miles north of the intersection of this dirt road and New Mexico Highway 48. The dirt road intersects highway 48 about 3.1 miles east of a cluster of buildings called Encinoso on area maps. The lower carbonate tongue forms a well exposed resistant outcrop, but the underlying lower Glorieta tongue is very poorly exposed and only the lithology can be determined.

The remainder of the section was measured in outcrop B, which is about 1.5 miles north of the ranch headquarters and about 250 yards east of the dirt road leading northward from the ranch headquarters.

Fort Stanton (NE$\frac{1}{4}$, section 15, T.9S., R.15E.)

The section was measured on the north side of U.S. Highway 380 about 7.7 miles east of the town of Capitan.

Fox Cave (Outcrop A: NW$\frac{1}{4}$, section 7, T.11S., R.15E. and outcrop B: NE$\frac{1}{4}$, section 12, T.11S., R.14E.)

The section below the upper Glorieta tongue was measured in outcrop A on the north side of U.S. Highway 70 about .25 miles west of the entrance to Fox Cave. The remainder of the section was measured in outcrop B, a gully, on the north side of U.S. Highway 70 about .7 miles west of the entrance to Fox Cave.

Hondo (SE$\frac{1}{4}$, section 19, T.10S., R.17E.)

The section was measured on the northeast side of U.S. Highway 380 about 3.6 miles northwest of the intersection of U.S. Highways 380 and 70.

Sunset (NW$\frac{1}{4}$, section 29, T.11S., R.19E.)

The section was measured on the north side of U.S. Highway 70/380 about 2.1 miles west of a cluster of buildings called Riverside on area maps.

Bluewater (NE$\frac{1}{4}$, section 8, T.9S., R.18E.)

The section was measured on the east side of New Mexico Highway 368 about .15 miles north of the intersection of Highway 368 with a dirt road that leads westward.

APPENDIX II

INTERPRETATION OF PLATES I TO VIII

INTRODUCTION

Figure 28 illustrates the heading used in Plates I to VIII. The sedimentary parameters listed in the heading are discussed in the text of this report. Most sedimentary parameters are described graphically in two general ways: 1) presence or absence (b,e, and g of figure 28), and 2) relative abundance or degree of development (i.e. well-developed versus obscure; c, d, f, and h of figure 28). The indication of presence or absence is discussed for each parameter in the next section.

Relative abundance is described qualitatively as rare, rare to common, and common to abundant. Figure 29 illustrates how these terms are represented on Plates I to VIII for fauna,

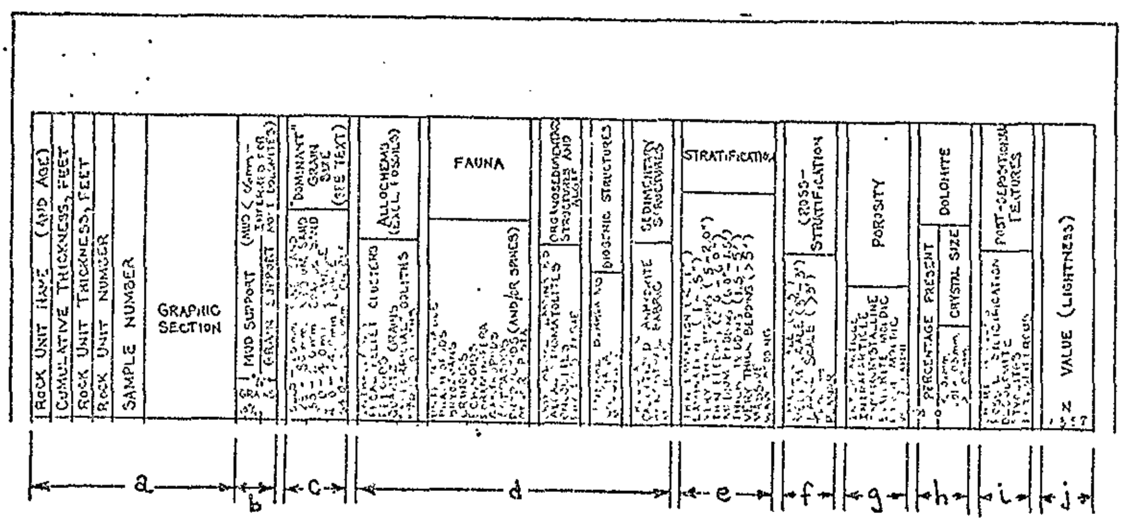


FIGURE 28 HEADING USED IN PLATES I TO VIII (LETTERS a THROUGH j USED IN TEXT TO REFER TO PARTS OF HEADING)

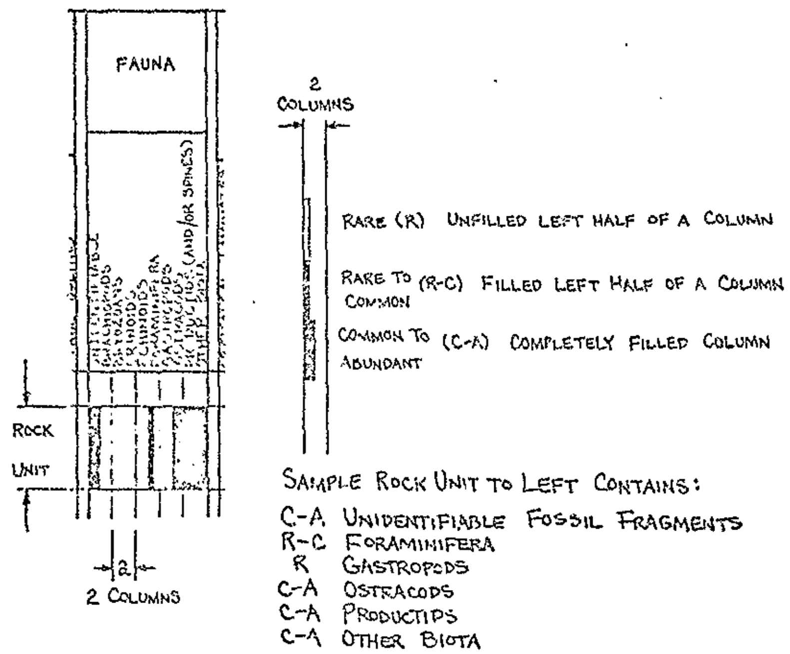


FIGURE 29 ILLUSTRATION OF HOW TO INTERPRET RELATIVE ABUNDANCES OF SEDIMENTARY PARAMETERS FROM PLATES I TO VIII USING FAUNA AS AN EXAMPLE (ALSO VALID FOR ALLOCHEMS, ORGANO-SEDIMENTARY STRUCTURES, BIOGENIC STRUCTURES, SEDIMENTARY STRUCTURES, POROSITY, AND POST-DEPOSITIONAL FEATURES)

for example. Thin, vertical lines separate the faunal types into groups of two, each group consisting of two "columns" (e.g. group "a" in figure 29 consists of a bryozoan "column" and a crinoid "column"). Rare occurrences are noted by a thin line along the center of a column and no filling in of the left-hand half of the column (e.g. gastropods in figure 29). Rare to common occurrences are noted similarly to rare occurrences, except that the left-hand half of the column is filled in (e.g. Foraminifera in figure 29). Common to abundant occurrences are noted by completely filling in an entire column (e.g. unidentifiable fossil fragments, ostracodes, etc.). A detached heading, Plate XI, is included with Plates I to VIII. It may be moved along each plate to aid in interpreting relative abundances.

HEADING OF PLATES I to VIII

The constituent parts of the heading used in Plates I to VIII (figure 28) are discussed below:

a The symbols used in the graphic sections of Plates I to VIII are illustrated in figure 30.

b Rock classification is after Dunham, 1962.

c "Dominant" grain size refers to the size of grains which are as large as or larger than 90% of the grains present in the rock unit. It is described using the Wentworth (1922) size scale. The "dominant" grain size is indicated by a completely filled column.

d Relative abundances may be determined using the introductory information and figure 29.

e Figure 31 illustrates the interpretation of stratification thickness. A completely filled column indicates well-developed to obscure bedding planes. A filled left half of a column indicates bedding planes are very obscure, if only one stratification thickness is present (e.g. very thin bedding). However, two stratification thicknesses in the same rock unit (e.g. very thin

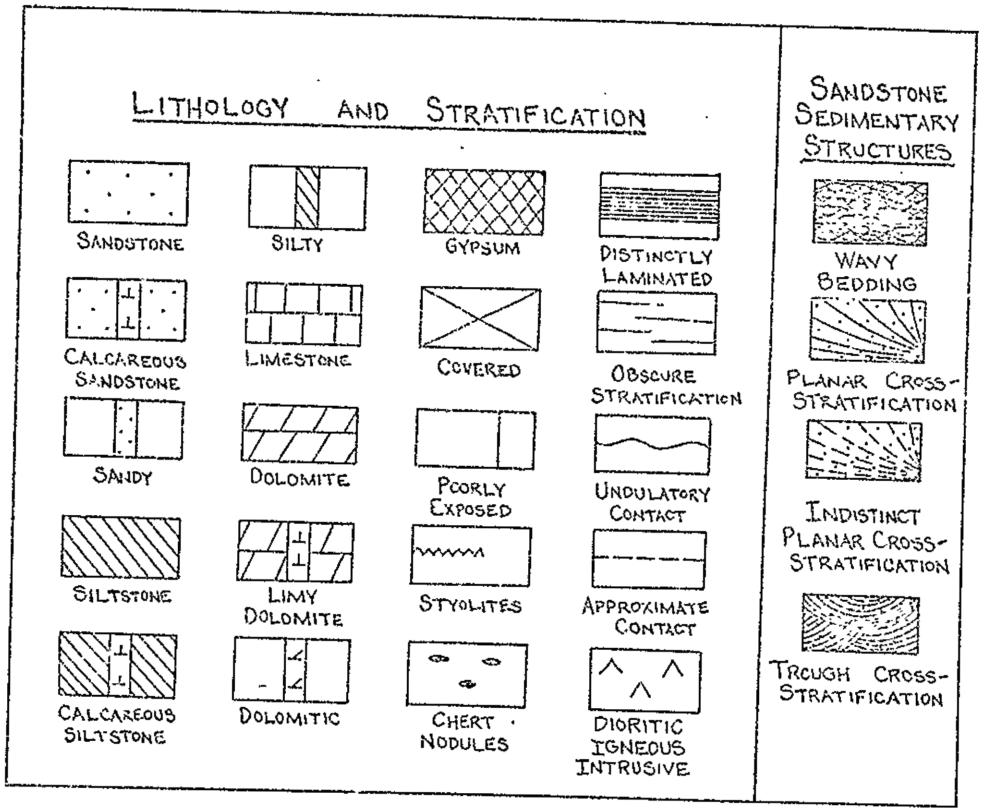


Figure 30 Symbols used in graphic sections on Plates I to VIII.

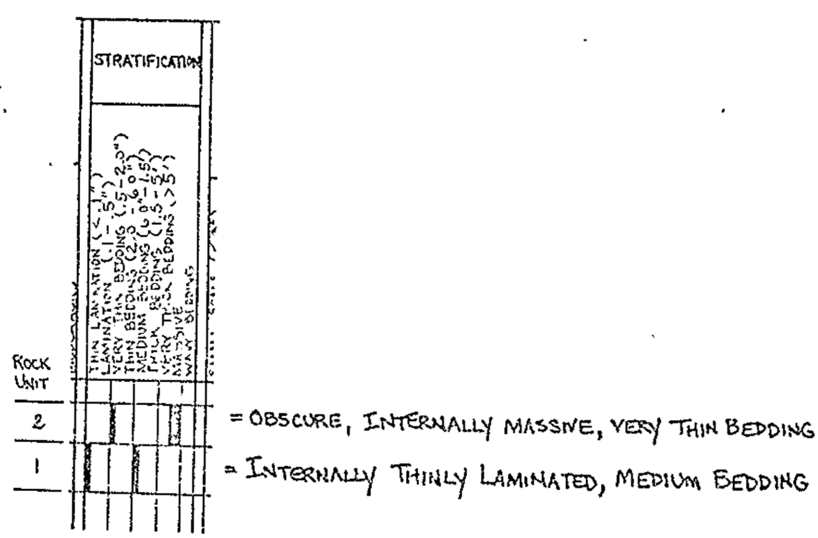


FIGURE 31 ILLUSTRATION OF HOW TO INTERPRET STRATIFICATION IN ROCK UNITS FROM PLATES I TO VIII

bedding and internal lamination) are indicated by the left half of the appropriate columns being filled.

The term massive refers to the absence of internal lamination. It is indicated by a completely filled column. The term wavy bedding is only used to describe sandstones in this report. A completely filled column indicates well-developed wavy bedding, whereas a filled left half of a column indicates obscure wavy bedding.

f   Cross-stratification scale (small, medium, and large): A completely filled column indicates well-developed cross-stratification, whereas a filled left half of a column indicates obscure cross-stratification. Cross-stratification type (planar and trough): A completely filled column indicates the type of cross-stratification present.

g   Relative abundances may be determined using the introductory information and figure 29.

h   The percentage of dolomite present is self-explanatory. The dominant dolomite crystal size is indicated by a completely filled column.

i   Relative abundances may be determined using the introductory information and figure 29.

j   The value (i.e. lightness) of the carbonate rock units has been noted after Goddard et al (1970).

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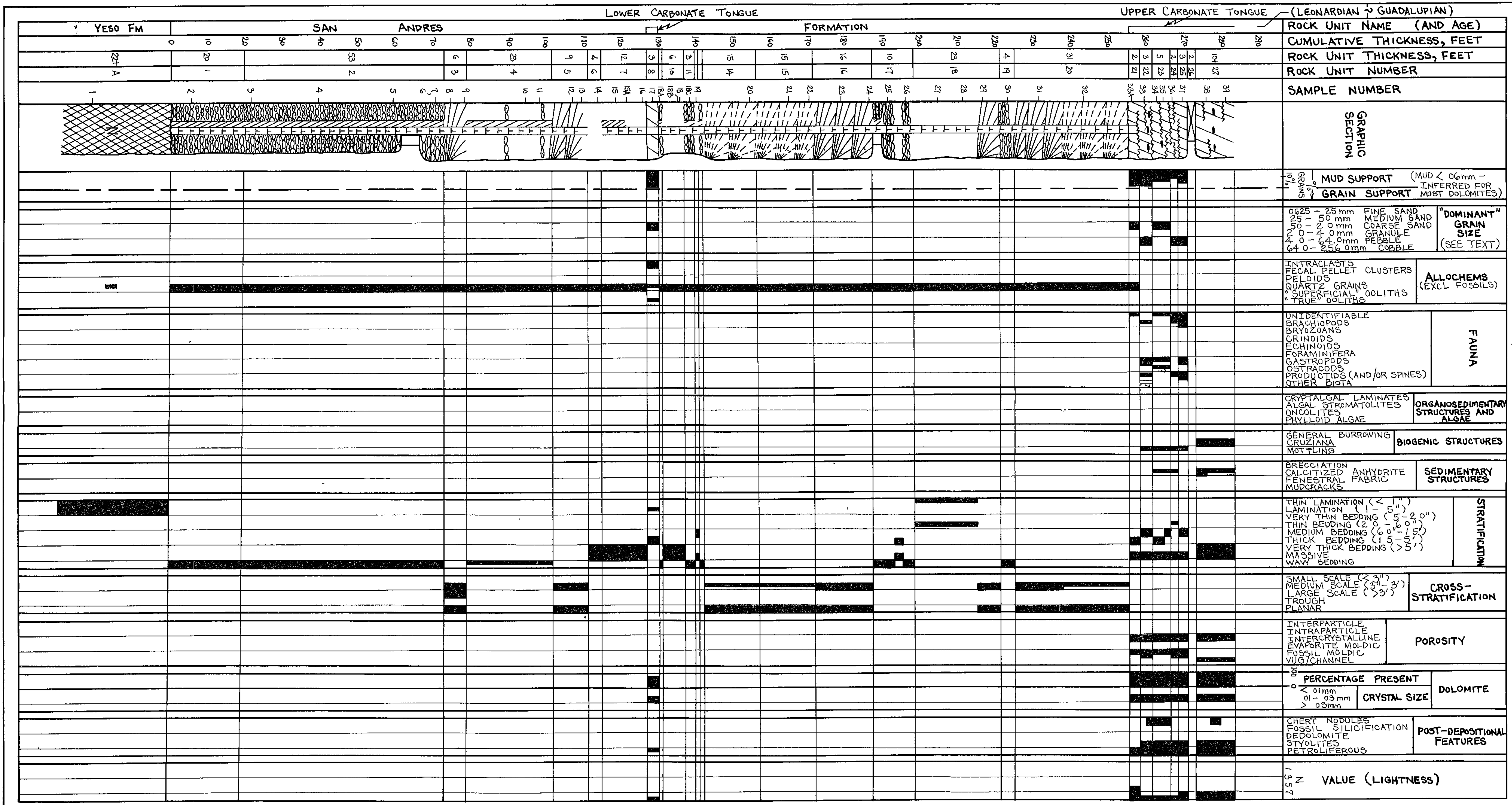
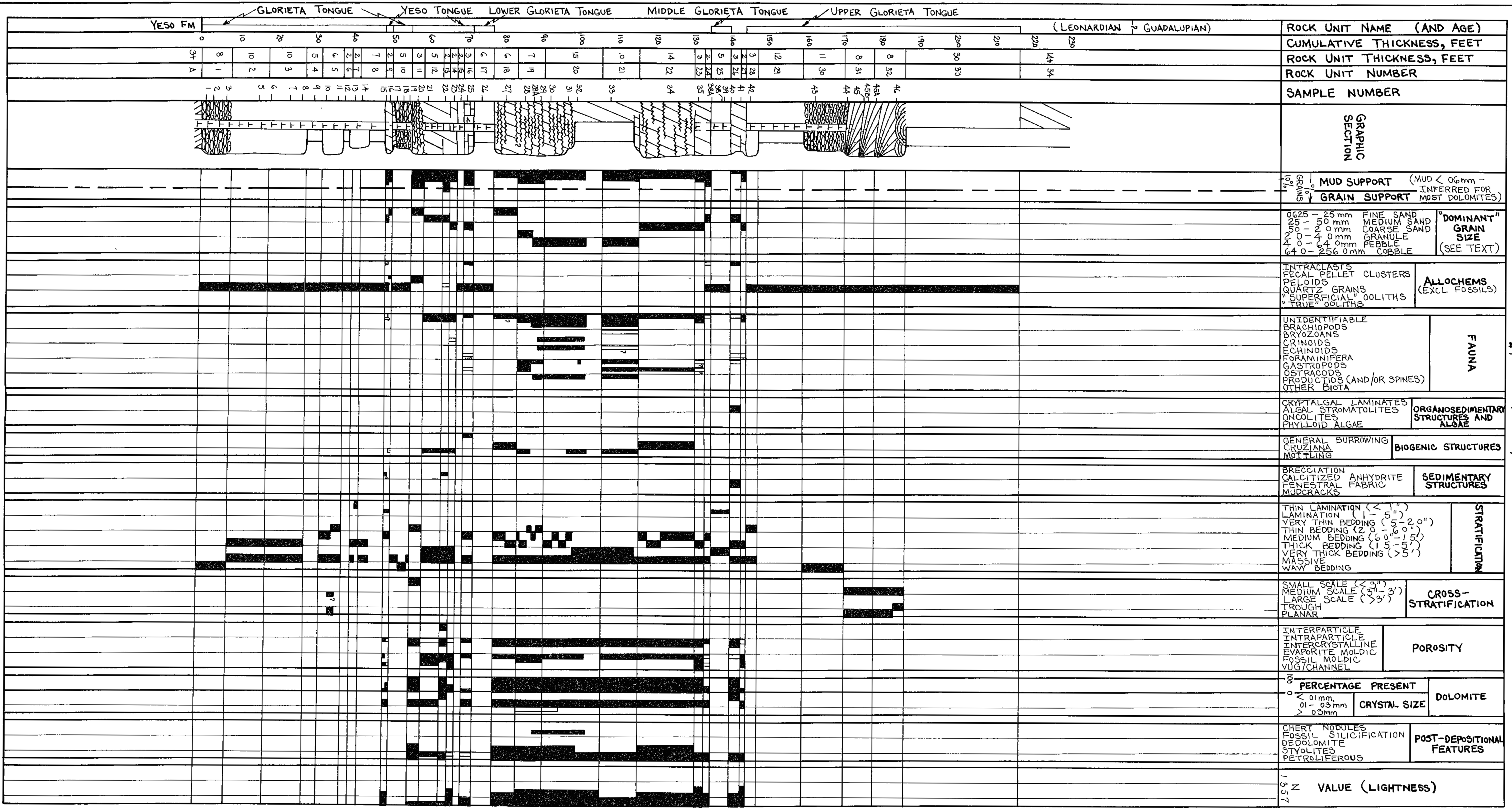


① WALKER RANCH
NE $\frac{1}{4}$, SEC 17, T 2S, R 13E

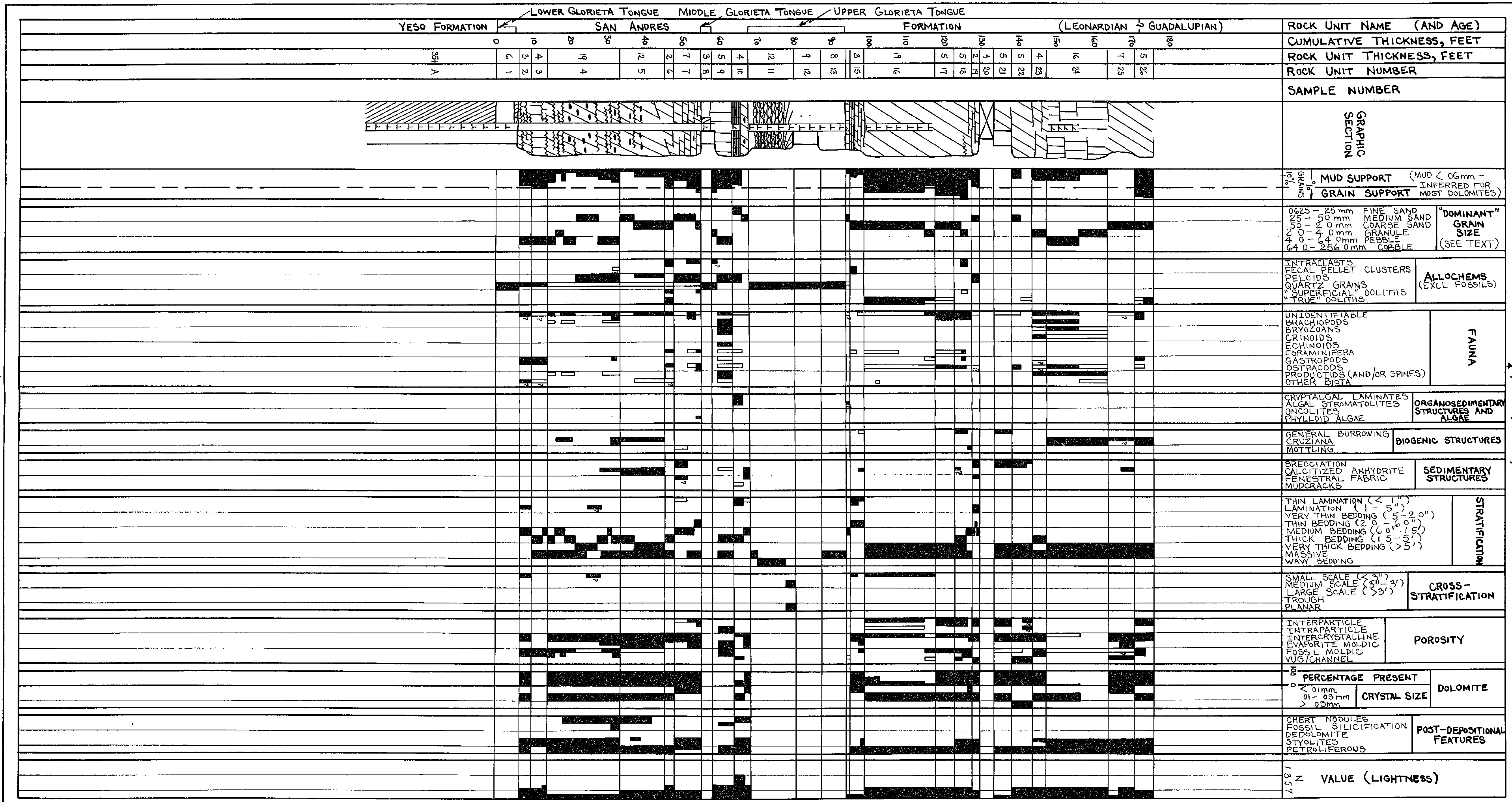
PLATE I



② BOGLE DOME

E½, SEC 19, T 4S, R 15E
SW¼, SEC 20, T 4S, R 15E

PLATE II

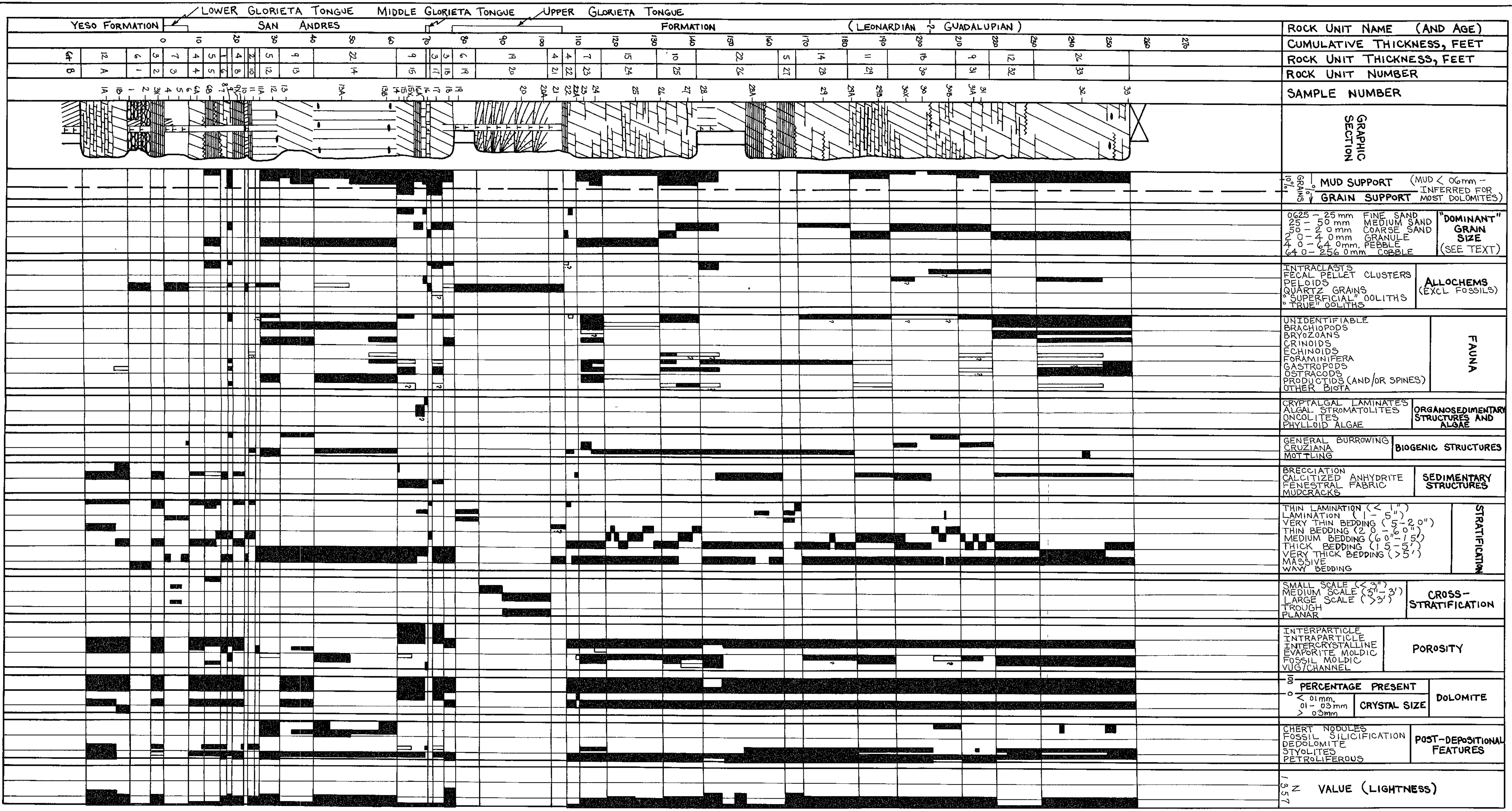


③ CANNING (BLOCK) RANCH

SW 1/4, SEC 6, T 7S, R.16E

NE 1/4, SEC 1, T 7S, R 15E

PLATE III



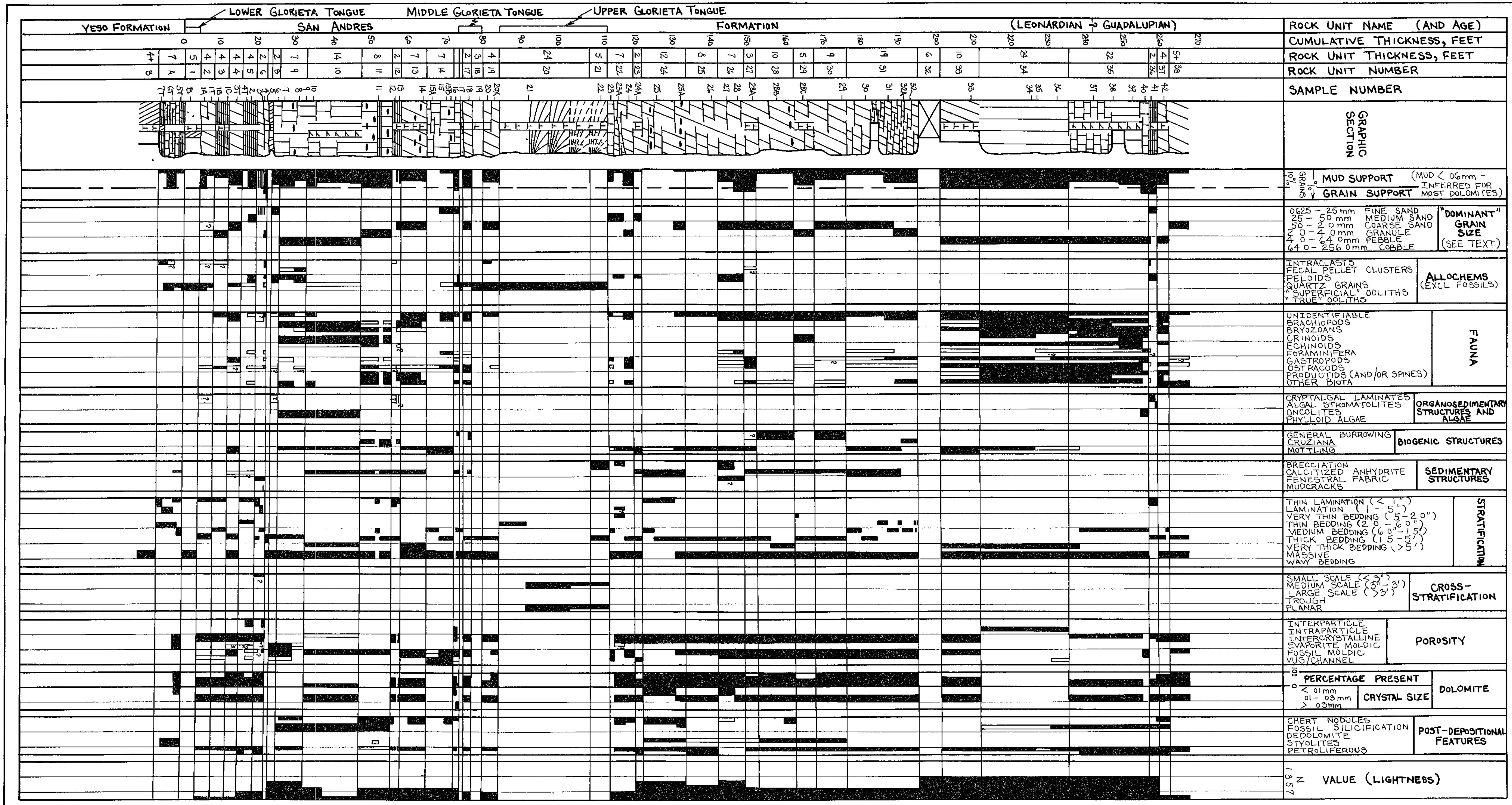
④ FORT STANTON

NE 1/4, SEC 15, T 9 S, R 15 E

PLATE IV

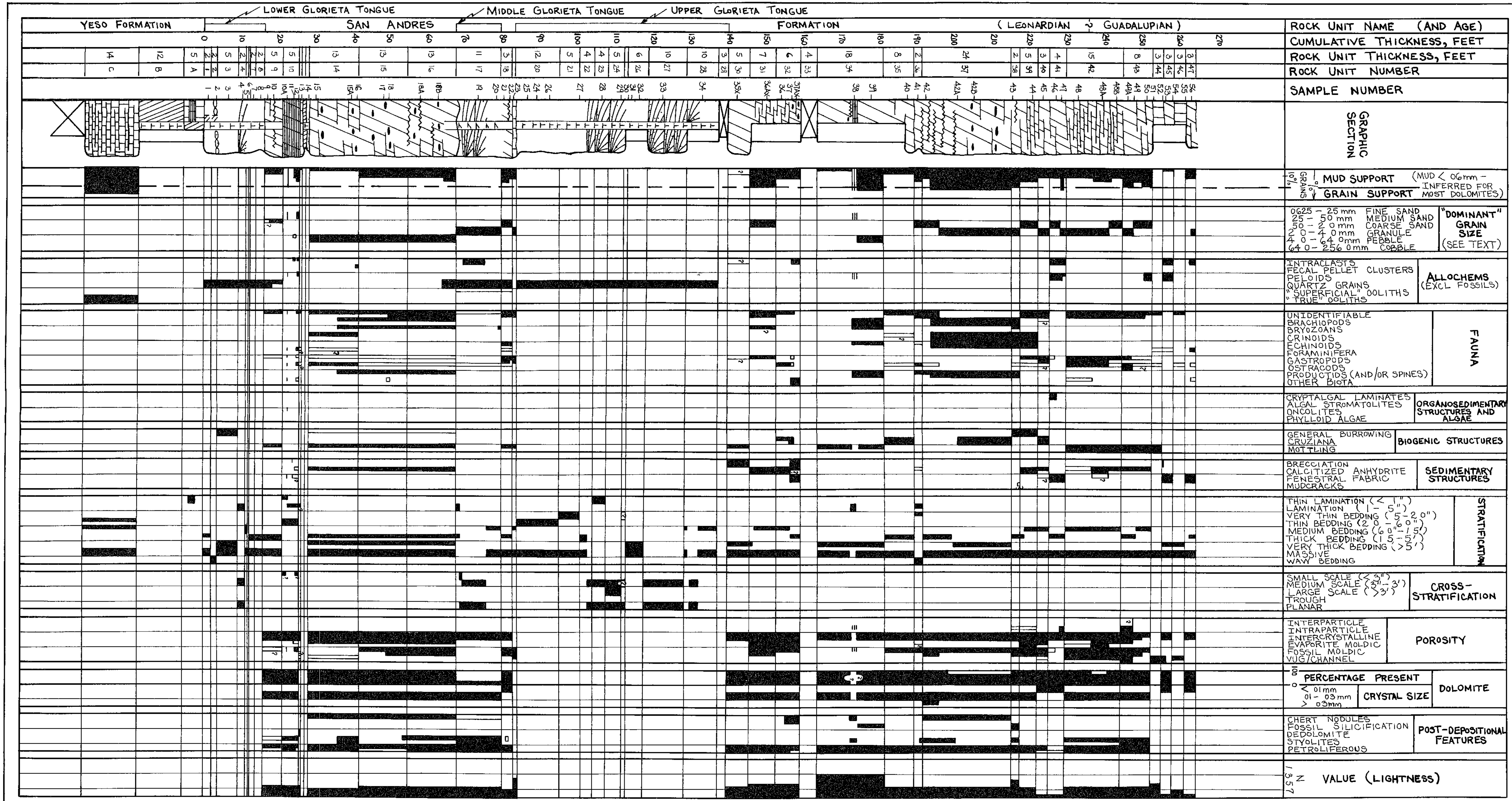
(5)
Fox Cave
NW 1/4, SEC 7, T 11S, R 15E
NE 1/4, SEC 12, T 11S, R 14E

PLATE V



⑥ HONDO
SE 1/4, SEC 19, T10S., R 17E

PLATE VI



⑦ SUNSET
NW¼, SEC 29, T 11 S, R 19 E

PLATE VII

(8) BLUEWATER
NE 1/4, SEC. 8, T.9S., R.18E.

PLATE VIII

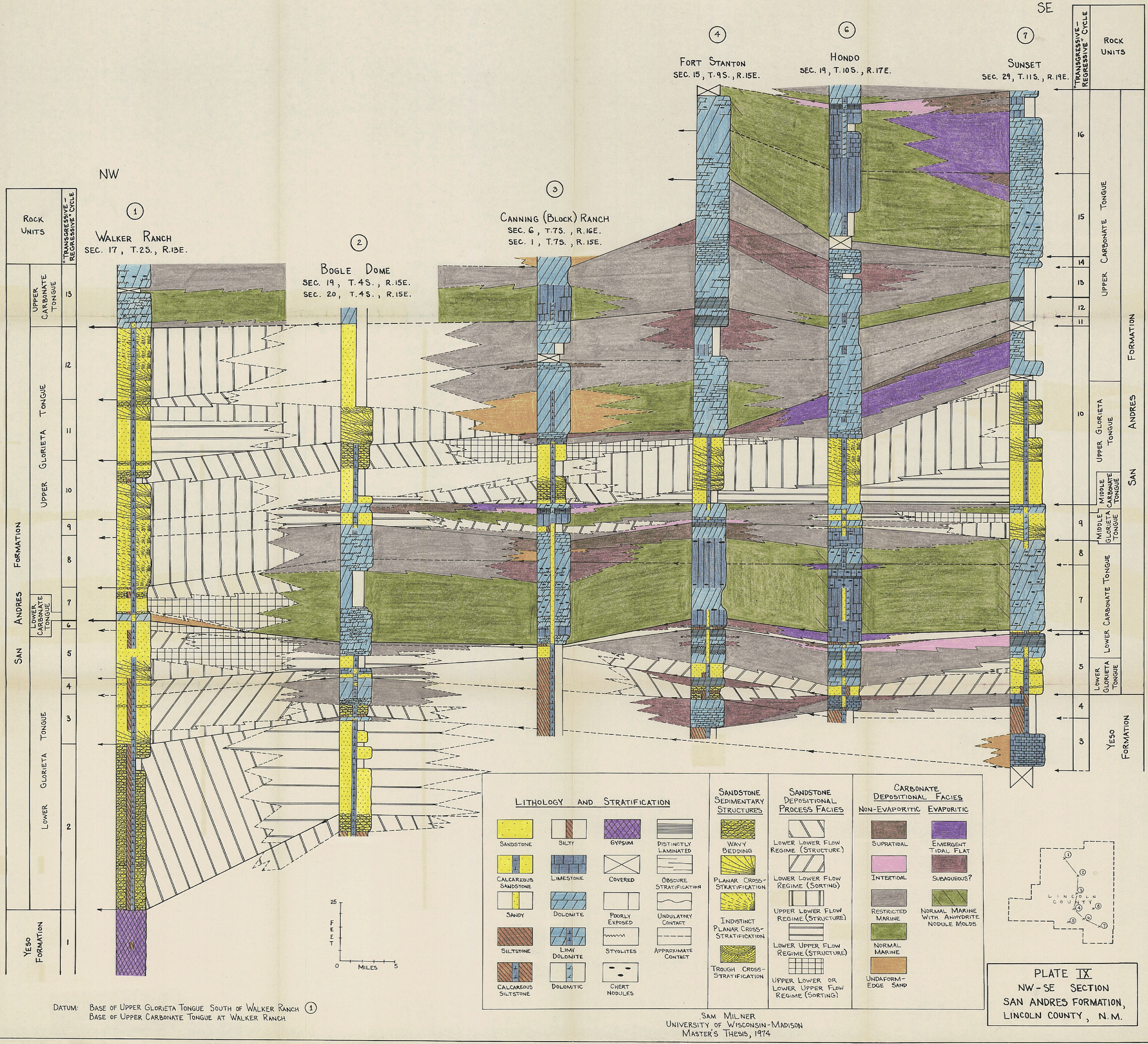
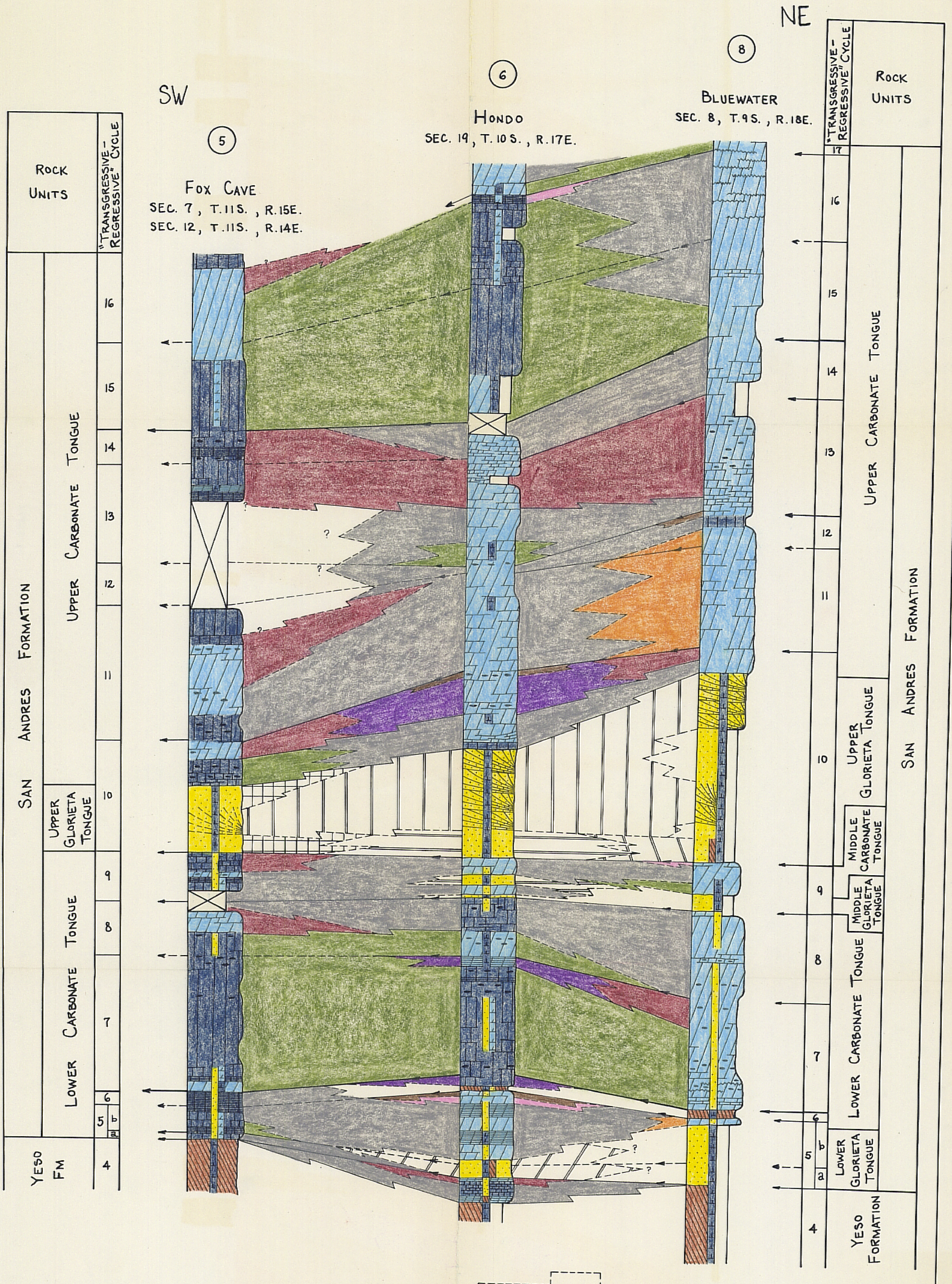
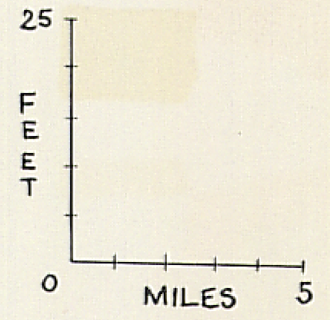
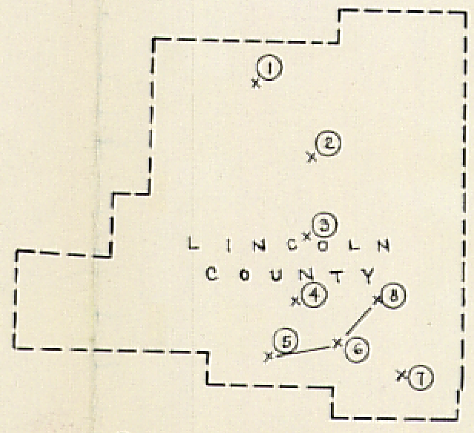


Plate IX
NW-SE Section
San Andres Formation,
Lincoln County, N.M.







Datum: Base of Upper Glorieta Tongue

Note: Igneous Intrusions Not Included In Fox Cave Section

Sam Milner
University of Wisconsin–Madison
Master's Thesis,
1974

Legend on Plate IX

Plate X
NE - SW Section
San Andres Formation,
Lincoln County, N.M.

PLATE XI

ROCK UNIT NAME (AND AGE)	
CUMULATIVE THICKNESS, FEET	
ROCK UNIT THICKNESS, FEET	
ROCK UNIT NUMBER	
SAMPLE NUMBER	
GRAPHIC SECTION	
10% GRAINS: MUD SUPPORT / GRAIN SUPPORT	(MUD < .06mm – INFERRED FOR MOST DOLOMITES)
.0625 – .25 mm FINE SAND .25 – .50 mm MEDIUM SAND .50 – 2.0 mm COARSE SAND 2.0 – 4.0 mm GRANULE 4.0 – 64.0mm PEBBLE 64.0 – 256.0 mm COBBLE	"DOMINANT" GRAIN SIZE (SEE TEXT)
INTRACLASTS FECAL PELLET CLUSTERS PELOIDS QUARTZ GRAINS "SUPERFICIAL" OOLITHS "TRUE" OOLITHS	ALLOCHEMS (EXCL. FOSSILS)
UNIDENTIFIABLE BRACHIOPODS BRYOZOANS CRINOIDS ECHINOIDS FORAMINIFERA GASTROPODS OSTRACODS PRODUCTIDS (AND/OR SPINES) OTHER BIOTA	FAUNA
CRYPTALGAL LAMINATES ALGAL STROMATOLITES ONCOLITES PHYLLOID ALGAE	ORGANOSEDIMENTARY STRUCTURES AND ALGAE
GENERAL BURROWING CRUZIANA MOTTLING	BIOGENIC STRUCTURES
BRECCIATION CALCITIZED ANHYDRITE FENESTRAL FABRIC MUDCRACKS	SEDIMENTARY STRUCTURES
THIN LAMINATION (< 1") LAMINATION (1 – 5") VERY THIN BEDDING (.5 – 2.0") THIN BEDDING (2.0 – 6.0") MEDIUM BEDDING (6.0" – 1.5') THICK BEDDING (1.5 – 5') VERY THICK BEDDING (> 5') MASSIVE WAVY BEDDING	STRATIFICATION
SMALL SCALE (< 3") MEDIUM SCALE (3" – 3') LARGE SCALE (> 3') TROUGH PLANAR	CROSS-STRATIFICATION
INTERPARTICLE INTRAPARTICLE INTERCRYSTALLINE EVAPORITE MOLDIC FOSSIL MOLDIC VUG/CHANNEL	POROSITY
100 – 0 PERCENTAGE PRESENT < .01mm, .01 – .03mm, > .03mm CRYSTAL SIZE	DOLOMITE
CHERT NODULES FOSSIL SILICIFICATION DEDOLOMITE STYOLITES PETROLIFEROUS	POST-DEPOSITIONAL FEATURES
N 1 3 5 7	VALUE (LIGHTNESS)